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REPORT

The hydrogeologic connectivity of a low-flow saline-spring fen peatland within the Athabasca oil sands region, Canada

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Abstract Saline springs can provide clues as to the nature of groundwater flow, including how it relates to subsurface wastewater storage and the distribution of solutes in the landscape. A saline-spring peatland neighboring a proposed in-situ oil facility was examined near Fort McMurray, Alberta (Canada). The study area is situated just north of a saline groundwater discharge zone, which coincides with the erosional edge of the Cretaceous Grand Rapids Formation. Na^+ (mean 6,949 mg L^{-1}) and Cl^- (mean 13,776 mg L^{-1}) were the dominant salts within the peatland, which increased by an order of magnitude in the opposite direction to that of the local groundwater flow. Rivers and freshwater wetlands within the study area had anomalously high salinities, in some cases exceeding 10,000 mg L^{-1} total dissolved solids within deeper sediments. Saline-spring features were observed as far as 5 km from the study area. A low-permeability mineral layer underlying the peatland restricted vertical groundwater exchange (estimated to be less than several mm over the 4-month study period). Sand and gravel lenses underlying the fen's high-salinity zone may function as areas of enhanced discharge. High Cl/Br ratios point to halite as a potential source of salinity, while $\delta^{18}O$ and $\delta^{2}H$ signatures in groundwater were lower than modern-day precipitation or Quaternary aquifers. The complex connectivity of saline-spring wetlands within the landscape has implications for industry and land-use managers, and justifies incorporating them into monitoring networks to better gauge the magnitude and flow history of natural saline discharge in the oil sands region.

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Introduction

Saline-spring features have been observed historically throughout the Western Boreal Plains (WBP) of Canada, and their study has provided useful insight into origin and connectivity of regional flow systems (Grasby and Chen 2005; Grasby 2006; Grasby and Londry 2007), as well as the magnitude and distribution of saline discharge in the landscape (Hitchon et al. 1969; Jasechko et al. 2012; Gibson et al. 2013). While discrete, high-salinity springs have been studied in detail in Alberta's Boreal Plains, less is known about the hydrologic function of saline spring wetlands, whose discharge tends to be more diffuse (Scarlett and Price 2013; Wells and Price 2015). Understanding the function and connectivity of these discharge features can provide important clues into the nature of groundwater flow in the Athabasca oil sands region (AOSR), including the flow history of brines, the influence of saline discharge on ecosystem function and the link between springs and subsurface wastewater containment (Carrigy and McLaws 1973; Hackbarth and Nastasa 1979; Gordon et al. 2002; Gupta et al. 2012; Ferguson 2014). With over 80 % of the recoverable bitumen too deep for traditional surface mining, in-situ operations are expected to quickly become the dominant oil sands extraction method in the near future (Jordaan 2012). Consequently, successful subsurface extraction and storage requires a sound understanding of all possible surface–subsurface hydrologic connections (Gordon et al. 2002; Jasechko et al. 2012).

In the AOSR, saline springs typically consist of an observable discharge outlet connected directly to Paleozoic era Devonian carbonates that either subcrop or are exposed completely to the surface (Hitchon et al. 1969; Grasby 2006). These springs are typically karstic in origin and are found along the banks of the Athabasca and Clearwater rivers, where erosion has deeply incised into the exposed carbonate rocks (Ozoray et al. 1980; Ford 1998; Jasechko et al. 2012; Gibson et al. 2013; Broughton 2013). Sodium chloride springs comprise 4 % of the springs in Alberta and are found exclusively in the northeastern region of the province (Borneuf 1983), where the composition of subsurface brines represent a mixture of geochemical end members related to seawater, evaporite dissolution and freshwater mixing (Rittenhouse 1967; Connolly et al. 1990a; Michael et al. 2003; Gupta et al. 2012). Within the Fort McMurray and Wood Buffalo regions of the AOSR, isotopic evidence and major ion composition of both high- and low-flow springs indicate that discharge water is not related to evaporated brine but is of meteoric origin, with elevated salinity a result of contact with buried evaporite beds, namely halite (Last and Ginn 2005; Grasby 2006; Grasby and Londry 2007; Berard et al. 2013).

Owing to the expansion of in-situ projects within the AOSR, considerable industry attention has been given to the subject of in-situ extraction and subsurface wastewater disposal (Carrigy and McLaws 1973; Hackbarth and Nastasa 1979; Gordon et al. 2002; Ferguson 2014). Due to the shallow depth of the regional stratigraphic package and the limited number of confining layers isolating disposal zones from the surface, the potential for leakage and horizontal and upward migration of disposal fluids is large (Hackbarth and Nastasa 1979; Bachu et al. 1989; Gordon et al. 2002). Structural complexities related to Paleozoic salt bed erosion (e.g. massive-scale karst) and Pleistocene glacial events (e.g. Quaternary incised channels), the outcropping of potential disposal zones at or near the surface and saline springs connected to the subsurface intensify the risk for cross-formational flow (Gordon et al. 2002; Andriashek and Atkinson 2007; Broughton 2013; Cowie et al. 2015). The storage of process water within the subsurface may create extra pressures that could augment groundwater flow and establish new connections with deeper flow systems causing higher flow rates from springs as well as increasing the proportion of salt in discharge waters (Carrigy and McLaws 1973; Hackbarth and Nastasa 1979). The gravity of this issue is particularly relevant to the saline spring wetland complex that forms the basis of this study, where a steam-assisted gravity drainage (SAGD) pilot plant aims to inject wastewater within the underlying McMurray Formation. In order to better understand the heterogeneous nature of the regional hydrogeological flow system and assess saline spring wetlands as conduits for subsurface discharge, knowledge of spring hydrology and their linkage to deep groundwater is required. With this in mind, the specific objectives of this study are to (1) identify and describe the connectivity of a low flow saline spring wetland located near an in-situ extraction site and investigate its potential as a conduit for deep groundwater discharge; and (2) link site-scale geochemistry to regional-scale fluid flow to identify the connection of spring discharge to underlying formation waters.

Site description and hydrogeologic setting

Regionally, the AOSR is located on the northeastern margin of the Alberta Basin, a sub-basin of the Western Canadian Sedimentary Basin that forms a simple sedimentary wedge resting unconformably on buried Precambrian rocks of the Canadian Shield. To the west, the sedimentary package exceeds 5,700 m but thins to a northeastern zero-edge where the Precambrian Shield becomes exposed as a result of depositional thinning and erosion (Grasby and Chen 2005; Connolly et al. 1990a). The simplified modern-day hydrodynamic regime of the Alberta Basin is predominantly south to north through Cambrian sandstones and Devonian through Mississippian carbonates. Thick sequences of shale and silt units form regional aquitards through most of the overlying Mesozoic strata; however, interbedded sandstones form local and in some cases regional-scale aquifers (Bachu 1995). Throughout most of the Alberta basin, local and regional-scale flow processes are modified by highly permeable Upper Devonian and Carboniferous carbonate rocks that channel flow from the entire basin northward where it discharges in the AOSR (Hitchon 1969). Considerable postglacial erosion within the AOSR has exposed Paleozoic strata to atmospheric conditions and, in general, formation waters that follow the basin-wide trend begin to show a modification in their flow paths due to atmospheric exposure and the influence of topographic and physiographic features (Bachu et al. 1993). Regional-scale fluid flow follows a northeast direction while near-surface Cretaceous aquifers show strong local flow characteristics and correspondingly low salinities caused by the influx of meteoric waters.

The saline fen study site (56°34′28.84″ N, 111°16′38.39″ W) is located approximately 10 km south-southeast of the AOSR hub of Fort McMurray, Alberta (Fig. 1), within the Central Mixedwood Subregion of the Boreal Plains Ecozone (Natural Regions Committee 2006). Several km east of the study site is a SAGD pilot project, a 3-year operation aiming to test the reliability of the in-situ process and regional caprock integrity. At peak production it will produce 1,000 barrels of crude oil per day from the McMurray Formation, which will also serve as the disposal reservoir for process-affected wastewater (Value Creations Inc. 2012).

The fen lies at approximately 400 m above sea level (a.s.l.) within the McMurray lowlands subdivision of the Dover Plains, a relatively flat region characterized by thick, widespread organic deposits (Andriashek 2003). Several prominent upland features roughly encircle the broad lowlands surrounding the Fort McMurray area, the closest of which is the

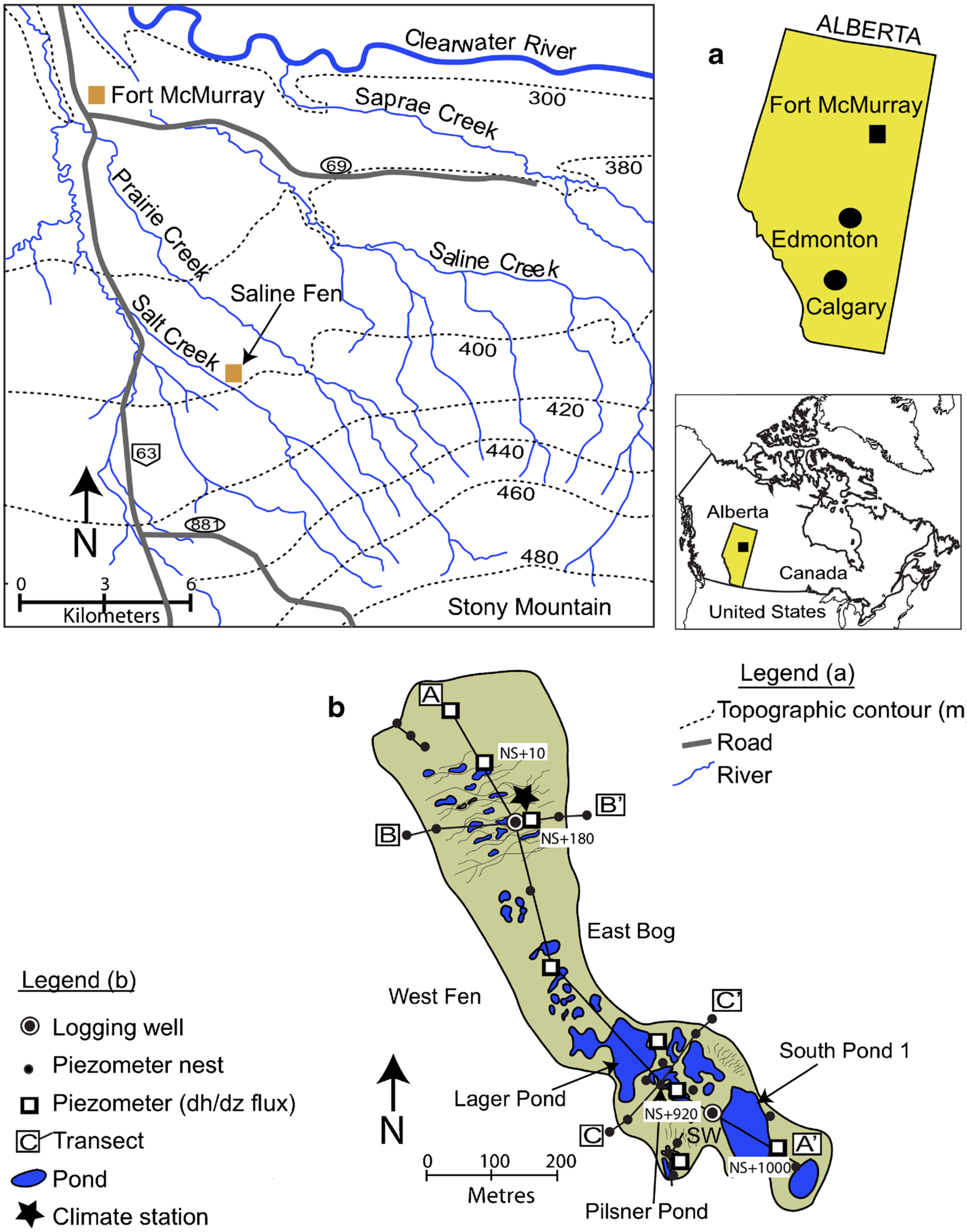

Fig. 1 **a** Regional map showing the location of Fort McMurray within Alberta, Canada and local map of the study area and **b** map of the saline fen study site, including transect locations and instrumentation (adapted from Wells and Price 2015)

Stony Mountain complex approximately 15 km south of the saline fen (Fig. 1; Hackbarth and Nastasa 1979). Flowing northwestward from the Stony Mountain uplands through the study area are the primary tributaries of the Hangingstone River; the Saline River, Prairie Creek and Salt Creek basins. Comprising an area of approximately 27 ha, the saline fen lies adjacent to several other large peatland complexes of similar salinity and configuration. The surface elevation of the fen declines northward and is characterized by a steep gradient in the south (~8 m km^{-1}) that transitions into a gently sloping plain in the north half of the fen (~2.7 m km^{-1}; Fig. 2). A large pond network comprises ~19 % of the fen surface. The fen's southern region contains a number of spring-like features, including salt surface crusting, halophytes and extremely saline 'hot spots' devoid of vegetation (Wells and Price 2015)

Around the saline fen study region, glacial drift is variable (5–30 m thick) and ranges from clay-rich glacial till to poorly

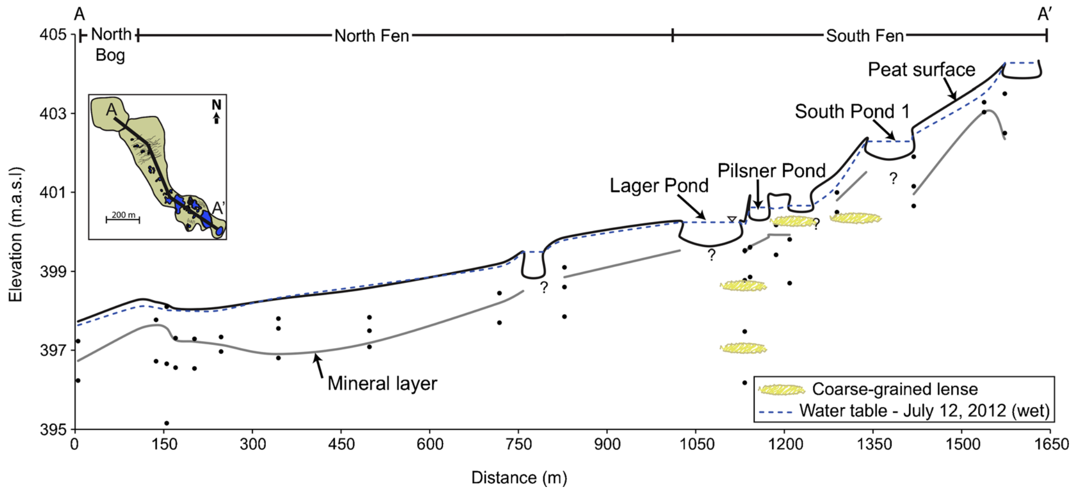

Fig. 2 Cross-section of the saline fen along the primary *A–A′* transect (see Fig. 1b), showing wetland soil thickness and depth to underlying mineral sediment along with a typical water-table position during a wet period. *Question marks* denote areas where location of mineral sediment is unknown while *black dots* show piezometer locations. Coarse-grained lenses in the south fen (*yellow hash marked ellipses*) were located during drilling and their lateral and vertical extent is unknown (adapted from Wells and Price 2015)

sorted sands (Fig. 3). Underneath the glacial drift lies the shale-dominated Clearwater Formation (70–90 m thick), which towards its base grades from sandy shale and sandstone to marine shale (Figs. 3 and 4; Andriashek 2003; Value Creations Inc. 2012). The Clearwater functions as a regional caprock, with a median hydraulic conductivity of approximately 1×10^{-7} m s^{-1} (Hackbarth and Nastasa 1979). The thickness of the bitumen-bearing McMurray Formation varies from 40 to 80 m within the study area and consists of shales and sandstones resting unconformably on the Devonian Beaverhill Lake Group (Figs. 3 and 4; Value Creations Inc. 2012). The McMurray Formation is also targeted as the disposal zone for wastewater produced by the nearby SAGD facility. Devonian age limestone of the Beaverhill Lake Group underlies the McMurray Formation at a depth of approximately 180 m. Calcareous shales and dolomites along with non-calcareous mudstones also characterize this group. The Lower Cretaceous Grand Rapids Formation typically forms the bedrock surface for most of the Dover Plains but extensive erosion has truncated the formation to just south of the study site (Fig. 4). Sands saturated with freshwater can be found along the bottom of the Grand Rapids Formation; however, saline groundwater plumes have been identified south of the study area which flow northeast and discharge just south of the wetland complex (Fig. 4; Value Creations Inc. 2012).

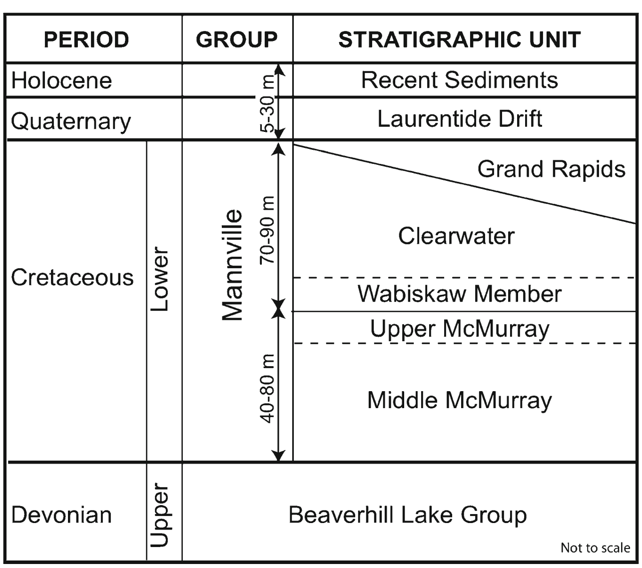

Fig. 3 Simplified stratigraphic chart for the study region. The erosional edge of the Grand Rapids Formation is just south of the saline fen complex and thus is not present in the study area. Note the location of the McMurray Formation, which is the proposed disposal zone for the adjacent SAGD facility (adapted from Value Creations Inc. 2012)

Methods

Groundwater and soil characteristics

Nests of wells and piezometers were installed in three transects (A–A′, B–B′ and C–C′) across the fen and into adjacent wetlands (30 total nests; Fig. 1) by pre-auguring a hole and manually inserting the pipes. For installation into the underlying mineral layer or into peat that was particularly dense, a mallet was used to drive the pipes the remaining distance. All nests were constructed from 2.5-cm-inner-diameter polyvinyl chloride pipes with each nest consisting of a well slotted along its entire length below the ground surface and two to five piezometers that were sealed at the bottom with 17-cm slotted screens

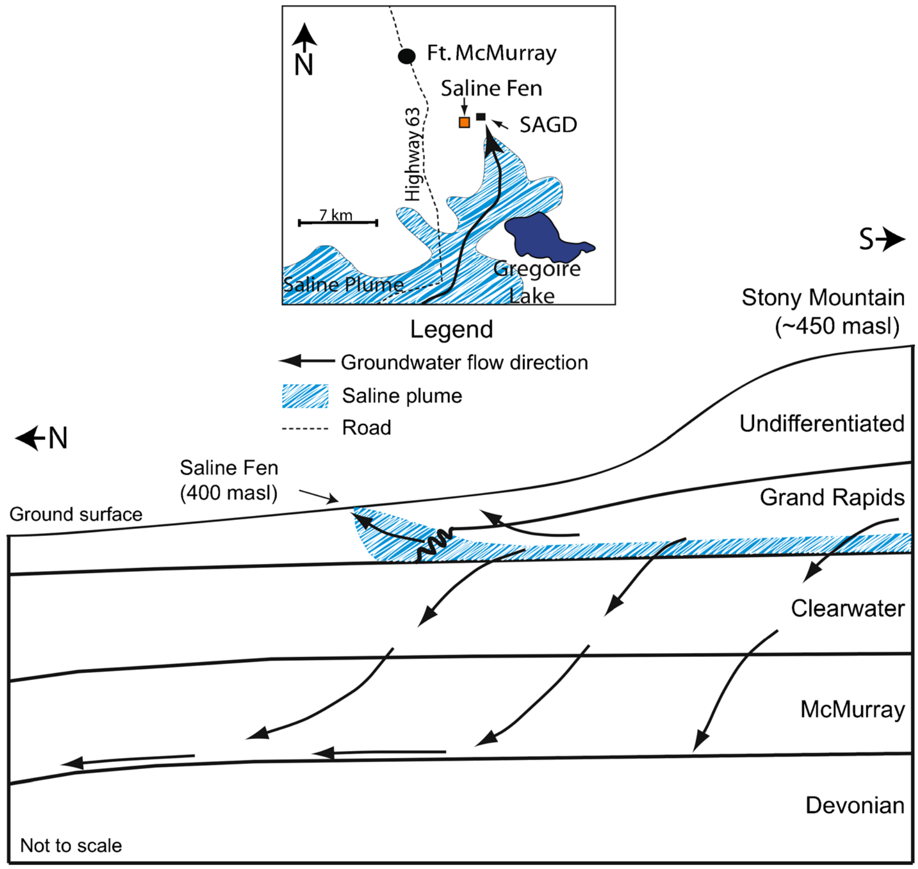

Fig. 4 Simplified hydrogeologic cross section of the saline fen study area. A saline plume (*cyan hash marked region)* flowing northeastward within the Grand Rapids Formation discharges at the formation's erosional edge just south of the study area. The *inset map* shows the approximate location of the saline plume and its flow direction (adapted from Value Creations Inc. 2012)

covered in well sock. Piezometer depths varied according to peat thickness but were usually centered at 0.50 and 0.75 m within the peat and between 1.0 and 3.0 m within the mineral layer. Nests located within zones of very high salinity had additional piezometers set at depths ranging from ~3.0 to 4.0 m. Pressure transducers (Schlumberger Mini-Divers, accuracy±0.5 cm H_2O) were installed at two wells located in the north (NS+180) and south end (NS+920) of the primary transect (A–A′, Fig. 1); manual measurements were taken at least once per week between June and September in 2011 and April and September in 2012. Fen topography and pipe-top elevations were measured and referenced to sea level using a dual-frequency survey-grade differential global positioning system (DGPS) in real-time kinematic survey mode (Topcon GMS-2). Survey precision was manually set at 0.003 m (z) and 0.005 m (x,y) and the DGPS only recorded points where these conditions were met. Pumping tests (Hvorslev 1951) were completed on 30 piezometers in peat and 11 piezometers in the mineral sediment for the estimation of horizontal saturated hydraulic conductivities. In-field assessment of soil cores was conducted using methods described in the Standard Practice for Description and Identification of Soil (Visual Manual Procedure), ASTM Standard D2488-09a (2009).

Darcy's Law was used to estimate groundwater fluxes to and from the peatland (Freeze and Cherry 1979)

$$Q = -KA\frac{\Delta z}{\Delta l} \quad (1)$$

where Q is the discharge ($m^3\ s^{-1}$), K is the saturated hydraulic conductivity ($m\ s^{-1}$), A is the cross-sectional area (m^2) and $\Delta h/\Delta l$ is the hydraulic gradient (dimensionless). Vertical fluxes were calculated using two methods. First, K values determined for piezometers where bail tests were completed were used for the calculation of flux at that particular location. Because hydraulic conductivities could not be determined for all nests used for the calculation of vertical hydraulic gradients ($\Delta h/\Delta l$), a geometrically averaged K obtained from the till was used. Vertical flux rates were determined by using $\Delta h/\Delta l$ between the piezometers in the mineral and the water table measured within an adjacent well.

Due to elevated groundwater salinities within piezometers, hydraulic heads had to be corrected for differences in density and converted to freshwater equivalents before vertical gradients and fluxes could be calculated. Below 10,000 mg L^{-1} total dissolved solids (TDS) and at temperatures below 100 °C, groundwater is considered to have densities comparable to freshwater (Freeze and Cherry 1979). Therefore, only piezometer locations where TDS exceeded this threshold were corrected (Freeze and Cherry 1979). Hydraulic heads were corrected to freshwater equivalents where necessary using the method described in Fetter (2001) and a full description of density corrections can be found in Wells and Price (2015).

Geochemistry

Groundwater was sampled from each piezometer along the A–A′, B–B′ and C–C′ transects in July of 2011 and in June and August of 2012. Pond surface-water samples were obtained only in 2012 (both June and August) from selected ponds and pools that were also measured in-situ at least once per week during the season. Plastic tubing with foot-valves were used to extract groundwater samples and tubing was rinsed thoroughly with distilled water after each extraction. Piezometers were evacuated several days before sampling to ensure representative pore water was obtained. Unstable parameters (pH, temperature, electrical conductivity and salinity) were measured in the field by a handheld device (YSI 65 m) calibrated daily. Electrical conductivity (EC) measurements were corrected in the field to 25 °C. For the remaining parameters, samples were collected, filtered and preserved on ice in the field and frozen before laboratory analyses.

Major ion concentrations and alkalinity were determined at the University of Waterloo (Wells and Price 2015). Analytical error in concentration measurements was determined to be less than 5 %. The concentration of TDS was estimated by summing the concentrations of the individual major ions (Fetter 2001). Bromide was determined separately using neutron activation analyses at the University of Alberta's SLOWPOKE Nuclear Reactor Facility. Saturation indices were calculated in PHREEQC using the Pitzer aqueous model for high-salinity waters (Parkhurst and Appelo 2013), where a saturation index >0 is saturated with respect to that mineral. Stable isotope data were determined at the University of Waterloo Environmental Isotope Laboratory. $\delta^{18}O$ was determined by CO_2 equilibration measured on an IsoPrime continuous flow isotope ratio mass spectrometer system (CF-IRMS). Deuterium (δ^2H) was measured using hydrogen gas produced by chromium reduction. Highly saline samples were pre-processed using azeotropic distillation for the determination of $\delta^{18}O$ and δ^2H following the methods of Dewar and McDonald (1961). Results for $\delta^{18}O$ and δ^2H are referenced to the Vienna Standard Mean Ocean Water (SMOW) standard. Analytical errors for isotope analyses were estimated to be ±0.2 ‰ for $\delta^{18}O$, ±0.8 ‰ for δ^2H.

Local and regional hydrogeology

Hydrogeology and surface- and formation-water chemistry data for the study area was compiled from field assessments conducted for the TriStar Pilot Project (Value Creations Inc. 2012) and the Alberta Geological Survey (Stewart and Lemay 2011). Local geology was determined by drilling supplemented with borehole and petrophysical analyses. Groundwater flow direction was estimated through the use of pressure transducers installed in wells while formation water chemistry was determined by calibrating open-borehole resistivity logs to measurements of TDS (Value Creations Inc. 2012).

Results

Stratigraphy and hydraulic conductivity

Peat thickness averaged 1.2 m and varied considerably across the fen, ranging from 1.5 m at its depocenter in the north half of the fen (Fig. 2) to almost zero along a thin band towards the fen's southwest margin (not shown). North of Lager Pond, the peat deposit thickened and the underlying mineral layer formed a basin-like morphology that quickly transitioned into an elevated mound along the bog-saline fen margin. Field-based classification of the underlying mineral sediment indicated a high clay fraction. A larger fraction of coarse-grained sediments was observed in the south end of the system, including shell fragments and a distinct hydrocarbon odour. Field estimates of horizontal saturated hydraulic conductivities (K_H) for peat and mineral are shown in Fig. 5. The geometric mean K_H of the fen peat was 1.8×10^{-5} cm s^{-1}, or 1.6 cm d^{-1} (n=18) with considerable range both spatially across the fen and with depth. Underlying the peat and found throughout the fen, including ponds and pools, was a fine-grained mineral layer. A geometrically averaged field estimate of mineral K_H was found to be 5.5×10^{-7} cm s^{-1}, or 0.05 cm d^{-1} (n=11). Spatially, in-the-field inspection suggested minimal variability in mineral layer properties; however, K_H varied between 10^{-5} and 10^{-8} cm s^{-1}, with the highest K_H observed in the high-salinity zones in the fen's southern section.

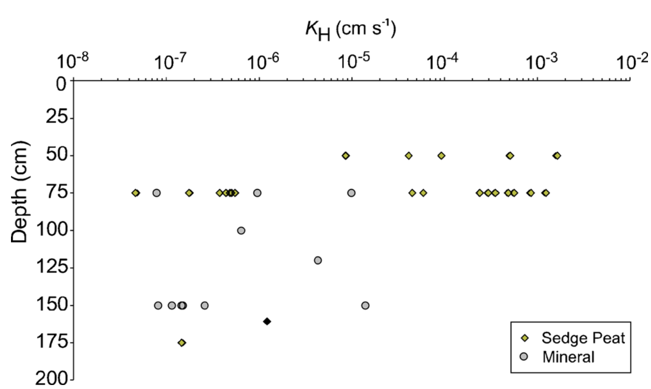

Fig. 5 Field (>50 cm depth) estimates of saturated horizontal hydraulic conductivities for peat and underlying mineral sediments (adapted from Wells and Price 2015)

Long-term regional precipitation trends

It is important to consider the hydrologic function of the saline fen during the current (2011–2012) study period in the context of the long-term climate trends for the Fort McMurray area (Fig. 6), typically represented by dry or mesic conditions punctuated by wet periods that occur on decadal to multi-decadal cycles (Bothe and Abraham 1993; Marshall et al. 1999; Devito et al. 2012). According to the historical data, above-average precipitation over a 10-year period between 1967 and 1977 helped to eliminate the accumulated moisture deficit developed in previous years, as indicated by a positive cumulative departure from the long-term mean (CDLM). A long-term moisture surplus was sustained until the mid-1990s, after which a return to a dry period of the climate cycle saw a gradual redevelopment of a multi-year deficit. While the long-term record is incomplete (no annual totals for 2007–2008 or 2011–2012 study years), monthly totals during the 2011 study season (June to mid-September, 193 mm) were all well below monthly climate normals for the Fort McMurray area (273 mm for the same period). The saline fen study area saw an above average input of rainfall during the summer of 2012 (366 mm between April and mid September), but based on the long-term trend and average for the region (465 mm/year) this was likely insufficient to eliminate entirely the cumulative long-term moisture deficit. This places the 2011–2012 study period into a dry period of the climate cycle.

Vertical groundwater input to the saline Fen

In 2012, groundwater transects were expanded and the longer study season (late April to mid-September) provided a larger sample size compared to 2011. Thus, only 2012 groundwater data are presented. Vertical groundwater input to the fen was calculated using *dh*/*dz* determined between the underlying mineral sediments and overlying peat. Following the spring freshet in late March, water tables rose rapidly, temporarily flooding its northern extent (nest NS+180; Fig. 7). Following a dry spring and early summer, water tables gradually decreased until a series of storms beginning in late June and early July. Across the fen water tables routinely breached the surface during these wetting events but, in the north, flooding conditions persisted for the majority of the season. In the south fen (nest NS+920, Fig. 7), hydraulic head measurements for the piezometer located within the underlying mineral layer rose gradually between early May and mid-June. This is in contrast the local water table, which decreased in response to minimal rainfall. Piezometers were sampled on June 15th and thus provided no reliable data until they had recovered (hence the gap in the data series in Fig. 7). Before this period hydraulic head in the piezometer at NS+920 plateaued and on June 11th *dh*/*dz* indicated discharge conditions until a minor rain event resulted in a rapid water-table rise. The piezometer at NS+920 did not recover after water sampling until the end of the summer season but a measurement in later October indicated strong recharge conditions. Hydraulic heads within the north fen nest (NS+180) followed more closely the local water table (Fig. 7). As water tables decreased, discharge conditions were observed temporarily in late May. While hydraulic heads recovered more rapidly at NS+180 post-sampling, *dh*/*dz* indicated recharge conditions for the remainder of the season.

Due to the generally low K_H of the mineral layer (site geomean of 5.5×10^{-7} cm s^{-1}) and the sharp contrast in permeability between it and the overlying peat, site-scale trends in *dh*/*dz* (and thus fluxes) were difficult to elucidate.

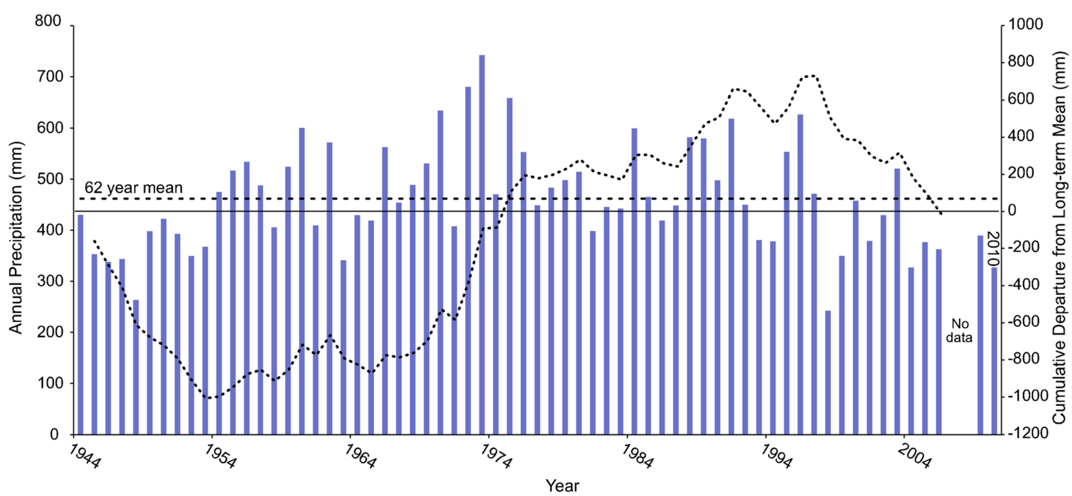

Fig. 6 Long-term precipitation trends (1944–2006) for the Fort McMurray area. The *62-year mean* (465 mm) is shown as the *dashed horizontal line*. The cumulative departure from long-term mean (CDLM) is shown as the *fluctuating black dotted line*, which corresponds to the secondary y-axis. When the CDLM is negative, the region is in a cumulative moisture deficit while a positive CDLM indicates a cumulative moisture surplus. Annual precipitation totals for the two study years (2011 and 2012) are not shown due to the lack of a complete annual dataset for those years (Environment Canada 2014)

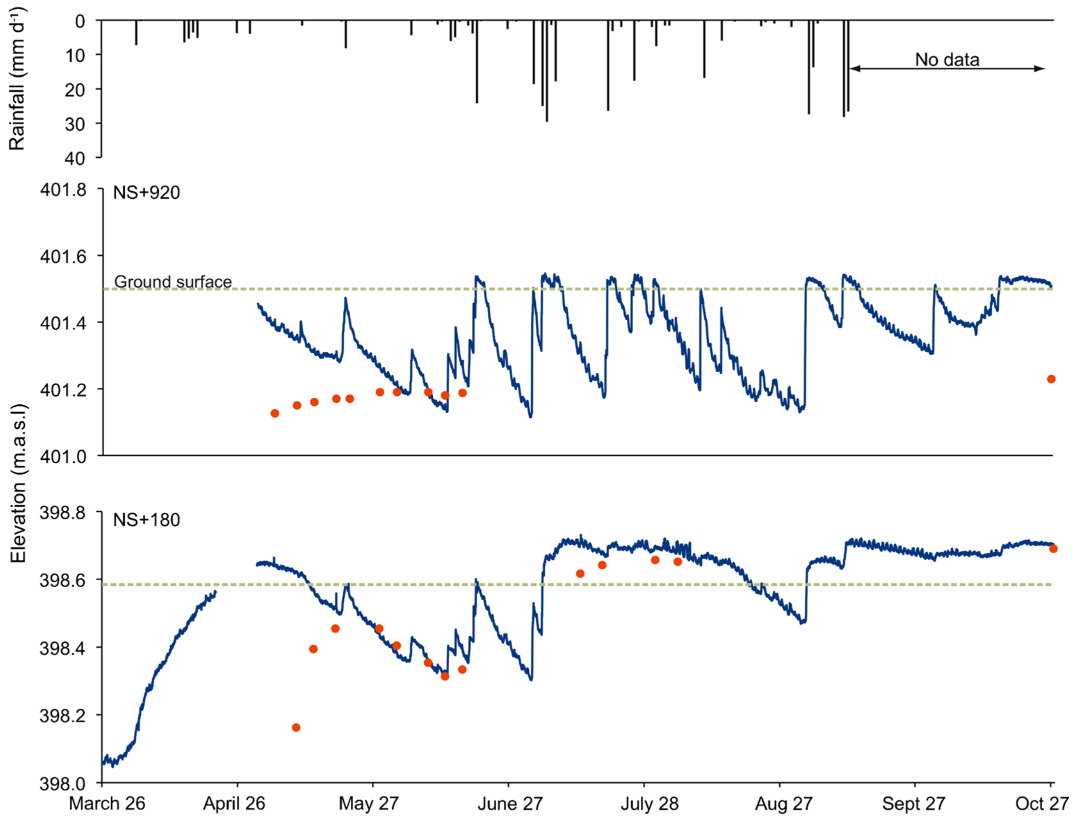

Fig. 7 Rainfall and water table hydrographs of the north (NS+180) and south (NS+920) fens for the 2012 study season. Hydraulic head measurements for adjacent piezometers located within the underlying mineral till are shown as *orange dots*. Note the measurements taken at the *end of October*. See site map for nest locations

For many nests, *dh*/*dz* had to be interpreted with caution due to the possibility of piezometer lag-time errors that may have artificially indicated discharge conditions in response to changing boundary conditions. If piezometers did not fully recharge after installation or sampling and if time-lag periods exceeded measurement cycles, *dh*/*dz* values were discarded prior to analyses. To determine if time-lag errors between deep piezometers and the water table were ubiquitous across the site, individual nests were investigated more closely. In most cases, absolute change in hydraulic head decreased with depth across the fen; however, for some nests, changes in hydraulic head within deep piezometers (i.e. within the mineral sediments or deep basal peat) closely matched changes recorded at the water table (Fig. 8c). Rapid equilibration with changing pore-water pressures indicates that these nests provide accurate estimations of recharge or discharge conditions at the saline fen. For other nests with similar response (e.g. NS+1,000, Fig. 8a), discharge conditions were often consistent despite fluctuations in the water table. In contrast, other piezometers at different nests were insensitive to short-term weather changes and water-table fluctuations (e.g. NS+920, Fig. 8b). After the spring piezometer purge in May, hydraulic heads within the 1.0 m piezometer continued to increase despite site-scale drying trends, which led to questionable discharge conditions between day of year (DoY) 159 and 163. After the sample period on DoY 167, the piezometer never recharged.

For the calculation of vertical groundwater flux into the saline fen from the underlying mineral layer, a site-average K_H was applied due to the lack of nest specific K_H data for the entire piezometer network. Based on *dh*/*dz* from nests that equilibrated rapidly enough to changing boundary conditions and a site-scale average K_H of the mineral layer, the flux of deep groundwater to or from the fen was estimated to be very low. Over the 110-day study period, groundwater discharge was estimated to be less than several mm. Nevertheless, the estimated input of deep groundwater could be much higher, as indicated by K_H in some locations several orders of magnitude higher than the site-average. At a high-salinity zone just south-east of Lager Pond, a coarse mineral layer composed of sands and fine gravel at a depth of 1.50 m had a K_H of 10^{-5} cm s^{-1}. Based on seasonal average *dh*/*dz* of −0.06 at this nest, specific discharge occurred at a rate of 8.5 mm d^{-1}. While only three of the eleven locations tested for mineral K_H were faster than 10^{-7} cm s^{-1}, the potential of other high-K_H zones may together increase the bulk hydraulic conductivity and, thus, magnitude of groundwater flux at the fen. The function of some of the larger ponds as discharge windows could not be confirmed (e.g. Lager Pond or South Pond 1) and at no point during the study period were active spring outlets observed.

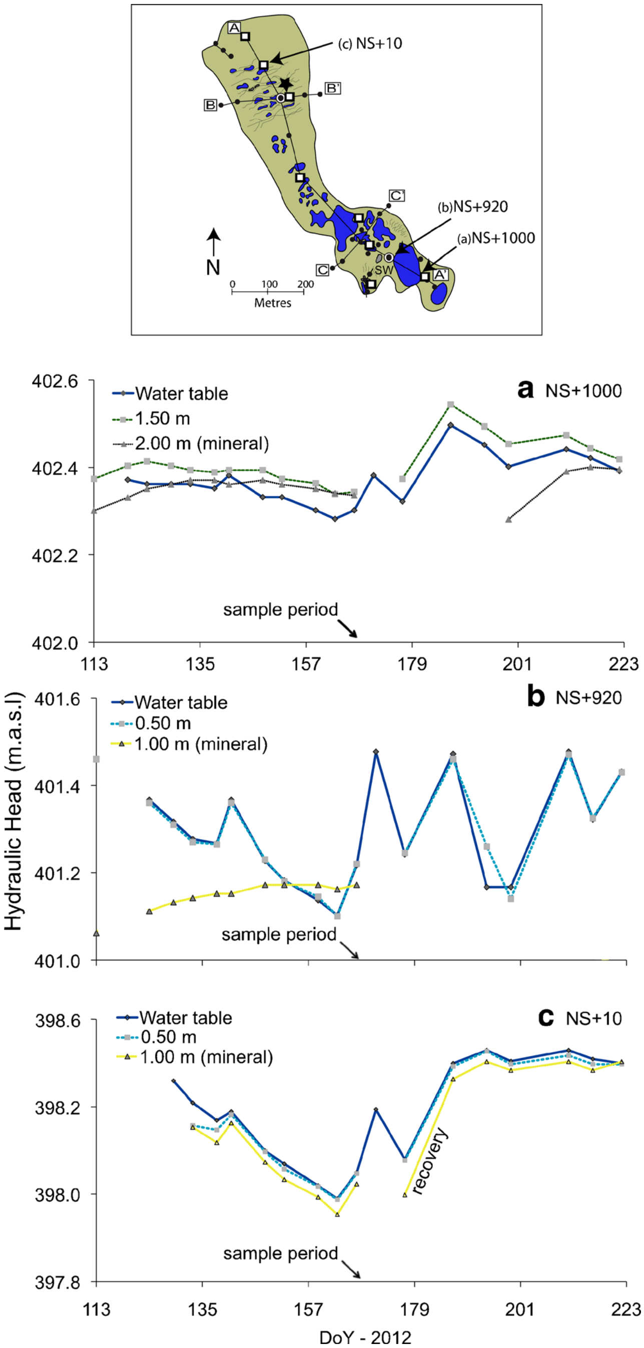

Fig. 8 Comparison of absolute change in hydraulic head between deep piezometers and the water table for select nests for the 2012 study season (see *inset map*). **a** NS+1,000: the deep piezometer closely matches water-table change and discharge is consistent throughout the season; **b** NS+920: change in hydraulic head with depth is reduced and is less sensitive to drying trends; **c** NS+10: deep piezometers closely match water-table change but show consistent recharge over the season

Salinity distribution

The TDS content of groundwater and surface waters varied widely across the fen, from slightly brackish (2,893 mg L^{-1}) to hyper-saline (87,971 mg L^{-1}; Table 1). For the entire fen, average groundwater TDS was 22,230 mg L^{-1} and TDS was only slightly greater within the fen peat on average (mean 26, 668 mg L^{-1}) compared to the underlying mineral layer (mean 24,464 mg L^{-1}). Surface-water features (i.e. ponds and pools) were typically less saline than the adjacent peat, with some exceptions in the fen's southern region (Table 1). Along the primary transect (A–A′), TDS increased steadily southward in the opposite direction to that of local groundwater flow (Fig. 9). A sharp rise in TDS was observed in groundwater and surface waters in the relatively small area bordered by South Pond 1 and Lager Pond. Upslope of South Pond 1, TDS decreased sharply but remained generally high, increasing again towards the fen's southern-most margins at the border of South Pond 2. While the adjacent freshwater wetlands were generally less saline than the saline fen, TDS concentrations were still high within the underlying mineral layer, most notably within the western fen (17,485 mg L^{-1}; Table 1).

Surface-water samples collected during hydrogeologic investigations for the nearby SAGD project (June 2011 and late June, early July 2012; Value Creation Inc. 2012) and from the Alberta Geological Survey (September 2011; Stewart and Lemay 2011) were compared against samples collected at the saline fen over the 2-year study to determine the spatial extent of saline discharge for the study area (Fig. 10). In general, the presence of elevated salinity was largely restricted to the area around the saline fen and the Salt Creek Basin that runs through it. TDS increased from 500 mg L^{-1} upstream to 1,470 mg L^{-1} downstream along the reach adjacent to the saline fen. Here, a saline discharge feature similar to the saline fen (TDS of 6,430 mg L^{-1}) was found bordering the western edge of Salt Creek. Downstream, TDS remained high but decreased steadily up to the confluence between the eastern and western branches of Salt Creek. For the Prairie Creek and Saline Creek tributaries, TDS concentrations were typically no greater than 300 mg L^{-1}, with the exception of a distinct high-salinity zone along the eastern branch of Saline Creek (Fig. 10). A large saline wetland 500 m east of the saline fen in between the Prairie Creek and Salt Creek basins also showed very high salinities similar to that of the saline fen (TDS 23, 200 mg L^{-1}).

Groundwater and surface-water chemistry

Groundwater and surface waters were all dominated by Na^+ and Cl^-, which on average accounted for over 90 % of the TDS (Fig. 11). The average concentration of Na^+ at the saline fen was 6,949 mg L^{-1} (minimum 195 mg L^{-1}, maximum 25, 680 mg L^{-1}), while Cl^- was 13,776 mg L^{-1} (minimum 1, 785 mg L^{-1}, maximum 56,249 mg L^{-1}; Table 1). SO_4^{2-} was also quite high, averaging 728 mg L^{-1} with a maximum of 3, 080 mg L^{-1}. The concentration of all dissolved ions within the underlying mineral layer, with the exception of Mg^{2+} and HCO_3^-, increased by at least an order of magnitude southward

Table 1 Major ion composition of saline fen groundwater and ponds, along with wetlands to the west and east of the saline fen. Cl^{-}/Br^{-} and Na^{+}/Cl^{-} ratios are also shown for the saline fen. Groundwater samples were taken from piezometers and wells along all three transects (see Fig. 1)

Parameter (mg L^{-1})		Saline fen		Adjacent wetlands (groundwater[c])	
		Groundwater[a]	Ponds[b]	West Fen	East Bog
Cl^{-}	Mean	13,776	5,688	10,543	3,895
	Min	1,785	1,785	–	–
	Max	56,249	12,095	–	–
HCO_3^{-}	Mean	134	84	65	99
	Min	20	129	–	–
	Max	627	52	–	–
SO_4^{2-}	Mean	728	418	695	–
	Min	28	48	–	–
	Max	3,080	1,590	–	–
Ca^{2+}	Mean	391	150	650	157
	Min	48	48	–	–
	Max	1,696	515	–	–
Mg^{2+}	Mean	268	73	330	94
	Min	25	25	–	–
	Max	2,875	208	–	–
Na^{+}	Mean	6,949	2,903	5,148	1,937
	Min	108	892	–	–
	Max	25,680	6474	–	–
Alk	Mean	110	69	54	81
	Min	16	42	–	–
	Max	514	105	–	–
TDS	Mean	23,084	9,254	17,488	9,961
	Min	2,825	2,825	–	–
	Max	87,708	20,947	–	–
Cl^{-}/Br^{-}	Mean	6,331	7,654[d]	–	–
	Min	4,722	4,411[d]	–	–
	Max	9,807	10,896[d]	–	–
Na^{+}/Cl^{-}(meq/L)	Mean	0.79	0.78	–	–
	Min	0.60	0.72	–	–
	Max	0.98	0.84	–	–

[a] Includes both mineral till and peat samples (55–60 samples)

[b] Sample size of 8

[c] Sample size of <3

[d] Sample size of 2

(Fig. 12). Similar spatial trends were observed within both peat and pond surface waters, although the magnitude of increase was not as pronounced for the latter (data not shown). The sharp rise in Na^{+}, Cl^{-} and SO_4^{2} within a saline 'hot spot' at 1,000 m within the south fen is followed by a marked decrease in salts that coincides with the north end of Pilsner Pond (see Fig. 1). The south end of Pilsner Pond (1,200 m) marks the peak of salt concentration at the fen, followed by a trough that borders South Pond 1. Within the mineral layer of the adjacent freshwater wetlands, one round of groundwater sampling revealed high concentrations of dissolved salts (Table 1). Groundwater related to the dissolution of halite has a Na^{+}/Cl^{-} ratio close to 1:1. Ratios of Na^{+}/Cl^{-} (in meg/L) within fen groundwater averaged 0.80, increasing to 0.81 south of Lager Pond (minimum of 0.70, maximum of 0.98) and decreasing to 0.75 for the north fen (minimum of 0.60, maximum of 0.83). Despite the dominance of Na^{+} and Cl^{-}, fen groundwater was several orders of magnitude undersaturated with respect to halite (saturation index>0 when saturated). A modest but distinct increase towards saturation is observed moving southward in conjunction with salinity, from −3.4 in the

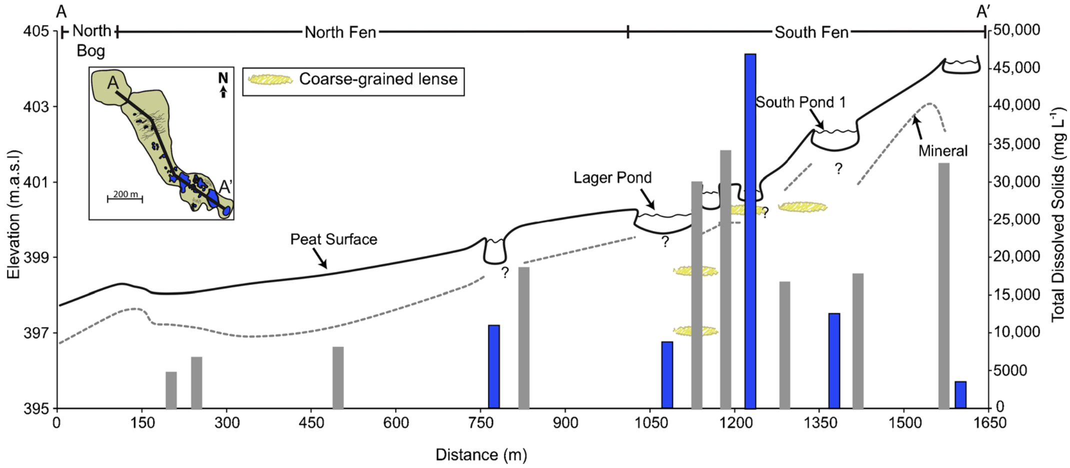

Fig. 9 TDS concentrations in groundwater within the fen's underlying mineral till (*solid grey vertical bars*) and pond surface water (*solid blue vertical bars*) along the primary *A–A′* transect (see *inset map*). *Question marks* denote locations under some larger ponds where the mineral sediment (*grey dashed line)* could not be mapped

north fen to −2.8 in the south (Table 2). The same trend is observed for gypsum and anhydrite, with groundwater in the south fen approaching saturation for both minerals (−0.97 and −1.38, respectively).

The conservative ions of Br^- and Cl^- were compared to deep formation waters (Connolly et al. 1990a) and saline springs (Grasby 2006) throughout central and northeastern Alberta (Fig. 13). The experimentally derived seawater evaporation/

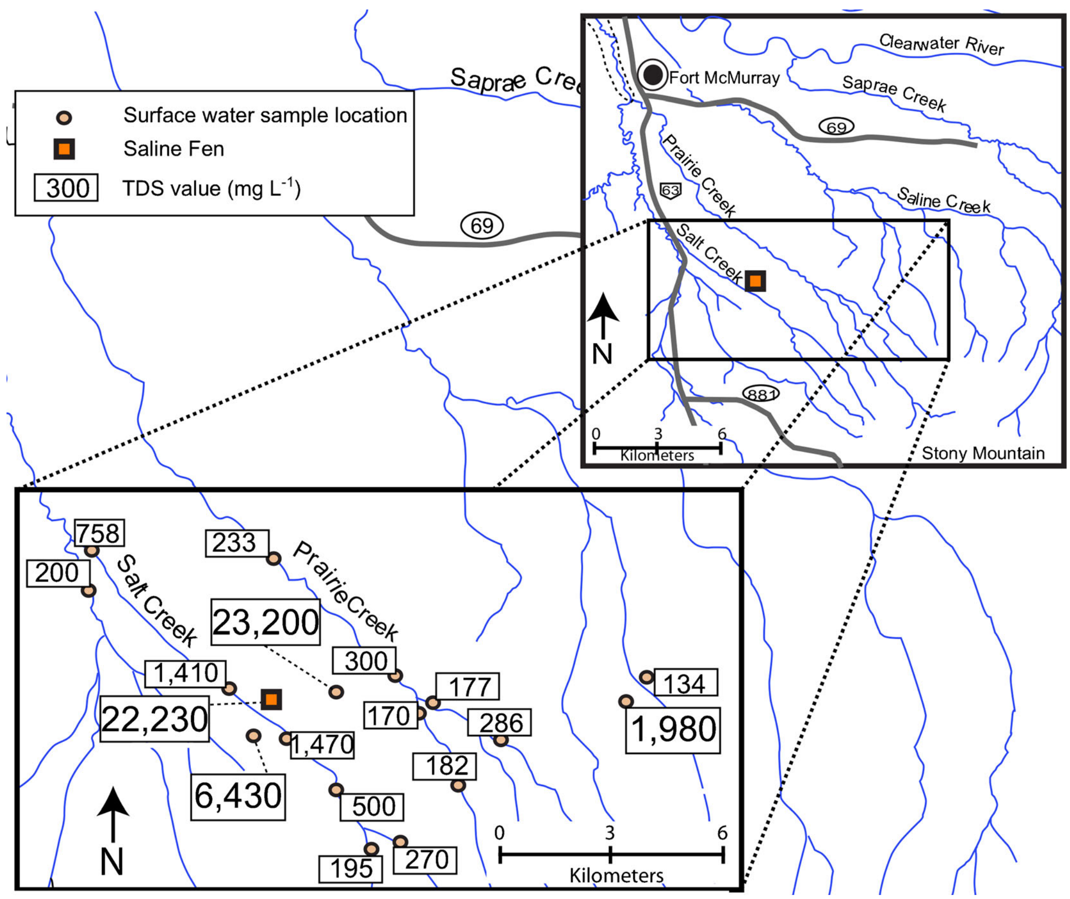

Fig. 10 Sample locations and corresponding TDS concentration (*orange circles and boxes*) in surface waters around the saline fen study area. Samples were taken from adjacent river systems and other distinct saline surface features. Compiled from 2011–2012 field data from this work along with data from field investigations by Stewart and Lemay (2011) and Value Creations Inc (2012)

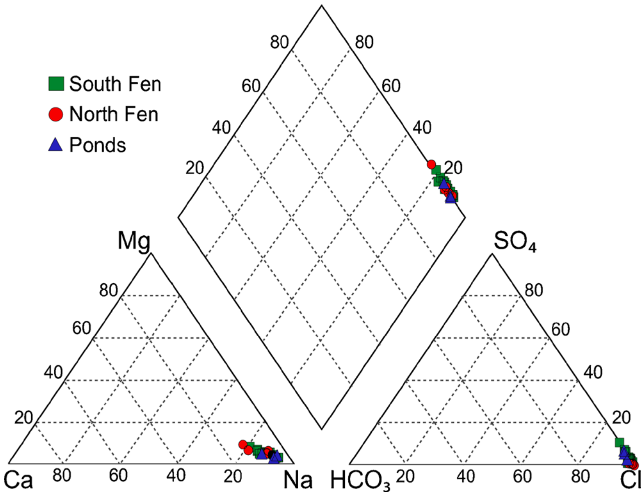

Fig. 11 Piper plot showing the relative equivalent fractions of major ions for pond and peat water samples collected during the 2012 study season

dilution trajectory (SET) is also shown (Carpenter 1978). The distribution of formation waters shown in Fig. 13 relative to the SET can indicate different origins and processes that have affected water chemistry during its fluid history. Similar to other springs, groundwater from the fen clusters to the left of the SET due to an excess of Cl^- relative to Br^-, with an average Cl^-/Br^- ratio of 7,500 due to Br depletion. This contrasts with formation brines that plot on or to the right of the trajectory, indicating an evaporated seawater component that is not derived from halite dissolution. The saline fen and Fort McMurray springs also show a more diluted signature compared to the halite-saturated springs in the Wood Buffalo region.

O and H stable isotope data

At the saline fen, $\delta^{18}O$ and δ^2H showed a broad range in values, generally falling far right of the local meteoric water line (AEMWL) for Edmonton (IAEA/WMO 2001) with a low slope indicative of an evaporation trend ($\delta^2H=4.6\delta^{18}O-60.2$; Fig. 14). While the majority of samples exhibited patterns similar to those recorded by Grasby and Londry (2007) for low-flow springs with a strong evaporative component, several samples of pond surface water and groundwater in the underlying mineral sediments (depth>1 m) within the south fen plotted close to or along the AEMWL. In a number of cases, samples within the basal peat and mineral sediments from the south fen were close to or well below the average value for local precipitation and near-surface Cretaceous aquifers, with one sample having a $\delta^{18}O$ value of −21 ‰.

Discussion

Spring function

While the fen exhibited a similar configuration to other low-flow springs in the region—a sloped topography with a dense pond-pool configuration found along its topographic high—no active discharge outlet was observed over the course of the study (Timoney and Lee 2001; Grasby and Londry 2007). Recharge-discharge patterns between the underlying mineral sediment and peat were variable both spatially and over time and the overall estimate of vertical groundwater flux incorporated some uncertainty. This was despite a relatively dense piezometer network and a 2-year intensive monitoring program. It has been observed in low-conductivity substrates that piezometers can encounter a time lag in trying to reach equilibrium compared to the rapidly responding well; thus, head differences, and consequently estimates of *dh*/*dz*, can be artifacts of the design (Fig. 8b). Excessive time lag or the inability of a piezometer to reach equilibrium post-sampling meant that many had to be discarded from the analyses; however, a subset with sufficient spatial coverage did respond to changes in

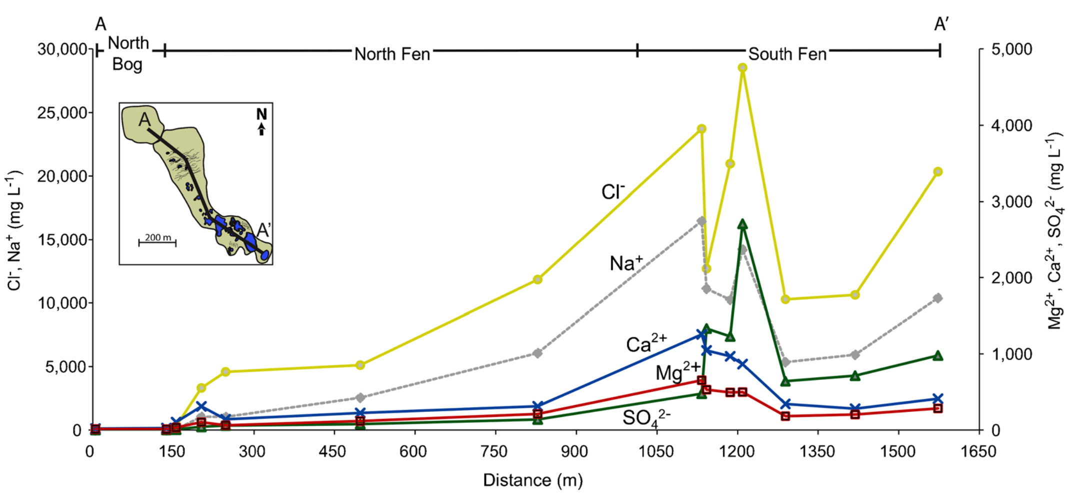

Fig. 12 Spatial distribution of major ion concentrations within the underlying mineral sediments along the primary A–A′ transect (see *inset map*). Each *point* represents an average concentration for a piezometer obtained over two measurement periods in 2012

Table 2 Saturation indices for halite, gypsum and anhydrite minerals in saline fen groundwater and ponds

		Halite	Gypsum	Anhydrite
North Fen	Mean	−3.42	−1.88	−2.31
	Max	−2.88	−1.59	−2.06
	Min	−4.21	−2.24	−2.49
South Fen	Mean	−2.86	−0.97	−1.38
	Max	−1.70	−0.19	−0.57
	Min	−3.94	−1.75	−2.14
Ponds	Mean	−3.46	−1.32	−1.72
	Max	−2.88	−0.55	−0.88
	Min	−3.94	−1.75	−2.44

water table rapidly enough to allow for a coarse estimation of vertical gradients across the fen (Fig. 8). Based on the use of a site-scale average hydraulic conductivity, the overall flux of groundwater through the underlying mineral layer was estimated to be less than several mm. This is despite generally high groundwater and surface-water salinities that increased markedly within a small region in its southern extent (Table 1; Figs. 9 and 12). Mapping of fen stratigraphy in 2011 revealed that a dense, clay rich layer was present throughout the fen, with low hydraulic conductivities similar to the tills of northern prairie wetland regions (van der Kamp and Hayashi 2009). Nevertheless, variability in mineral sediment permeability by several orders of magnitude (between 10^{-8} to 10^{-5} cm s^{-1}) suggests that fractures, locally thin, or more permeable lenses may be present. Sand and gravel deposits or fractures juxtaposed with low-permeability sediments is common for glacial sediments (Sharp 1984; Keller et al. 1988; Stephenson et al. 1988; Haldorsen and Kruger 1990; Hinton et al. 1993) and the influence of these locally conductive zones can have a disproportionately large effect on the bulk hydraulic conductivity of a system (Keller et al. 1988), much more so than the estimated average hydraulic conductivity measured by piezometers (van der Kamp 2001). This can partly be explained by the fact that piezometers have the tendency to underestimate hydraulic conductivity (Hanschke and Baird 2001; Seo and Choe 2001; Surridge et al. 2005). The location of sand and gravel lenses in the high-salinity south fen coincided with spikes in major ion concentrations (Figs. 2 and 12), suggesting enhanced permeability that may not have been adequately captured by the piezometer network. Consequently, the use of an average hydraulic conductivity based on bail tests alone may lead to underestimation of the true magnitude of discharge. A more robust investigation of the physical characteristics of the underlying mineral layer, including hydraulic conductivity and the potential influence of fracturing, is needed to obtain a more confident evaluation of natural saline groundwater discharge at the fen. This includes an assessment of the connectivity of some of the larger saline ponds and pools in the fen's southern region.

In a concurrent study looking at the site-scale hydrology of the saline fen, an assessment of its water balance showed that the exchange of shallow groundwater between the fen and adjacent freshwater wetlands during the summer months was low (Wells and Price 2015). Minimal groundwater exchange was supported by a sharply defined transition between saline and non-saline groundwater along the wetland margins, which in part appeared to be controlled by the presence of subsurface

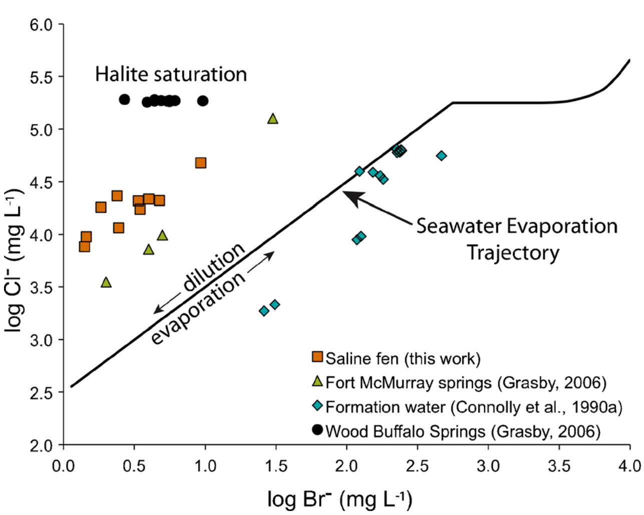

Fig. 13 Log of chloride and bromide concentrations for fen groundwater plotted against the experimentally derived evaporation trajectory (SET) for seawater (Carpenter 1978). Compositions for other springs in the Fort McMurray and Wood Buffalo regions are also shown (Grasby 2006), along with values for formation waters found throughout the Alberta Basin (Connolly et al. 1990a)

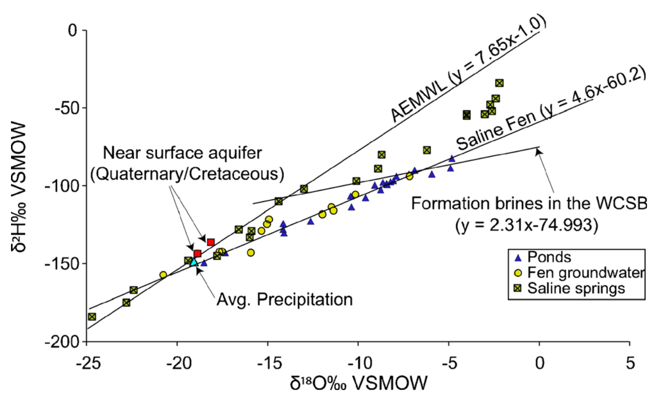

Fig. 14 Relationship between $\delta^{18}O$ and $\delta^{2}H$ isotope ratios for ponds (*blue triangles*) and groundwater taken from piezometers in saline fen (*yellow circles*). Average values taken from the Fort McMurray region for Quaternary and the Lower Cretaceous Grand Rapids formation are also shown (*red squares*; Lemay 2002), along with values from other springs found in the region (Grasby and Chen 2005; Grasby and Londry 2007). An average value for regional precipitation was calculated from data obtained from the approximate Edmonton meteoric water line (*light blue triangle*; AEMWL). The formation water line obtained by Connolly et al. (1990b) is shown for comparison

mineral ridges. While the input of saline groundwater discharge was estimated to be low at the fen during this study, a significant amount of salt can still be transported via regional groundwater flow over thousands of years, despite the fact that it has little significance on the system's overall water balance (van der Kamp and Hayashi 2009). Weak but consistent *dh*/*dz* over the long-term in a wetland that effectively detains solutes can accumulate salts despite a relatively low overall flux of groundwater (van der Kamp and Hayashi 2009). The fen's current geochemical setting may be the result of a similar mechanism, where minimal horizontal groundwater exchange between adjacent systems combined with small vertical inputs through low hydraulic conductivity substrates can result in a net gain of salt over very long time-scales.

Historical records show that saline spring discharge can vary considerably over time, with rates fluctuating or stopping entirely for some springs over the last 100 years (McKillop et al. 1992; Grasby and Londry 2007). Often, active spring seeps are coated with extensive microbial biofabrics that tend to dry out and develop into characteristic 'brain-textured' surfaces as spring discharge decreases (Grasby and Londry 2007; Berard et al. 2013). Similarly textured microbial mats coat many of the dry adjacent areas surrounding what appear to be relict discharge features, while preliminary analysis of microfossil assemblages in pond cores points to shifts in salinity over the long term (O. Volik, University of Waterloo, unpublished data, 2015). The connection of discharge wetlands to regional groundwater flow systems can vary as a result of long-term drought and precipitation cycles (Winter and Rosenberry 1998); thus, it is possible that the minor groundwater input estimated at the saline fen may be due to the ephemeral nature of its discharge, which could be partly explained by the fact that the Boreal Plains region is currently in a long-term regional water deficit (Fig. 6; Devito et al. 2012).

Despite uncertainties in the true magnitude of groundwater flux at the fen, strong geochemical evidence in groundwater and surface waters supports the interpretation that the fen functions as a saline spring during at least some periods of its evolution. This conceptual model is supported by the high concentrations of Na^+ and Cl^- within a regional landscape that is otherwise generally low in dissolved salts. An order of magnitude rise in Na^+, Cl^- and other ions in the opposite direction to that of the local groundwater flow within a relatively small region in the south fen (Figs 9 and 12), along with the presence of distinct spring-like features restricted to that area (e.g. halophytic vegetation, salt crusting, developed pond-pool network) suggests that discharge is or at one time was strongly focused in the fen's southern extent. The presence of other saline surface features within the study area, along with high TDS concentrations within the subsurface of surrounding 'freshwater' wetlands (Table 1) and nearby tributaries (Fig. 10) suggests that saline groundwater discharge plays an important role in this landscape. Thus, incorporating these discharge regions into long-term monitoring networks will be important for land-use decision-making, particularly as it pertains to oil sands extraction and storage.

Regional groundwater connection

A saline plume within a near-surface Cretaceous Formation connected to a surface discharge region adds to the complexity of the modern-day interpretation of fluid flow in the AOSR. Upper Cretaceous aquifers such as the Grand Rapids tend to be strongly influenced by topography in the study region (e.g., Stony Mountain, Figs. 1 and 4) and typically indicate downward flow with low salinity due to meteoric input (Bachu et al. 1993). The Clearwater Formation, which acts as a regional aquitard, also protects them from high salinities in lower Cretaceous Formations such as the McMurray (Freeze and Cherry 1979; Bachu and Underschultz 1993, Bachu et al. 1993; Cowie et al. 2015); however, a distinct saline groundwater plume within the Grand Rapids Formation was found to be discharging towards the surface at its erosional edge south of the town of Fort McMurray (Athabasca Oil Sands Corp. 2011; Value Creations Inc. 2012). The saline fen study area is found just north of where the Grand Rapids terminates, corroborating hydrogeologic assessments that the area is in a zone of groundwater discharge. Within the regional framework of the saline fen study area, a depth-related decrease in hydraulic head below the Grand Rapids saline plume points to a disconnect between Cretaceous flow systems and underlying halite bearing Devonian deposits (Hackbarth and Nastasa 1979; Athabasca Oil Sands Corp. 2011; Value Creations Inc. 2012). Based on this interpretation, the Grand Rapids saline plume is hydrologically uncoupled from the Devonian within the immediate study region; however, elevated Na^+, Cl^- and SO_4^{2-} concentrations (Table 1) and a strong Cl^-/Br^- in fen groundwater and surface water (Fig. 13) suggest that salinity is influenced by evaporite dissolution. Due to the relatively conservative nature of Na^+, Cl^- and Br^- in most groundwater settings, the relationship between these ions has proved useful in the determination of the origin and evolution of formation waters (Carpenter 1978; Walter et al. 1990; Kesler et al. 1995; Davis et al. 1998; Gupta et al. 2012). The average Cl^-/Br^- ratio of groundwater in the high-salinity discharge zone (south fen) was 7,500 and was well within the range of other subsurface brines and saline springs influenced by halite dissolution (Carpenter 1978; Davis et al. 1998; Grasby and Chen 2005; Grasby and Londry 2007; Berard et al. 2013).

The relationships among Na^+, Cl^- and Br^- points strongly to halite dissolution as a source of salt at the fen but biogeochemical processes such as sorption and plant uptake, can influence the concentration of ions in the wetland setting. Br^- has traditionally been considered non-reactive in soils; however, the sorption of Br^- by up to 10 % has been reported in various materials, including clays and organic soils (Wilson and Gabet 1991; Behl 1990 in Davis et al. 1998). In their investigation of Br^- as an appropriate tracer in wetlands, Xu et al. (2004) found that typical wetland plants (*Typha latifolia* and *Phragmites australis*) can take up significant quantities of Br^- in root and leaf tissues. This is unlikely to be an issue at the fen since all samples used for Cl^-/Br^- analyses were taken well below the root layer within the basal peat (>1.0 m depth) or underlying mineral layer. Moreover, Cl^- has been shown to strongly inhibit the uptake of Br^- in plants, which in highly saline environments like the saline fen may reduce or eliminate Br^- removal from groundwater (Xu et al. 2004).

Cretaceous aquifers south of the study region have shown a mix of NaCl–HCO_3 and NaCl dominated brines comparable to fen discharge water, but Cl^-/Br^- ratios were consistently similar to that of seawater (between 250 and 450) with no evidence of contact with halite (as indicated by low Cl^-/Br^- ratios; Lemay 2002). TDS concentrations within these formations were typically well below what would be expected for connate seawater alone (~35,000 mg L^{-1}), suggesting they may not be solely influenced by deep formation brines and have undergone some level of mixing with freshwater resulting in dilution. Some of the high-salinity discharge zones in the south fen (ponds and mineral piezometers>1 m depth) were similar to the mean for Cretaceous aquifers in the study region and plotted close to the AEMWL (Fig. 14). The wide range in TDS found within the Grand Rapids Formation, typically less than 1,000 but as high as 10,000 mg L^{-1} within the saline plume, points to dilution as a result of mixing with freshwater sources similar to the process described by Lemay (2002). The fen's connection to a Cretaceous saline plume influenced by freshwater recharge explains the generally low salinities found at the saline fen compared to other springs typically connected directly to subcropping or exposed Devonian halite (Grasby 2006). One location within the south fen's high-salinity discharge zone showed a $\delta^{18}O$ value of −21 ‰. This is much lower than mean precipitation for Edmonton (−19 ‰, Fig 14) and lower than the average of −19 ‰ for modern locally recharged Quaternary groundwater for northeastern Alberta (Grasby and Chen 2005). Similarly low $\delta^{18}O$ values have been observed in other saline springs in Fort McMurray and west-central Manitoba, which have been interpreted as being related to Pleistocene meltwater that originated during a colder climate than present (Grasby and Chen 2005). These spring systems are distinct from deep basin brines and are the result of meteoric water that has recharged deep enough to dissolve buried halite deposits and recirculate back to the surface (Grasby and Londry 2007). Isotopic signatures lower than modern-day precipitation or local groundwater at the fen suggest the possibility of a similar mechanism, which may explain a halite signature in groundwater despite the apparent disconnect between the Grand Rapids Formation feeding the fen and underlying halite bearing formations within the immediate study area.

Sub-surface connections between formation waters have been observed and considered feasible within the AOSR (Bachu et al. 1993; Mahood et al. 2012; Schneider et al. 2012) and while previous studies have shown a predominantly downward flow direction (Hackbarth and Nastasa 1979; Bachu and Underschultz 1993; Barson et al. 2001), upward vertical flow from sub-Cretaceous strata can be a potentially important regional mechanism that may lead to increased salinities within overlying formations (Cowie et al. 2015). Field evidence includes drill stem pressure tests that report Devonian strata with hydraulic head values higher then overlying McMurray Formations (Nexen Inc. and OPTI Canada Inc 2007 cited in Cowie et al. 2015) as well as the puncture of a deep, saline Devonian aquifer that eventually filled a tailings pit at the Muskeg River Mine (Cooper 2011). The high salinities observed within lower Cretaceous Formations (e.g., the McMurray) have been attributed to this upward flux, which is likely enhanced by the presence of extensive evaporite karst structures (Broughton 2013) that function as preferential flow conduits (Cowie et al. 2015). Within the immediate study area of the saline fen, numerous sub-Cretaceous features such as fault structures and sinkholes related to halite dissolution have been observed (Value Creations Inc. 2012). Structural lows related to differential compaction were also identified that developed continuously into the Clearwater caprock and above, suggesting the possibility of reduced caprock integrity in the region. The presence of these features precludes the assumption that the saline fen is not connected to Devonian brines within its flow path. While the potential for subsurface connections leading to cross-formation flow cannot be validated at the resolution of this study, the presence of saline springs within a complex hydrogeologic setting constitutes that careful examination of all possible surface-subsurface connections within the region. This is particularly relevant to in-situ wastewater disposal, where injection pressures may augment groundwater flow and establish new connections with deeper flow systems causing higher flow rates from springs (Carrigy and McLaws 1973; Hackbarth and Nastasa 1979).

Conclusions and implications for in-situ oil sands development

The fen and surrounding saline surface features provide an opportunity to examine the complex nature of groundwater flow within the AOSR. Its location just south of the oil sands hub of Fort McMurray places it within a region of intensive development, while its location far removed from a major river system makes its hydrogeologic position more different than other saline springs studied in the AOSR. Elevated salinities combined with other spring-like features indicate that discharge is or at one time was strongly focused within this zone. The present magnitude of saline groundwater discharge was estimated to be small due the presence of low-permeability mineral sediments underlying the system; however, it is possible that the true rate of groundwater input to the fen from the Grand Rapids saline plume was underestimated due to locally conductive zones not captured by the piezometer network. Installation of a piezometer network constructed specifically for dense, low-conductivity materials (e.g. sand packs around piezometer openings, longer open screen length) with even greater coverage both spatially and with depth may allow for a better characterization of mineral substrate heterogeneity and, thus, a more accurate estimation of hydraulic conductivity in these systems. Groundwater and surface-water sampling programs could allow for targeted drilling so that the underlying sediments can be characterized. Similar to this study, systems underlain by dense, low-permeability sediments lacking an observable spring outlet may have a minimal impact as potential discharge windows for subsurface storage, but long-term monitoring should be implemented to determine the potential variability in deep groundwater discharge, particularly as it relates to long-term climate cycles in the AOSR.

The anomalously high concentration of dissolved salts within the surrounding wetlands and river systems indicates that the aerial extent of groundwater discharge is large and the study area's position just north of the erosional edge of the Grand Rapids saline plume points to a direct connection between a shallow Cretaceous aquifer and the surface. Saline groundwater discharge over the long-term likely plays an important geochemical role in ecosystem function and water quality. Hydrogeologic evidence points to a disconnect between the Grand Rapids saline plume feeding the study area and the underlying Devonian salts, so the distinct halite signature in fen groundwater suggests that the contribution of evaporites may come from somewhere deeper and further south in the basin. Erosional features throughout the stratigraphic package but most notably in the Devonian within the study region enhance the possibility of upward flow between these formations that up to this point have not been directly identified.

In the AOSR, subsurface wastewater containment related to in-situ development is considered a safe and viable disposal option only when the formation can be deemed suitable for maintaining the ongoing confinement of the disposal fluid (ERCB 1994), a prerequisite that poses a challenge for developers in many parts of the region. Discharge features such as the saline fen complex have important implications for the safe disposal of wastewater by deep well injection, since storage zones may be hydrologically linked to discharge features well beyond the immediate production and storage area. For example, saline springs could intensify the risk for the discharge of wastewater to the surface, as it is unclear what impact injection pressures may have on subsurface connections. Careful examination of these saline spring features is required to obtain a confident estimate of the magnitude of discharge in the AOSR. This study has provided a preliminary assessment of these atypical saline surface features that have to this point not received much attention in the literature. In a region under considerable developmental stress, effective management will require a sound understanding of groundwater flow systems at multiple scales, with particular attention being paid to high-salinity regions as potential discharge conduits.

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