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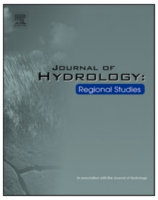

# Preferential recharge in a reclaimed tailings sand upland: Implications on solute flushing

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ABSTRACT

*Study region:* A peatland watershed was constructed on a post-mined oil sands lease in Northern Alberta, Canada, with the intention of replicating the function of natural wetlands removed by surface mining.

*Study focus:* Given the potential for moisture limited conditions due to the sub-humid regional climate, ensuring sufficient water availability in these landscapes is a principal concern. This research demonstrates how small recharge basins can modify the hydrology to promote groundwater recharge critical for sustaining saturated conditions in a downgradient wetland.

*New hydrological insights for the region:* Location was important in determining the efficacy of recharge basins. Specifically, basins placed at the confluence of two hillslopes detained substantial volumes of runoff due to large upslope areas, contributing ~30% of the groundwater budget to the fen, while only occupying 1% of the upland area. Basins situated near low relief hillslopes or altogether isolated from a hillslope did not detain appreciable runoff and therefore had a minor role in recharging groundwater. Groundwater in the vicinity and downgradient of active recharge basins had considerably lower solute concentrations because of dilution. This suggests that basins can not only enhance recharge within engineered landscapes, providing a consistent and focused supply of water to upland aquifers, but offer relatively fresh groundwater to downgradient ecosystems. This could ameliorate the impact of high salinity present in oil sands process-affected materials.

## 1. Introduction

Disturbance associated with surface mining of oil sands has affected over 900 km$^2$ of the Athabasca Oil Sands Region (AOSR) in the Western Boreal Plains (Government of Alberta, 2018). The oil sands companies are required to reclaim the post-mined landscape to an equivalent capability (OSWWG, 2000), and given the abundance of wetlands in the undisturbed AOSR (Turchenek and Pigot, 1988; Vitt et al., 1996; Zoltai et al., 1988), exploring the viability of fen peatland construction has been deemed a regulatory priority (Daly et al., 2012; Ketcheson et al., 2016; Pollard et al., 2012). In 2012, the Nikanotee Fen Watershed (NFW), a pilot fen reclamation project, was constructed on a post-mined lease from mine waste and salvaged materials to test the feasibility of peatland reclamation (Daly et al., 2012; Ketcheson et al., 2016; Price et al., 2010). Construction was completed in January 2013 and planting of wetland and upland vegetation occurred over the following growing season. NFW relies on groundwater recharge from a upland aquifer constructed

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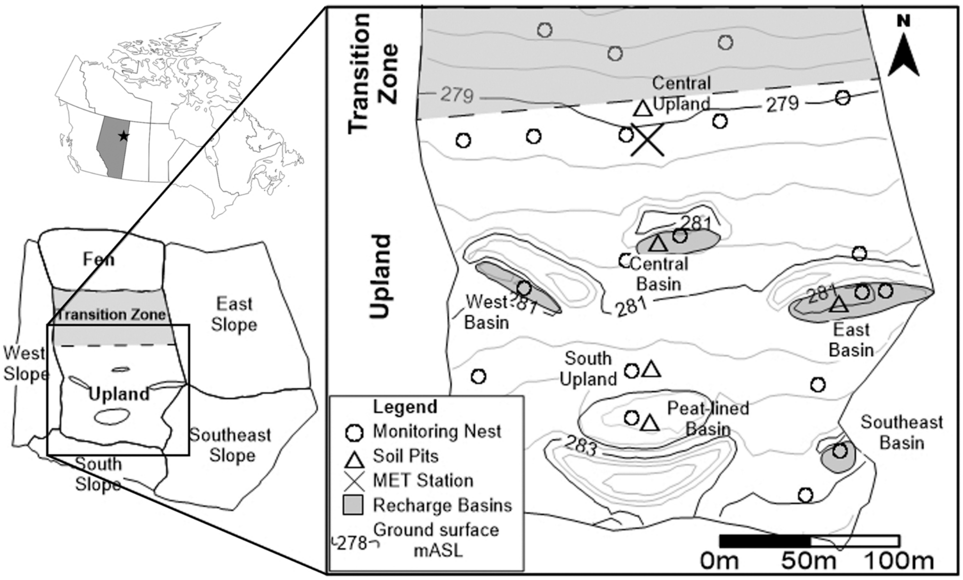

**Fig. 1.** Map of Nikanotee Fen upland in plan-view with hummock and recharge basin features illustrated. The east and southeast recharge basins were instrumented (monitoring nest) in 2014. The central and west recharge basins were instrumented in 2015.

from coarse tailings sand, and supplemented with runoff from the surrounding reclaimed hillslopes, to supply sufficient quantities of water to the downgradient fen (Ketcheson and Price, 2016a; Ketcheson et al., 2017; Price et al., 2010). Thus far, the system design has been successful in maintaining a water table near the surface of the fen, where evapotranspiration was the dominant water flux from the system (Ketcheson et al., 2017). The tailings sand used to construct the upland aquifer, an abundant byproduct of the oil sands extraction process, contains elevated concentrations of salts such as $Na_2SO_4$, $MgSO_4$, $CaSO_4$ and naphthenic acids in the pore-water (Mackinnon et al., 2001; Scott et al., 2005). These salts are mobile in groundwater (Gervais and Barker, 2005; Kessel et al., 2018: Simhayov et al., 2017) and can be toxic to aquatic vegetation (Trites and Bayley, 2009; Rezanezhad et al., 2012). Given the potential for large evaporative losses within constructed wetland areas (Devito et al., 2012; Ketcheson et al., 2017; Scarlett et al., 2017) and the elevated residual sodium ($Na^+$) in the tailings sand (Biagi et al., 2019; Kessel et al., 2018; Simhayov et al., 2018), there are concerns for both water quantity and quality that could steer the ecological and hydrological trajectory of the fen peatland (Daly et al., 2012; Ketcheson et al., 2016; Pouliot et al., 2012; Simhayov et al., 2017).

Ketcheson (2016) and Kessel (2016), among others (e.g. BGC Engineering Inc., 2010; Pollard et al., 2012; Wytrykush et al., 2012) suggest using depressional features in the design of the reclaimed landscape to enhance recharge by detaining surface runoff. This strategy has been successfully applied to promote groundwater recharge in arid regions and areas prone to water shortage (Asano, 1985; Bear and Cheng, 2010; Bouwer, 2002). However, in the context of a reclamation watershed, promoting infiltration and subsurface storage of freshwater can mobilize solutes present within the unsaturated zone and accelerate the transport of these solutes within groundwater (Biagi et al., 2019; Sutton, 2021). Given the large pool of $Na^+$, the primary solute of concern, contained within the constructed tailings sand aquifer (Kessel et al., 2018), this mobilization could lead to the accumulation of salts within the rooting zone of the fen peat (Simhayov et al., 2017), which could affect the establishment and productivity of wetland vegetation (Pouliot et al., 2012; Rezanezhad et al., 2012). However, high $Na^+$ pore-water concentrations may be mitigated by dilution of saline groundwater from focused basin recharge (Kessel et al., 2018).

Since groundwater storage has been identified as a necessity for maintaining the ecological functioning of a constructed fen peatland (Ketcheson et al., 2016; Price et al., 2010), the potential of depressional features to enhance recharge and redistribute salts must be evaluated. Recent investigations into the geochemical conditions generated by tailings sand materials in a reclaimed landscape have been reported by Simhayov et al. (2017) and Kessel et al. (2018); yet the role of system design and materials on recharge and transport processes responsible for the redistribution of $Na^+$ within such constructed upland-fen systems are undocumented and poorly understood. Therefore, the primary objectives of this study are to (1) evaluate the efficacy of recharge basins on groundwater recharge, (2) assess the optimal geometry (size and shape) and positioning of the recharge basins necessary to maximize recharge, and (3) determine the implications for enhanced recharge on preferential flushing of $Na^+$ within the tailings sand upland. The findings from this study will further contribute to the growing body of literature on techniques to aid in the reclamation of the post-mined oil sands landscape. Specifically, this work will inform reclamation practitioners and mine operators of the value of surface flow detention structures in creating upland landforms with more consistent hydrologic behavior, that can efficiently partition water to groundwater recharge.

**Fig. 2.** East recharge basin empty (left) and full shortly after a large rain event (right). Photos taken in May 2015.

## 2. Study site

### 2.1. Constructed tailings sand upland

NFW is a constructed upland-fen system situated on an oil sands mine lease (56°55.94’N, 111°25.04’W) ~25 km north of Fort McMurray, Alberta. NFW was designed with the aid of modeling that indicated the requisite morphology to maintain an adequate water supply to the fen under the periods of water stress that occur frequently in the AOSR (Daly et al., 2012; Price et al., 2010). The upland consists of a ~3 m tailings sand aquifer overlain by a 0.3–0.5 m layer of LFH-mineral mix (herein referred to as “LFH”), an over stripped forest-floor soil commonly used in oil sands reclamation (Naeth et al., 2013; Sutton and Price, 2020a). The upland and fen are underlain by an impermeable geosynthetic clay liner on a 3% grade that establishes a hydraulic gradient towards the fen, and vastly reduces percolation losses to the regional groundwater flow system. The fen peat is underlain by a highly permeable petroleum coke underdrain layer (~0.5 m thick) that projects 100 m upslope beneath the tailings sand upland, a subregion of the upland herein referred to as the ‘transition zone’ (shaded area in Fig. 1). The entire upland – fen system (10.6 ha; Fig. 1) is situated in a much larger reclaimed watershed (32.1 ha) composed of four primary hillslopes. The west (2.4 ha) and southeast (8.4 ha) hillslopes were reclaimed in 2011 and had immature and relatively sparse vegetation communities at the time of this study. The east (8.1 ha) hillslope was reclaimed and planted in 2007 and had developed a substantial vegetation cover. The southeast and west slopes were found to generate considerable runoff during rainfall events that flowed over the upland, some of which infiltrated and contributed to the groundwater that sustains the fen (Ketcheson and Price, 2016a). The south hillslope is an undisturbed hillslope, which despite the steep relief does not contribute to upland recharge due to its small size, dense vegetation, undisturbed soil and position with respect to the geosynthetic clay liner (Ketcheson and Price, 2016a).

Several meso-scale raised landforms (10–100 m width by 1 m height) were incorporated within the upland in which tailings sand was piled and capped (~20 cm) with LFH reclamation soil, similar to the surrounding upland. Over the 2013 season, these raised landforms (herein referred to as ‘hummocks’) detained and trapped a small amount of overland flow behind their upslope side; however, this water did not notably enhance recharge compared to the surrounding upland because the LFH that covered all upland areas had a relatively low infiltration capacity and high water holding capacity (Ketcheson, 2016; Sutton and Price, 2020a). Thus, in late August 2013, several modifications were made to the configuration of the upland with the intention of promoting groundwater recharge. First, a bulldozer equipped with a ripper shank was used to till furrows (furrow dimension typically approximately 24 cm wide, 10 cm deep, with ~85 cm spacing; Ketcheson, 2016) to retain overland flow, increase water detention and thus infiltration. Second, the LFH on the upslope side of the hummocks was excavated to expose the tailings sand. The excavated soil material was placed at each end of the hummocks thereby extending them to further increase their detention capacity. The resulting depressional features (~30–50 cm deep; herein referred to as ‘recharge basins’; Fig. 2) were capable of detaining much larger volumes of overland flow, and effectively increased the percolation to the tailings sand aquifer by removing the LFH reclamation soil. A total of four recharge basins were added; the east (area=700 $m^2$), central (450 $m^2$), west (400 $m^2$) and southeast (100 $m^2$) recharge basins (Fig. 1). In the several growing seasons post-construction, hillslope runoff from the southeast slope during heavy rainfall resulted in substantial fine-grained materials transported into the east and southeast recharge basins, forming a 20–30 cm cap across both basins.

## 3. Methods

The study was conducted during the snow-free periods of May to October for 2013, 2014, 2015 and 2016. As shown by early field observations, the east recharge basin received the most surface runoff and therefore was chosen for the most detailed monitoring and instrumentation.

### 3.1. Instrumentation and hydrological monitoring

In addition to the monitoring network of wells and piezometers within the upland and fen described in detail by Kessel et al. (2018), additional monitoring locations 2.25–2.75 m below ground surface (bgs) were instrumented within the east and southeast recharge basin in May 2014. Monitoring wells and piezometers (2.75 m bgs) were instrumented in the central and west recharge basins in May 2015. All groundwater wells had fully slotted intakes with depth ranging 2.6–3.7 m bgs; piezometers had a 0.2 m slotted intake centered around their installation depth. Water tables were automatically recorded with water level loggers or pressure transducers (Dataflow Systems Ltd Odyssey Capacitance Water Level Logger; Schlumberger Limited Mini Diver; Onset Hobo U20). Manual measurements of hydraulic head were performed every ~5 to 7 days to validate all autologging water levels. Initially, in May and June 2014, an incremented rod was installed to monitor pond height (stage) within the east recharge basin but was replaced by a fully slotted standpipe with water level logger in July 2014, which recorded stage at 15-minute intervals. The stage accurately monitored ponded water within the recharge basin only when it was above a threshold capacity of 10 cm, due to the minimum height required for the water level logger. Detailed stage measurements were quality assured by field observations and manual measurements of pond depth.

In May 2013, two vertical soil moisture profiles were instrumented within the variably saturated layer of the tailings sand aquifer; one in the south end of the upland and the other in the center of the upland, ~15 m downslope of the central recharge basin. These are herein referred to as the south and central upland *VWC* stations, respectively (Fig. 1). Soil moisture profiles consisted of 8 dielectric impedance reflectometry soil moisture probes (Stevens Water Monitoring Systems Inc. Hydra II); four within the LFH soil cap and four within the underlying tailings sand, typically at depths of 0.05, 0.10, 0.15, 0.40 m and 0.50, 0.60, 1.00, 1.50 m bgs, respectively. Probe depths varied slightly depending on LFH layer thicknesses. In May 2015, the east and central recharge basin were instrumented with similar vertical soil moisture profiles within the variably saturated tailings sand. Two soil moisture profiles were instrumented in the east recharge basin ~10 m apart and consisted of 5 and 3 sensors at 0.05, 0.25, 0.40, 0.60, and 1.00 m bgs and 0.05, 0.25, 0.60 cm bgs, respectively. One soil moisture profile consisting of five probes at 0.05, 0.25, 0.40, 0.60, and 1.00 m bgs was placed within the central recharge basin. All soil moisture probes were calibrated to tailings sand and recorded in-situ volumetric water content (*VWC*) every 30–240 min to CR1000 data loggers (Campbell Scientific Canada Corp.).

Precipitation (*P*) was measured by a tipping bucket rain gauge (Texas Instruments Canada Ltd. TR-525 M) located at the upland meteorological station (Fig. 1). Potential evapotranspiration rates (*PET*) were calculated using the Priestley-Taylor approach (discussed later) based on data from the fen meteorological station, which was assumed to be most representative of open water evaporation, to simulate the evaporative loss of the ponded water within the recharge basins (discussed further below). *P* and *PET* values measured were cumulative rates for 30-minute intervals. Specific methods of calculating *PET* are reported by Scarlett et al. (2017).

### 3.2. Groundwater sampling

Groundwater samples were taken periodically from monitoring wells and piezometers within the recharge basins and surrounding upland throughout the duration of the study period. Several grab samples were also taken from the water ponded within the recharge basins following large rain events (24-hr period >10 mm). All samples were stored at 4 °C until being passed through a 0.45 μm cellulose nitrate filter within 24 h of being retrieved, after which they were frozen until analysis. $Na^+$ concentrations were determined in all water samples by Ion Chromatography (DIONEX ICS 3000, IonPac AS18 and CS16 analytical columns) with analytical precision to ±1.0 mg $L^{-1}$. Electrical conductivity (*EC*), temperature, and pH was determined for all samples using a multiparameter probe (Thermo Scientific Orion Star A329 pH/Conductivity Portable Multiparameter meter) at the time of retrieval in the field.

### 3.3. Soil hydraulic properties

Soil hydraulic properties including particle size distribution, porosity, and infiltration capacity for upland LFH and tailings sands are reported in Ketcheson (2016). Single ring, constant head infiltration tests were conducted using 5 cm inner diameter steel rings for tailings sands within all four recharge basins. Infiltration tests within the east and southeast recharge basins included tests in which the fine-material over-wash sediments were excavated to expose the tailings sand. Due to the negligible surface overland flow into the central and west recharge basins, there was little to no introduction of fine sediments, therefore, no excavation was necessary and infiltration tests were simply conducted on the bare tailings sand. Additional single ring infiltration tests were conducted on the fine-grained over-wash material within the east recharge basin.

### 3.4. Recharge basin capacity and infiltration volumes

Recharge volumes were calculated for only the east recharge basin given its frequent filling with runoff. The stage (ponding water depth) versus bathymetry (volume) and infiltration area is documented in Appendix A (Fig. A1). Change in volume over time (*dV/dt*) of ponded water within the east recharge basin was determined by a water balance approach:

$$\frac{dV}{dt} = (P+R)_{in} - (ET+f)_{out} \tag{1}$$

where $P$ is precipitation (mm $hr^{-1}$), $R$ is runoff into the basin (mm $hr^{-1}$), $ET$ is evaporation of open water (mm $hr^{-1}$) and $f$ is the infiltration rate (mm $hr^{-1}$). *ET* was estimated using the Priestley-Taylor available energy approach for equilibrium evapotranspiration which applies an alpha of 1.0 to closely estimate the evaporation for open water (Priestley and Taylor, 1972). Given that there were no hydrometeorological measurements made above the recharge basins, net radiation and ground heat flux from the fen meteorological tower were used instead, which appropriately reflects the atmospheric and surface conditions of the recharge basins (Scarlett et al.,

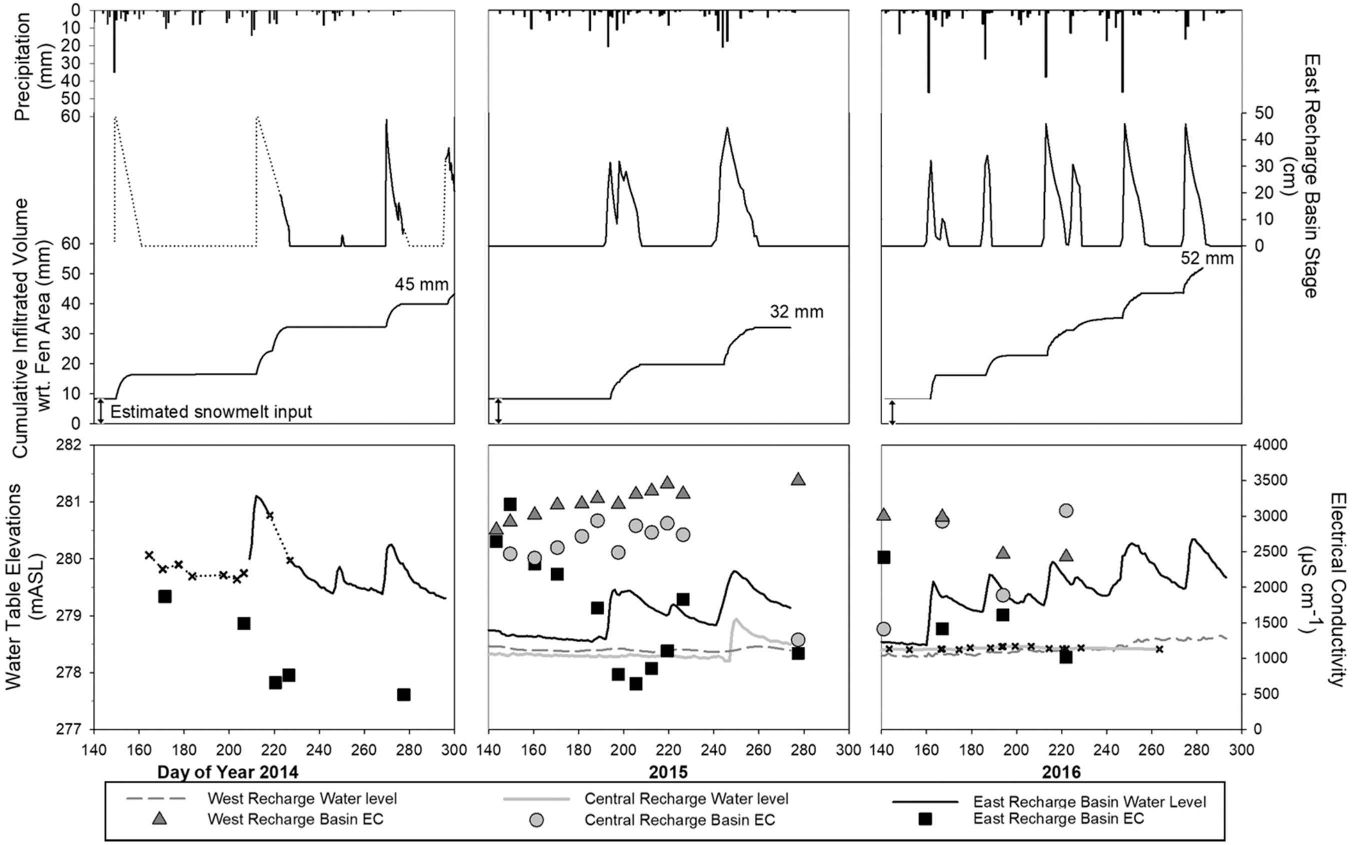

**Fig. 3.** Rainfall and the subsequent pond stage in the east recharge basin and cumulative infiltrated volume of water with respect to the fen area (2.9 ha) for 2014, 2015 and 2016 study periods are shown (top panel). Dotted stage values are interpolated from manual measurements. The water table elevations and EC underlying the east, central and west recharge basins for 2014, 2015 and 2016 (lower panel) are shown. Dotted lines with x's are the interpolated water table elevations using manual measurements.

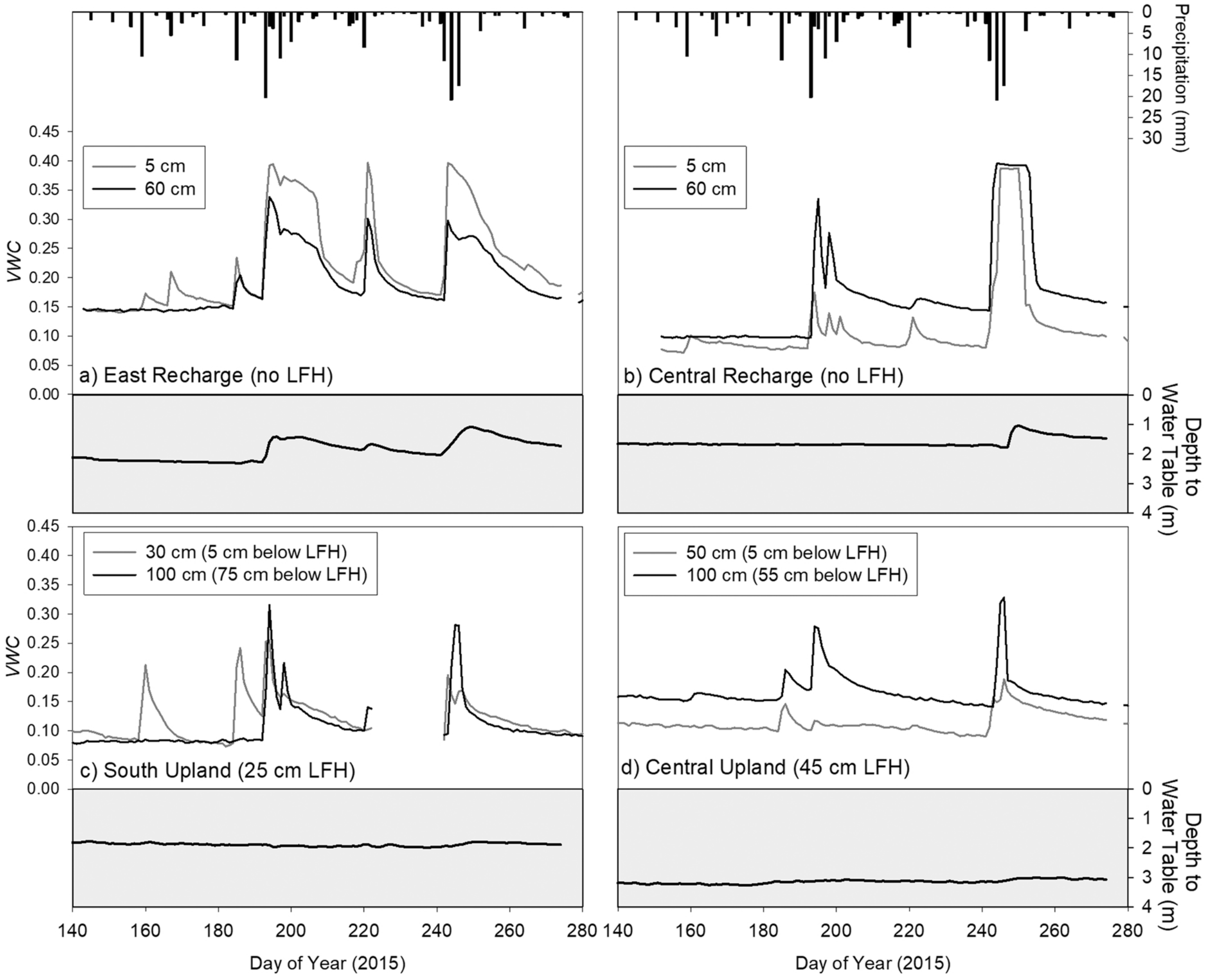

**Fig. 4.** *VWC* within tailings sand at 5 and 60 cm bgs in the east (a) and central (b) recharge basins (LFH removed) compared to similar depths in tailings sand below the LFH soil cap within the south (c) and central upland (d) stations over the 2015 study period. Depths to underlying water tables for each respective area are below in the gray shaded panels.

2017).

A base infiltration rate ($f$, mm hr$^{-1}$) for the recharge basin was approximated by back calculating Eq. (1) during periods of infiltration only. High intensity rainfall events ($\geq$10 mm hr$^{-1}$) resulted in rapid filling of the recharge basin. Immediately after the basin was filled, $P$ and $R$ following the rainfall event can be assumed to equal zero, and

$$f = -\left(ET + \frac{dV}{dt}\right) \tag{2}$$

Finally, the cumulative infiltrated volume of water through a recharge basin was the summation of the product of $f$ and the period of ponding for each time step ($\Delta t$=15 min), such that

$$Total\ Volume\ Infiltrated = \sum_{i=1} f_i(t_{i+1} - t_i) \tag{3}$$

Based on evidence from the field, it was assumed that a single basin capacity infiltrated through each recharge basin immediately following snowmelt (not included in the study period; Ketcheson and Price, 2016b; Sutton and Price, 2020a) which was included in each total seasonal recharge volume. By this method, it was determined that the total basin capacity of the east recharge basin was ~240 m$^3$, which equates to ~5 mm of $R$ from the east/southeast slope sub-catchment (4.9 ha).

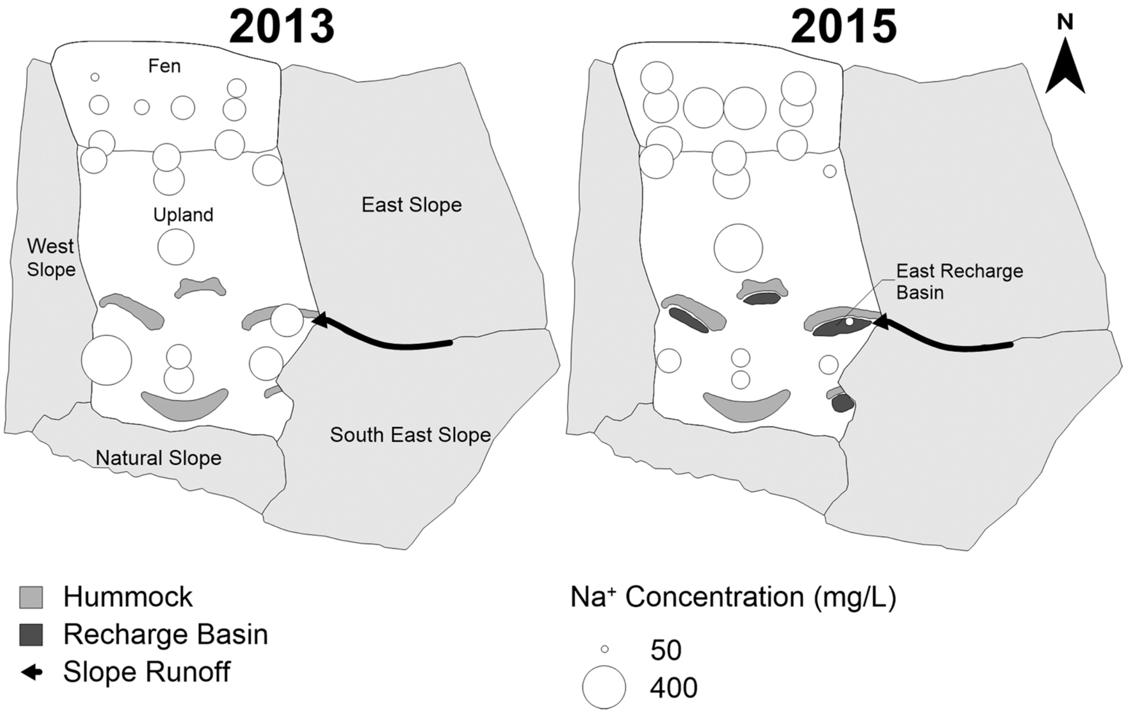

**Fig. 5.** Interpolated $Na^+$ concentrations in upland and fen groundwater before recharge basins (2013; left) and two years after being hydrologically active (2015; right). Runoff from the South East Slope – East Slope confluence is indicated by the bolded arrow in 2015.

## 4. Results

### 4.1. Hydrological context of recharge basins

A total of 254, 193, 126 and 222 mm of *P* were received between 17 May and 24 August in the 2013, 2014, 2015 and 2016 study periods, respectively. *P* in all seasons was dominated by infrequent but high intensity (24-hr period>10 mm) events (Fig. 3). Following *P* events that exceeded this intensity, the east recharge basin was observed to fill within 15 min of peak rainfall as a consequence of *R* from the east-southeast slope confluence (4.9 ha). Once filled, the ponded water spilled out around the edges of the raised hummock, continuing as overland flow towards the fen, largely intercepted by the aforementioned furrows. Some *P* events were not received in a single period of continuous rainfall but could span over 24–48-hour periods, resulting in partial re-filling of the east recharge basin, illustrated by the saw-tooth pattern in the ponded water level (stage) hydrograph (Fig. 3).

The infiltration rate, *f*, for the exposed tailings sand in recharge basins averaged 319 mm $hr^{-1}$ (sample size (n) for the east, central, and west recharge basin is 3, 9, and 6, respectively), which was higher than reported for the LFH upland soil cover using the same method (average of 66 mm $hr^{-1}$; Ketcheson, 2016) and within an order of magnitude of the average saturated hydraulic conductivity of the tailings sand aquifer (4 m/day or 167 mm $hr^{-1}$; Sutton et al., submitted). Recharge basins experienced stronger increases in *VWC* in the underlying tailings sand compared to that in tailings sands of the surrounding upland overlain by LFH (Fig. 4). *VWC* within the tailings sand layers (0.05 and 0.60 m bgs) in the east and central recharge basins responded to rainfall events greater than 10- and 15-mm $day^{-1}$ for each respective basin. The water table in the east recharge basin was shallower (ranging ~0.60 and 1.90 m bgs between 2014 and 2016) and responded to these events (Fig. 4). The water table beneath the central recharge basin was deeper (~2.60 m bgs) and did not appear to respond to any early season infiltration events (Fig. 4). Following the larger rainfall events that elicited large water table rise under the east recharge basin, no comparable water table responses (<0.2 m rise) were recorded in the LFH-covered south and central upland sites (Fig. 4 c and d). Periods of ponding within the recharge basins resulted in prolonged elevated *VWC* in the tailings sand, persisting above field capacity for ~20 days following large rainfall events (Fig. 4). Relatively dry periods between large rainfall events (~2 to 3 weeks) resulted in *VWC* returning to a residual water content (~0.10) at all locations, and the mounded water tables beneath the recharge basins to dissipate.

The east recharge basin received the most overland flow of all the recharge basins within the upland, having ponded water present for 27%, 23% and 30% of the 2014, 2015 and 2016 study periods, respectively (Fig. 3), compared to the central recharge basin which was ponded for less than 5% of both seasons. For the east recharge basin, periods of ponding typically persisted for ~5 to 12 days, except for a period of prolonged ponding for 15 days in 2015, due to successive rain events refilling the basin (Fig. 3). Cumulative infiltrated volumes through the east recharge basin were 1308, 928 and 1506 $m^3$ (45, 32 and 52 mm with respect to the fen area), in 2014, 2015 and 2016, respectively (Fig. 4). High overland flow rates from the southeast slope, which fed the east recharge basin,

**Table 1**
Recharge summary for the East Recharge Basin. Q is the recharge volume expressed as a total volume ($m^3$) and depth with respect to the fen area (mm).

| Year | Rainfall (mm) | Number of events | Avg. detention time (days) | $f_{avg}$ (mm $hr^{-1}$) | Q ($m^3$) | Q wrt to fen (mm) | $Q_{fen}$: $(ET+R-P-\Delta S)_{fen}$ (%) |
|---|---|---|---|---|---|---|---|
| **2014** | 193 | 5 | 8 | 2.38 | 1308 | 45 | 25 |
| **2015** | 126 | 2 | 14 | 10.3 | 928 | 32 | 17 |
| **2016** | 222 | 7 | 10.8 | 12.8 | 1506 | 52 | 33 |

resulted in a fine-grained material outwash that covered the entire basin. The value of *f* estimated by the measured change in ponded water levels within the east recharge basin ranged from 2 to 12 mm $hr^{-1}$ (mean of 8.0 mm $hr^{-1}$), which was reasonably close to the value approximated by single ring infiltration tests (mean of 4.6 mm $hr^{-1}$; sample size of 3; not shown).

### 4.2. Groundwater geochemistry

Groundwater *EC* and $Na^+$ concentrations within the tailings sand aquifer had a strong linear relationship (Fig. A2) and suggests *EC* is a good indicator of $Na^+$ concentrations. $Na^+$ concentrations in the upland groundwater were uniformly high (>200 mg $L^{-1}$) throughout the tailings sand aquifer in 2013 prior to the addition of recharge basins (Fig. 5). After the addition of recharge basins, groundwater concentrations rapidly decreased beneath the east recharge basin (<100 mg $L^{-1}$) (Figs. 3 and 5). In 2015, groundwater *EC* and $Na^+$ were relatively high before any ponding or response at the water table occurred, with mean concentrations of 2390 μS $cm^{-1}$ and 140 mg $L^{-1}$, respectively, decreasing considerably to below 1072 μS $cm^{-1}$ and 46 mg $L^{-1}$ below the east recharge basin immediately following ponding and percolation. Groundwater concentrations remained relatively low below the east basin for the remaining portion of 2015 seasons (Fig. 5) with similar patterns repeating in 2016 (Fig. 3). Comparable decreases in $Na^+$ concentrations in groundwater were observed downgradient of the east recharge basin, along the east side of the upland (Fig. 5). *EC* within the tailings sand aquifer below the central recharge basin remained relatively high (average 2690 μS $cm^{-1}$) throughout 2015 until a stark decrease to below 1300 μS $cm^{-1}$ late in the growing season following a slight rise in water table (Fig. 3). *EC* in groundwater beneath the west recharge basin did not decrease throughout 2015, remaining well above 2500 μS $cm^{-1}$ (Fig. 3). *EC* remained high beneath the central and west recharge basins throughout 2016 (Fig. 3).

## 5. Discussion

### 5.1. Recharge basins as recharge windows

Water availability is a primary concern when constructing a wetland within a sub-humid region where potential evapotranspiration generally exceeds precipitation, as is the case in the AOSR (Price et al., 2010; Devito et al., 2012; Ketcheson et al., 2017). This potential moisture limitation must be managed intentionally through landscape design, to ensure that water is partitioned and distributed efficiently. In all four years studied (2013–2016), NFW *AET* from the fen was greater than *P* (Kessel et al., 2018). Most notable was the large water deficit in the study period in 2015 ($P/AET$=30% for periods 17 May to 27 August 2015), which led to particularly dry conditions throughout the NFW and an advance of high $Na^+$ concentrations beneath the fen (Fig. 5).

The east recharge basin had prolonged ponding (Fig. 3 and Table 1), a persistent response in VWC (Fig. 4), and pronounced mounding in the proximal water table (Fig. 3). When compared to the central or west basins, the east basin was clearly the most successful in contributing groundwater recharge to the tailing sand aquifer. The recharge volumes calculated for the east recharge basin were 25%, 17% and 33% of the fen groundwater inflow component ($Q_{fen}$; as calculated by Ketcheson et al. (2017)) in 2014, 2015 and 2016, respectively (Table 1). Given the very small area of the east recharge basin relative to the rest of the upland (0.9%), these contributions scale to it being 22–53 times more effective at recharging the aquifer than the surrounding areas of upland overlain by LFH (98.0% of the area). The efficacy of the basin can be partly attributed to the large upslope catchment that contributed to this basin (4.9 ha), but perhaps of even greater consequence was the topography of the east and southeast hillslopes that converged flow into the confluence, thus providing limited opportunities for infiltration as the water moved downslope. Importantly, the topographic relief of the hillslopes did not appear to correlate with the propensity for runoff generation, as the west hillslope that produced negligible quantities of overland flow had the same grade as the southeast slope (19%), and a slightly steeper grade than the east slope (15%). The position of this basin at the toe of the confluence between the east and southeast hillslopes and large contributing catchment (4.9 ha), resulted in the east recharge basin filling to capacity (240 $m^3$≈8 mm depth over the fen area) after every rain event exceeding 10 mm $day^{-1}$ (Fig. 3). However, the capacity of the east recharge basin was easily overwhelmed, as seen by frequent filling to maximum stage. Runoff that exceeded the basin capacity flowed across the upland and infiltrated into the LFH, likely leading to water loss predominantly from soil evaporation or transpiration – as opposed to groundwater recharge (Sutton and Price, 2020a). Given the need for parsimonious water use on the reclaimed landscape, water lost as soil evaporation does not help achieve the primary reclamation objectives of supporting downgradient peatlands or contributing to the maintenance of upland forest. Therefore, ensuring that the basin has sufficient capacity to detain all runoff is a priority. Although the size of the west and central basins was appropriate, the east and southeast basins should have had a considerably larger capacity. Periodic scouring of the basins to remove sediment will not be a viable long-term strategy for maintaining the efficacy of the basins, however in the early-post construction period when the hillslopes are producing the most runoff and have the greatest potential for erosion it could be a valuable intervention. It was observed that a proportion of overland flow from the east recharge basin reached the central recharge basin where it likely further contributed to recharging the tailings sand aquifer, thus suggesting the utility of successive cascading basins to capture more surface flow.

Due to high runoff ratios from this catchment, hillslope erosion introduced a considerable amount of sediment (likely peat-mineral mix) that began to fill the east recharge basin, which decreased the infiltration rate (~319 to 5 mm hr$^{-1}$) of the basin. Yet, despite this reduction in infiltration capacity, the detention of water behind the hummock ultimately allowed for adequate opportunity time for ponded water to infiltrate, thereby recharging the aquifer (Figs. 3 and 4**).** Although sedimentation resulted in a decrease in basin efficacy at NFW, the hillslopes integrated into the Nikanotee watershed are steeper than is typically prescribed in other systems, thus strategies to control erosion and sedimentation may not need to be implemented at every site. For example, Biagi et al. (2021) reported no runoff from slopes at the nearby Sandhill Fen Watershed under any rainfall events. However, the propensity of a slope for runoff generation is not solely a consequence of slope grade, other factors such as whether the slope converges or diverges water flow, presence and density of vegetation, soil moisture storage, antecedent moisture, and hydraulic properties of the surficial soil will also exert an influence. Furthermore, due to the bulking factor associated with processing of surface mined oil sands, whereby the volume of tailings waste exceeds the pre-mined material by a factor of 1.4 (Mikula, 2012), the closure landscape is expected to be one of greater topographic variability than the pre-disturbance landscape (Rooney et al., 2012). Thus, the reclaimed areas will likely need to integrate undulating topography with slopes of varying grades.

In contrast to the east recharge basin, the small drainage area and placement of the central and west recharge basins minimized their contribution to subsurface recharge. The absence of sedimentation attests to the low rate and volume of runoff entering them. The central recharge basin was distant (~100 m) from surrounding hillslopes and isolated from upslope contributing areas. However, the central recharge basin did elicit responses in *VWC* following rainfall, although this did not result in appreciable water table rise except for one rainfall event in 2015 (Fig. 4). The size and positioning of the central recharge basin did not promote recharge to the same degree as the east recharge basin. The west recharge basin, situated adjacent to the relatively small and low-relief west slope, received very little runoff as there was no notable response in the water table directly beneath the basin (Fig. 3 and 4).

### *5.2. Implication for Na$^+$ flushing and migration*

Recharge basins had a considerable influence on the spatial distribution of Na$^+$ concentrations within the upland tailings sand aquifer. In general, freshwater recharge diluted groundwater concentrations in close proximity to and downgradient of recharge basins (Fig. 5). However, the enhanced recharge to the upland increased the flushing rates of Na$^+$ from the unsaturated regions of tailings sand in the vicinity below active recharge basins (Fig. 5), which may be an undesired effect when considering the water quality transmission to downgradient ecosystems (Daly et al., 2012; Simhayov et al., 2017). As a consequence of the higher hydraulic gradients instituted by the east basin recharge, the downgradient fen received a greater mass of sodium overall, and earlier arrival of Na$^+$ at the surface. Yet, it was apparent that dilution by the relatively fresh recharge water was capable of moderating the groundwater concentrations (Figs. 3 and 5). The east recharge basin was successful in providing recharge and kept groundwater concentrations well below 150 mg L$^{-1}$ along the east region of the upland for the duration of the study. Furthermore, there was no apparent accumulation or "hotspots" of Na$^+$ observed directly down-gradient of the east recharge basin at the fen or in the transition zone at the interface between fen and upland (Fig. 5). As such, at the NFW, the enhanced mobilization of Na$^+$ due to recharge basins is not a concern for down-gradient ecosystems with vegetation species with low salt tolerance.

The observed change in groundwater concentration below the central or west recharge basin was minor due to the smaller quantities of freshwater recharge, compared to the east recharge basin (Fig.s 3–5). Nevertheless, flushing rates of Na$^+$ below these less active basins are still greater compared to rest of the upland, as even in the absence of surface overland flow contributions bare tailings sand recharge greatly exceeded that in LFH covered areas (Sutton and Price, 2020a).

### *5.3. Recommendations for reclamation strategies*

This research demonstrates the disproportionate effectiveness of basins in contributing to groundwater recharge that sustains saturated conditions in the down-gradient wetland. Removing the LFH cover soil and exposing the underlying highly permeable tailings sand was a successful intervention that promoted groundwater recharge. In larger-scale closure landscapes, undulating topography where aquifer material outcrops in depressions could be used to promote localized recharge; this could offer a variety of hydrogeomorphic settings to encourage the establishment of diverse vegetation communities (Sutton and Price, 2020b). In this way, areas overlain with LFH or areas that will not receive the same degree of freshwater recharge will retain solutes for longer, extending the time that solutes take to arrive at down-gradient systems.

If the interaction of freshwater with unsaturated tailings sand is undesired, permeable underdrain layers of alternative materials can be extended beneath these recharge basins. For example, at the NFW, by extending the existing petroleum coke underdrain or moving the recharge basins down-gradient over the underdrain, recharging water would converge in the underdrain. Limiting the interaction with tailings materials through a reduction in horizontal groundwater flow through tailing sand would reduce mixing with saline porewater. Furthermore, increasing the thickness of LFH or comparable reclamation soil prescriptions across the remaining upland area would minimize the undesired mobilization of solutes that are held within the unsaturated zone of the tailings sand aquifer (Sutton and Price, 2020b). While this would lengthen the time for solutes to flush from a reclaimed watershed, it would decrease the peak solute concentration at the fen surface, thus ameliorating the negative ecological consequences of high salinity on fen vegetation (Pouliot et al., 2012; Vitt et al., 2020).

Recharge basins are not anticipated to maintain their efficacy in perpetuity as several processes will compromise their function. As mentioned previously, the runoff from the hillslopes contained large amounts of entrained sediment that was deposited in the basin. This not only decreased the infiltration rate due to the hydraulic properties of the highly organic sediment, but also reduced the total detention volume of the basin. While the east basin maintained its function throughout the study period, the detention capacity of the southeast basin was markedly reduced by sedimentation. The rate of sedimentation can be partially mitigated by implementing sediment controls, such as silt fencing, careful selection of hillslope soil prescriptions, or immediate post-construction planting of vegetation selected to increase slope stability and limit erosion. Furthermore, there may be an optimum topographic relief for hillslopes included in reclamation watersheds, that reaches a compromise between runoff generation and sediment production. Yet, this study offers limited insight into this issue as the differing morphology, reclamation age, hillslope size, and soil prescription confound such an analysis. Even if sedimentation can be reduced or eliminated, it is expected that hillslope surface runoff will decrease as soils evolve and vegetation develops on the slope (Ketcheson et al., 2016). However, this anticipated decrease in hillslope runoff was not observed in this study. Nevertheless, if the appropriate topography and watershed morphology allow for it, placing bare tailings basins in areas that receive surface runoff can greatly contribute to the initial saturation of upland aquifers. Given the importance of quickly establishing groundwater flow to fen peatlands in the early post-construction period to restrict peat oxidation and support wetland vegetation, recharge basins are valuable features to include in reclamation design.

### 5.4. *Empirical uncertainties*

There are several uncertainties that should be noted in this study. The average infiltration rate was calculated as a residual term within the water balance, Eq. (2), in which no error term is explicitly considered; however, since the infiltration rate approaches the saturated hydraulic conductivity of the material, a favorable comparison between the calculated infiltration rate and the measured hydraulic conductivity offers some validation. Since these were indeed similar, this gives confidence to the magnitude of infiltration and recharge rates reported here. Infiltration rates were also corroborated by the manual single ring infiltration tests. Any error introduced due to the method to estimate water loss by evaporation using the fen EC tower was thought to be negligible since evaporation constituted a very small proportion of water compared to total infiltration amount. Although there was no mass balance between the groundwater recharge and infiltrated volume, the large groundwater mound observed beneath the east recharge basin immediately following a recharge event, suggests that the infiltrated volumes are reasonable.

## 6. Conclusion

Given the abundance and ecological value of wetlands within the undisturbed landscape of the AOSR, reclaiming the post-mined oil sands landscape of the AOSR must include ecosystems that exhibit functional similarities characteristic of fens. Since these systems rely on groundwater to offset water deficits accrued over the growing season, reclamation strategies should include practices that enhance subsurface storage, and thereby ensure the long-erm sustainability of these systems. This study found a recharge basin ideally positioned at the confluence of two hillslopes strongly promoted groundwater recharge that supplied ~30% of the post-snowmelt water to the downgradient fen. Reclaimed uplands that are integrated to support wetlands or other aquatic ecosystems, and which are designed to promote recharge should incorporate recharge basins located accordingly. These basins require a relatively small footprint, thus allowing remaining upland areas to prioritize water storage for forest growth (Sutton and Price, 2020b). Isolated basins or those positioned next to low-relief slopes, albeit not as effective in promoting recharge, still encourage more recharge than the surrounding LFH cover soil.

In the early years post-construction, it is essential to ensure saturated conditions within fen peatlands, as the establishment of fen vegetation will be influenced by the position of the water table (Borkenhagen and Cooper, 2019). These recharge basins contribute disproportionally to the aquifer storage, while simultaneously moderating variability in groundwater flow to the downgradient peatland. This is especially valuable during dry years, when the maintenance of the water table near the surface of the fen is predominantly a consequence of groundwater contributions from the upland. Enhanced groundwater recharge also increased the mobility of solutes found in the process-affected tailings sand, which must be considered when incorporating recharge basins into the reclaimed landscape. However, due to dilution, the higher rate of $Na^+$ flushing from recharge basins was deemed an acceptable compromise; however, further research will be needed to identify whether the current mass flux rate affects the development of the wetland vegetation species in the fen. With time, as reclaimed hillslopes transition from water conveyance to water storage features (Ketcheson et al., 2016), and the detention and infiltration capacity of the basins decreases due to sedimentation, the efficacy of the recharge basins will likely diminish. Investigation of the longevity and future role of these recharge features is recommended.

## CRediT authorship contribution statement

**Eric D. Kessel:** Masters of Science student who conducted the field component of the research. Eric also analyzed the data and wrote the first draft of the manuscript. **Owen F. Sutton:** Mentored and collaborated on the conceptual ideas, helped with analysis, wrote and edited the manuscript. **Jonathan S. Price:** Supervised the research. Mentored and collaborated on the conceptual ideas, helped with analysis, wrote and edited the manuscript.

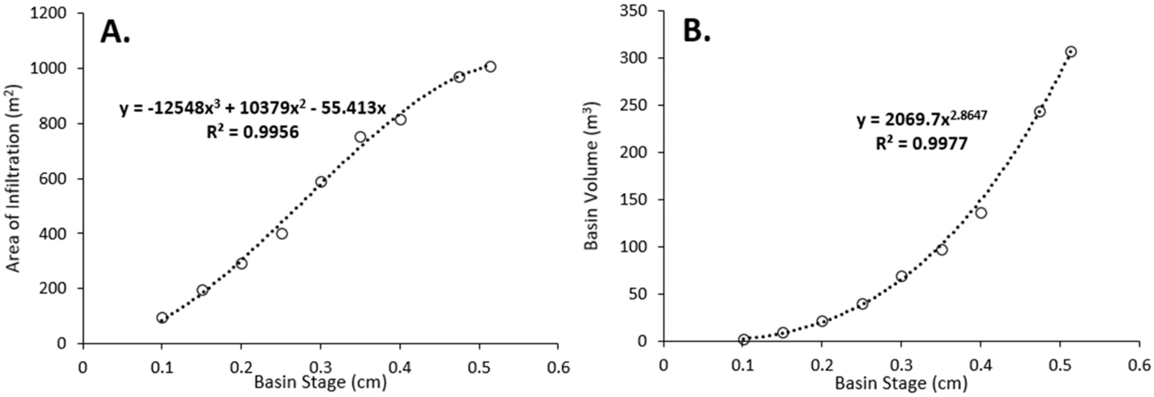

**Fig. A1.** Basin stage versus the area infiltration (A) and basin volume (B) for the east recharge basin determined by a ~1 m resolution ground survey.

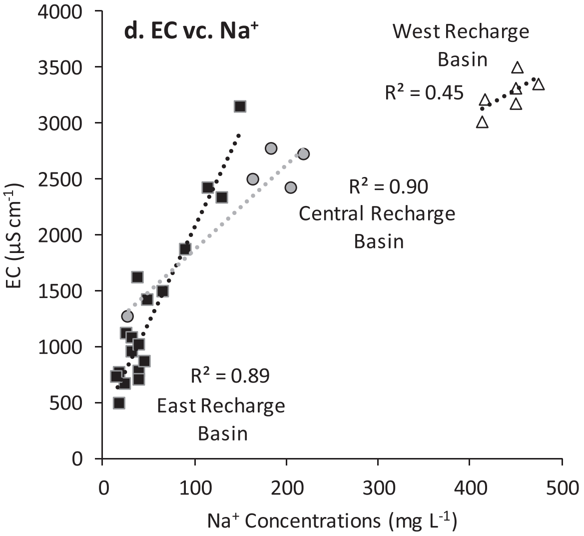

**Fig. A2.** Relationship between EC and $Na^+$ groundwater concentrations for beneath the east, central and west recharge basins.

## 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.

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## Appendix A

### *East recharge basin bathymetry*

A differential global positioning system (Leica Geosystems Viva GS14 GNSS RTK GPS) was used to survey the land surface of the east recharge basin (mASL; ±0.5 cm vertical accuracy). The bathymetry was used to determine the area of infiltration and basin volume, as a function of pond stage (Fig. A1).

### *EC vs. $Na^+$ groundwater concentrations*

The relationship between EC and $Na^+$ groundwater concentrations for beneath the east, central and west recharge basins are near linear relationships for each respective location, indicating only groundwater dilution and no other geochemical reactions are occurring. However, the linear relationship was different for beneath each basin, due to the geochemical variability in the tailings sand aquifer (Fig. A2).

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