An evaluation of water quality at Sandhill Wetland: implications for reclaiming wetlands above soft tailings deposits in northern Alberta, Canada

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Abstract The experimental Sandhill Wetland is the first permanent reclamation of a composite tailings deposit, and annual water quality monitoring is of specific interest for evaluating and predicting long-term reclamation performance. Here, we present water chemistry monitoring data obtained from Sandhill Wetland (years 2009–2019) and compare results to twelve natural reference wetlands and to environmental quality guidelines for Alberta surface waters. By comparing water quality at Sandhill Wetland and natural sites to established guidelines, we can begin to document the natural background water quality of wetlands in the region and examine if guideline exceedances are seen in natural undisturbed environments, or appear only at active reclamation sites. At Sandhill Wetland the dominant ions in near-surface water were bicarbonate, sulfate, chloride, sodium, calcium, and magnesium. Since the first growing season concentrations for these ions have increased

annually, causing concurrent increases in electrical conductivity. In year 2019, water chemistry at Sandhill Wetland was most comparable to regional saline fens, systems that exhibit elevated electrical conductivity and high sodicity. Near-surface water at Sandhill Wetland exceeded water quality guidelines for three substances/properties (dissolved chloride, iron, and total alkalinity) in the most recent year of monitoring. The saline fen natural sites also exceeded water quality guidelines for the same chemical substances/properties, suggesting guideline exceedances are a norm for some natural wetland site types in the region. Of note, in each year of monitoring at Sandhill Wetland, dissolved organic compounds evaluated in sub- and near-surface water were below detection limits.

Keywords Water quality · Sandhill Wetland · Oil sands · Boreal forest · Wetland reclamation · Peatland

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Introduction

In northeastern Alberta, Canada wetlands cover more than 25% of the Oil Sands Administration Area (OSAA) (Wieder et al. 2016a, 2019). The ecosystem services provided by these systems are numerous and typified by the high amounts of carbon stored and water associated with regional bogs, fens, and marshes (Gorham 1991; Loisel et al. 2014; Devito et al. 2005).

Open pit mining for bitumen, however, is a major economic focus in the region. Under a full development scenario to extract all oil resources, over 4500 km² of wetlands within the OSAA could be disturbed (Lee and Cheng 2009). Returning some of this disturbed area back to landscapes that support functional wetland ecosystems via reclamation efforts is a requirement for oil sands operators (Harris 2007). Although several challenges exist to reclaim tailings landscapes back to wetlands, a key challenge to overcome is ensuring water quality at reclaimed sites is suitable for return to the environment (Mitsch and Wang 2000; Thullen et al. 2002; Rousseau et al. 2008).

Located on the Syncrude Canada Ltd. mineral surface lease, the experimental Sandhill Watershed reclamation site is a full-scale research pilot study. The site was designed to test the feasibility of constructing a watershed capable of supporting a self-sustaining wetland above a composite tailings deposit—a backfilled open pit mine (Wytrykush et al. 2012). The cumulative size of Sandhill Watershed is 52 ha and the wetland residing within (which we refer to as “Sandhill Wetland”) is 17 ha (Fig. 1). Year 2013 was the first full growing season tracked for research purposes following wetting with fresh lake water. Several studies have examined temporal and spatial changes of ions associated with water and soil within Sandhill Wetland (Vitt et al. 2016; Hartsock et al. 2016, 2019; Biagi et al. 2019; Vessey et al. 2019; Clark et al. 2019). Over the first three years (2013–2015), Biagi et al. (2019) reported dissolved calcium, magnesium, sodium, sulfate, and chloride concentrations increased annually, and further, using stable isotopes showed the source of ion accumulation primarily stemmed from upward movement of oil sand process water (OSPW; water associated with composite tailings). While previous studies at Sandhill Wetland have focused on the behavior of dominant anions and cations, characterization of micronutrients, trace metals, heavy metals, and other organic compounds has not been done extensively with the exception of Oswald and Carey (2016), who found total mercury (THg) and methylmercury (MeHg) concentrations in sediments were lower than in two nearby natural fens. Because select trace metals and organic compounds are hazardous to biota at low concentrations, determining baseline concentrations of these elements at Sandhill Wetland is important.

The research presented here seeks to update and expand upon the chemical substances previously monitored in water at Sandhill Wetland. Further, this paper is focused on comparing water quality at Sandhill Wetland to natural reference wetlands and to established provincial surface water quality guidelines.

The Alberta government has developed water quality guidelines for the protection of freshwater aquatic life. These guidelines are based on national Canadian Council of Ministers of the Environment (CCME) environmental quality guidelines, and the protocol for guideline development is adapted from United States Environmental Protection Agency methods (Government of Alberta 2018). Monitoring water quality in wetlands residing on oil sands mineral surface leases and understanding if/where exceedances of the existing guidelines may occur is an important step in closing these mine sites after resource development is complete. By comparing water quality at Sandhill Wetland and natural wetlands to established guidelines, we provide valuable regional context for interpretation of water quality results. This work further documents natural wetland water quality in the region and provides insight into if guideline exceedances are the norm (due to environmental factors) or stem from mining activities.

Here, we present water chemistry data obtained from annual water quality monitoring at Sandhill Wetland spanning each growing season from 2013 to 2019. We also present data obtained from groundwater monitoring wells four years prior to site construction completion (years 2009, 2011, and 2012) to highlight baseline ion concentrations of water residing below the watershed. Lastly, we present water chemistry data obtained from several mature natural reference wetlands that represent potential successional outcomes for Sandhill Wetland. Our primary objectives are threefold: (1) compile and summarize ion concentrations measured at Sandhill Wetland over a ten year period, (2) determine whether ion concentrations at Sandhill Wetland are comparable to observations among natural reference wetlands, and (3) compare water quality among all sites to the Environmental Quality Guidelines for Alberta Surface Waters to examine if/where guideline exceedances occur.

Fig. 1 Map of Sandhill Wetland features (photo obtained from Google Earth year 2018). The black boarder delineates the wetland area from the adjacent uplands. In general, water flows across the site from west to east. Most near-surface water sampling was completed in proximity to the weir intake pond,

weir building, and sump (areas collectively referred to as the “outlet”). The rational for collecting water at the outlet was that water quality at the outflow location would be representative of water quality leaving the site. In later years (2018–2019) samples were also collected in proximity to boardwalks 1–3

Methods

Sandhill watershed background

The Sandhill Watershed design included placing various materials at prescribed depths and configurations above a composite tailings deposit. Composite tailings are a mixture of coarse and fluid fine tailings with gypsum added post-processing to promote aggregation of soft tailings (Oil Sands Wetland Working Group 2014). Composite tailings are poured back into mined-out pits in a slurry using OSPW. Oil sand process water contains high concentrations of soluble salts originating from naturally occurring marine sediments in the region and also added during bitumen recovery (MacKinnon et al. 2001; Chalaturnyk et al. 2002; Matthews et al. 2002). To allow access, promote trafficability, and reach the final elevation for the deposit, a 10 m tailings sand cap was placed across the entire research site. Of note, an underdrain system was installed within the tailings

sand layer to circumvent possible upward movement of OSPW. When in operation, water within the sand cap collects in the underdrain system and flows to a sump at the watershed outlet. Underdrain water mixes with surface water at the outlet location, where it is then pumped out of the watershed. Overtop the tailings sand, a 0.5 m layer of clay till was placed in the wetland area that was then overlain by a 0.5 m layer of freshly salvaged peat (obtained from a mixed peatland in the footprint of the mine advance). Surrounding the wetland area, uplands, and upland hills (called hummocks) were also constructed. The uplands were made from tailings sand and constructed with various configurations to test for optimal design to establish a local surface water system, separate from, but inevitably connected to the deeper composite tailings materials residing below.

The 17 ha wetland area was seeded with a myriad of peatland species in year 2011 (Vitt et al. 2016). In year 2012, active pumping of fresh water into the wetland from a nearby lake (Mildred Lake) facilitated

initial site wetting, however, year 2013 was the first full growing season tracked for research purposes. The underdrain system was used extensively in 2013 largely for testing purposes. In May 2014 underdrain usage ceased and no further management of OSPW has occurred (Nicholls et al. 2016; Spennato et al. 2018). Discharge of near-surface water from the wetland occurs via an outflow system that is turned on to prevent flooding following spring melt and heavy rain events. In general, water moves out of Sandhill Wetland on the east side from the discharge point (East of the weir building) only when pumps are turned on; passive drainage/movement of water out of the wetland is minimal (Twerdy 2019, *Thesis*).

Fens and marshes background

The experimental Sandhill Watershed was designed to expedite development of a self-sustaining wetland with structural, functional, and chemical attributes, including aspects of water quality, resembling those of regional fens or marshes. In Alberta, four fen site-types have been recognized (poor, moderate-rich, extreme-rich, and saline) and all fen types are desirable wetland reclamation outcomes. The chemical composition of surface and groundwater entering fens strongly influences successional trajectory towards a specific type (Environment and Parks 2015). Near-surface groundwater chemistry throughout the OSAA is highly variable, ranging from acidic to basic, and fresh to sodic, thus, all four fen types are present in the region. In brief, poor fens have acidic water with low reduced electrical conductivity (EC) typically less than $100 \mu\text{S cm}^{-1}$ (Sjörs 1950; Graham et al. 2016; Hartsock et al. 2016), moderate-rich fens have circumneutral water with EC generally less than $250 \mu\text{S cm}^{-1}$ (Vitt and Chee 1990; Gignac et al. 1991; Locky and Bayley 2010), extreme-rich fens have basic water, with EC ranging from 250 to $450 \mu\text{S cm}^{-1}$ (Slack et al. 1980; Rochefort and Vitt 1988; Hartsock and Bremer 2018) and saline fens have sodic water with EC ranging from 1000 to $30,000 \mu\text{S cm}^{-1}$ (Purdy et al. 2005; Stewart and Lemay 2011; Volik et al. 2017). In contrast to fens, the total area occupied by marshes in the OSAA is much smaller, nonetheless, marshes are an acceptable and achievable reclamation outcome (Raab and Bayley 2013). From a functional perspective, decomposition rates typically are higher in marshes compared to fens, resulting in shallower

peat deposits or an inability to form peat altogether (Bayley and Mewhort 2004). Marshes can associate with lakes, rivers, or seepage areas and thereby show marked variation in size, water table depth, emergent vegetation structure, and water chemistry characteristics. Near-surface water in marshes typically exhibits circumneutral to slightly basic pH levels, however, in terms of overall salinity, marshes can be fresh or slightly brackish (Bayley and Mewhort 2004; ESRD 2015). In some cases, marshes may exhibit elevated dissolved sodium concentrations (Purdy et al. 2005; Trites and Bayley 2009).

In total, twelve mature reference wetlands were monitored for making comparisons to Sandhill Wetland. When possible, multiple wetlands of the same type were monitored to better capture extant natural variation in the region. The reference sites included 3 poor fens, 1 open moderate-rich fen, 2 wooded moderate-rich fens, 1 extreme-rich fen, 3 saline fens, 1 fresh marsh, and 1 slightly brackish marsh. Of note, the naming system for reference fens was adopted from historic peatland characterization studies occurring in Alberta (Slack et al. 1980; Vitt and Chee 1990; Purdy et al. 2005). For marshes, sites were categorized using surface water salinity delineations from the Alberta Wetland Classification System (ESRD 2015). The reference wetlands are located along highways 881 and 63, the Clearwater River, and within Elk Island National Park (Table 1).

Water collections

Sandhill Wetland water collection

Annual water quality sampling has been carried out at Sandhill Wetland during ice-free months. Prior to site commissioning, in years 2009, 2011, and 2012, water was collected intermittently (May–September) from a subset of groundwater wells installed across the watershed area ($n = 15, 6$, and 14 , for years 2009, 2011, and 2012, respectively). Groundwater samples were pulled at depths ranging from 1.5 to 39.3 m below the soil surface with a mean sampling depth of 12.4 m. Collection of water from groundwater wells ceased after year 2012.

Annual water quality sampling of near-surface water began in 2013. For years 2013–2017, near-surface outflow water samples were obtained from the eastern boundary of the site where the collective study

Table 1 Wetland site locations and elevation

Site name	Wetland type	Location	Elevation (meters)
SHW	Reclamation wetland	57°02′25.32″ N 111°35′22.61″ W	311
PF1	Poor fen	56°22′35.21″ N 111°14′09.82″ W	743
PF2	Poor fen	55°53′50.14″ N 112°05′38.15″ W	695
PF3	Poor fen	55°32′17.78″ N 112°20′09.48″ W	727
MRF1	Open moderate-rich fen	54°28′28.93″ N 113°19′27.80″ W	669
MRF2	Wooded moderate-rich fen	55°40′25.85″ N 110°53′35.45″ W	565
MRF3	Wooded moderate-rich fen	55°14′56.96″ N 111°19′42.70″ W	569
ERF	Extreme-rich fen	56°56′56.52″ N 111°31′41.05″ W	314
Mf	Fresh marsh	53°39′35.05″ N 112°50′54.24″ W	720
Mb	Slightly brackish marsh	53°31′25.40″ N 112°56′15.93″ W	726
SAL1	Saline fen	56°40′45.25″ N 111°09′19.72″ W	255
SAL2	Saline fen	56°34′24.97″ N 111°16′34.14″ W	398
SAL3	Saline fen	53°31′21.38″ N 112°56′05.73″ W	729

SHW Sandhill Wetland, *PF* poor fen, *MRF* moderate-rich fen, *ERF* extreme-rich fen, *Mf* fresh marsh, *Mb* slightly brackish marsh, *SAL* saline fen

area drains because of a designed shallow slope towards the east. At the eastern boundary, water samples were obtained from either the weir intake pond, the physical weir (located inside the weir building), or the wetland sump (for years 2013–2017, $n = 11, 12, 10, 3$, and 10 , respectively). In brief, the weir intake pond is the source of water to the weir, the wetland sump is where water from the weir collects prior to being pumped out of the study site (when pumps are turned on). Because of the intimate connectivity between the weir intake pond, the physical weir, and wetland sump (especially after closing of the underdrain valve in May 2014), we hereafter refer to these three locations collectively as the “outlet”. The rationale for collecting water at the outlet was that water quality at the outflow location would be representative of water quality leaving the site. For year 2018, near-surface water was collected

from the outlet and from areas in proximity to the three boardwalks located in the central wetland area ($n = 20$). For year 2019, water was collected exclusively from areas near the three boardwalks ($n = 5$). Characterization of organic compounds in water was completed in year 2019 only. All water samples were analyzed by accredited commercial laboratories EXOVA Canada, Inc. (2009–2017) and later MAX-XAM Analytics, Inc. (2018–2019). Protocols and methods used by these labs are shown in supplementary Tables S1 and S2.

Reference site water collection

At reference sites, in 2018 and 2019 near-surface water samples were collected once per year from 2 to 4 random locations along transects established through the interior of each wetland (except for SAL1 that was

sampled in 2018 only). In 2018 water sampling was done in the last weeks of June, and in 2019 water collections occurred in the last weeks of July. At reference sites water samples were collected by hand. At sites where water table position was slightly below the ground layer vegetation, a small soil core was removed with an aluminum soil corer, allowed to fill with porewater, thereby allowing water to be collected. Characterization of organic compounds in water was completed in year 2019 only. Water samples from natural sites (2018 and 2019) were analyzed by MAXXAM Analytics, Inc.

Data analysis

Due to clear violation of analysis of variance (ANOVA) assumptions, namely, non-random sampling conducted at Sandhill Wetland, we were unable to use ANOVA for comparing differences between years at the reclamation site, and further, differences between Sandhill Wetland and reference sites. Using descriptive statistics, we present means $\pm$ standard deviations for all substances/properties measured. For reference wetlands, we lumped observations from wetlands of the same type, thus, we present means $\pm$ standard deviations for a saline fen group ($n = 15$), a moderate-rich fen group ($n = 19$), an extreme-rich fen group ($n = 7$), a poor fen group ($n = 15$), a slightly brackish marsh group ($n = 5$), and a fresh marsh group ($n = 6$).

This study compared water chemistry results to the Environmental Quality Guidelines for Alberta Surface Waters, which are published and updated by Alberta Environment and Parks (AEP). As stated in the guidelines, the purpose is to provide science-based recommendations that protect water uses and form a cornerstone of aquatic ecosystem management and protection. They are foundational elements in cumulative effects management (Government of Alberta 2018). The guideline document includes guidelines for surface water quality (to protect aquatic life, agricultural, and recreational uses). This study used the guidelines for protection of aquatic life only. We report any incidence where a long-term (chronic) or short-term (acute) exceedance was observed in at least one water sample for a given year. Long-term guidelines represent levels of a substance or condition that should result in negligible risk of adverse effects on growth, reproduction, or survival of aquatic biota

for an indefinite period. Short-term guidelines are derived from severe effects data and are meant to provide guidance on severe, but transient situations.

Results and discussion

Sandhill Wetland sub-surface water summary

Collection of water from groundwater wells during years 2009–2012 provided insight on sub-surface water quality prior to reclamation. The groundwater well data represents the OSPW type water associated with in-pit composite tailings porewater. For EC observations, values ranged from 2500 to 5290 $\mu\text{S cm}^{-1}$ with a mean EC of 4213 $\mu\text{S cm}^{-1}$. Sodium was the dominant cation, exhibiting concentrations ranging from 307 to 1370 mg L^{-1} . Due to OSPW influence in deeper wells, sodium concentrations were markedly higher than near-surface water observations. Dissolved calcium and magnesium concentrations in sub-surface water were lower than near-surface water, whereas sub-surface potassium was slightly higher than near-surface water by a small margin (Fig. 2; Table 2). Dissolved bicarbonate and chloride were dominant anions, exhibiting ranges of 548–1720 and 36–1180 mg L^{-1} , respectively. Sulfate concentrations generally were twofold lower than bicarbonate and chloride, except in year 2012 when concentrations were similar between the three dominant anions (Fig. 3). All organic compounds measured from groundwater wells were below detection limits (Table 3).

Sandhill Wetland sub-surface water quality assessment

The Sandhill Wetland reclamation design concept is based on natural regional analogues, whereby deeper groundwater (the basal aquifer and Devonian waters) displays poorer water quality compared to surface water systems (Devito et al. 2012; Volik et al. 2017). The following substances/properties from groundwater wells exceeded long-term guideline concentrations in at least one sample for a given year: Total alkalinity, ammonium, sulfate, chloride, iron, boron, aluminum, cobalt, molybdenum, silver, arsenic, thallium, and zinc. For iron, thallium, silver, zinc, and aluminum exceedances were infrequent, occurring in less than

Fig. 2 Bar plots of electrical conductivity and dissolved cations in sub- and near-surface water at Sandhill Wetland (years 2009–2019). Error bars are standard errors. The dotted line

indicates the completion of site construction, and the switch from annual sub-surface water quality monitoring to near-surface water quality monitoring

five water samples out of a cumulative total of 35 for each individual substance. Dissolved chloride was the only substance to exceed both long- and short-term recommendations (short-term chloride guideline: 640 mg L^{-1}). Recommended sodium concentrations and EC levels are absent from the Alberta surface water quality guidelines for protection of aquatic life, however, EC and sodium concentrations from groundwater well samples were higher than most reference wetlands except the saline fens. For specific water quality guideline values relevant to this study, refer to supplementary Tables S3, S4, S5, and S6.

Sandhill Wetland near-surface water summary

Due to mixing of freshwater being pumped into the wetland and sub-surface porewater being pulled from the underdrain system into the sump, EC levels of water collected at the outlet in years 2013–2014 were elevated due to OSPW influence (Fig. 2; Table 2). Suspending underdrain usage and closing of the underdrain valve in May 2014 resulted in marked EC decreases at the outlet in year 2015. However, EC levels have increased annually since 2015 in a linear fashion by about $283 \mu\text{S cm}^{-1}$ to current levels of $2560 \mu\text{S cm}^{-1}$ measured in 2019.

Table 2 Porewater concentrations at Sandhill Wetland

Year:	2009	2011	2012	2013	2014	2015	2016	2017	2018	2019
Sampling location:	GROUND- WATER WELLS	GROUND- WATER WELLS	GROUND- WATER WELLS	Outlet	Outlet	Outlet	Outlet	Outlet	Outlet and Wetland Boardwalks	Wetland Boardwalks
Replicate no:	n = 15	n = 6	n = 14	n = 11	n = 12	n = 10	n = 3	n = 10	n = 20	n = 5
Property										
pH	8.1 (0.1)	8.1 (0.1)	7.9 (0.4)	8.0 (0.2)	8.1 (0.1)	7.9 (0.2)	7.9 (0.2)	7.8 (0.1)	7.9 (0.2)	7.9 (0.1)
EC ($\mu\text{S cm}^{-1}$)	4456 (454)	4152 (328)	3978 (534)	1779 (769)	1692 (439)	1143 (275)	1380 (100)	1858 (219)	2310 (961)	2560 (305)
Hardness (CaCO_3)	140 (123)	72 (33)	226 (206)	343 (93)	468 (53)	383 (73)	447 (29)	512 (42)	587 (194)	676 (122)
T-Alkalinity (CaCO_3)	<u>923 (198)</u>	<u>819 (144)</u>	<u>843 (283)</u>	<u>365 (122)</u>	<u>280 (93)</u>	<u>219 (60)</u>	<u>266 (26)</u>	<u>302 (29)</u>	<u>307 (118)</u>	<u>362 (55)</u>
TDS (calculated)	2878 (365)	2647 (158)	2805 (338)	1117 (501)	1111 (273)	728 (204)	879 (39)	1177 (158)	1505 (698)	1640 (305)
SAR (calculated)	48 (17)	54.7 (15.7)	40.0 (21.5)	5.8 (2.6)	4.2 (2.2)	2.3 (0.8)	2.8 (0.2)	4.6 (1.0)	5.3 (2.8)	5.8 (0.8)
Bicarbonate	1126 (241)	999 (178)	1028 (347)	445 (149)	342 (113)	267 (73)	324 (32)	369 (35)	374 (143)	398 (67)
Ammonium—N	n.d.	<u>5.24 (2.40)</u>	<u>8.22 (4.09)</u>	<u>2.54 (1.75)</u>	<u>< 5.92</u>	<u>0.05 (0.04)</u>	<u>0.10 (0.13)</u>	<u>< 0.17</u>	n.d.	n.d.
TKN	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.89 (0.82)	2.14 (0.29)
Nitrate—N	< 0.10	< 0.14	< 1.80	< 0.54	< 0.47	< 0.18	< 0.05	< 0.08	< 0.061	< 0.010
Nitrite—N	< 0.05	< 0.02	< 0.07	< 0.14	< 0.01	< 0.005	< 0.02	< 0.02	< 0.010	< 0.010
Phosphorus (P)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	< 0.10	< 0.10
DOC	n.d.	66 (10)	79 (14)	n.d.	n.d.	n.d.	n.d.	n.d.	56 (24)	58 (13)
Sulfate	<u>351 (156)</u>	<u>341 (111)</u>	<u>627 (381)</u>	346 (170)	413 (69)	258 (74)	275 (13)	357 (50)	<u>566 (296)</u>	622 (205)
Chloride	<u>849 (169)*</u>	<u>790 (145)*</u>	<u>608 (228)*</u>	<u>161 (86)</u>	<u>154 (41)</u>	95 (34)	<u>142 (19)</u>	<u>224 (38)</u>	<u>247 (145)</u>	<u>246 (53)</u>
Sodium	1065 (152)	985 (83)	965 (178)	260 (139)	206 (104)	105 (45)	135 (7)	253 (78)	301 (185)	344 (60)
Calcium	34 (37)	15 (9)	53 (50)	97 (26)	131 (14)	109 (19)	125 (10)	152 (27)	162 (52)	184 (38)
Magnesium	13 (8)	8 (3)	23 (21)	24 (7)	34 (4)	27 (7)	33 (2)	41 (6)	44 (16)	53 (7)
Potassium	13.0 (2.3)	11.3 (1.7)	17.4 (5.5)	7.0 (2.5)	4.6 (1.7)	3.2 (1.3)	8.2 (0.4)	9.0 (2.1)	7.0 (2.8)	6.9 (1.8)
Cadmium ($\mu\text{g L}^{-1}$)	0.05 (0.01)	< 0.05	< 0.2	< 0.01	< 0.02	< 0.05	< 0.01	< 0.02	< 0.18	< 0.02
Iron	< 0.05	< 0.05	< 5.8	< 0.35	< 0.84	0.07 (0.03)	0.06 (0.050)	0.16 (0.14)	< 1.30	<u>0.39 (0.29)</u>
Lithium	0.28 (0.03)	0.28 (0.01)	0.33 (0.06)	0.09 (0.01)	0.07 (0.04)	0.04 (0.01)	0.04 (0.00)	0.08 (0.03)	0.09 (0.05)	0.13 (0.06)
Manganese	0.09 (0.04)	< 0.07	0.57 (1.05)	< 1.25	< 0.74	< 0.54	< 0.25	< 1.72	0.39 (0.49)	0.28 (0.38)
Strontium	0.9 (0.4)	0.6 (0.1)	1.2 (0.8)	0.8 (0.1)	0.8 (0.1)	0.6 (0.2)	0.7 (0.1)	0.8 (0.2)	0.8 (0.3)	1.0 (0.3)
Barium ($\mu\text{g L}^{-1}$)	169 (65)	142 (83)	118 (110)	77 (9)	59 (5)	52 (7)	51 (3)	64 (17)	44 (20)	28 (8)
Silicon	5.5 (1.0)	4.4 (0.9)	5.9 (1.3)	3.8 (0.6)	2.6 (0.7)	1.2 (1.0)	0.8 (0.2)	5.1 (1.5)	5.9 (2.5)	5.5 (1.7)
Boron	<u>3.07 (0.29)</u>	<u>3.07 (0.37)</u>	<u>3.06 (0.41)</u>	0.86 (0.14)	<u>0.5 (0.37)</u>	0.21 (0.09)	0.20 (0.01)	0.29 (0.21)	0.40 (0.21)	0.48 (0.35)
Aluminum ($\mu\text{g L}^{-1}$)	<u>11 (11)</u>	< 20	< 1780*	< 14	14 (7)	6 (3)	< 2	< 9	< 18	< 5
Chromium ($\mu\text{g L}^{-1}$)	< 13	7 (2)	< 4	< 1	< 1	< 1	< 1	< 1	< 1	< 1

Table 2 continued

Year: Sampling location:	2009 GROUND- WATER WELLS n = 15	2011 GROUND- WATER WELLS n = 6	2012 GROUND- WATER WELLS n = 14	2013 Outlet n = 11	2014 Outlet n = 12	2015 Outlet n = 10	2016 Outlet n = 3	2017 Outlet n = 10	2018 Outlet and Wetland Boardwalks n = 20	2019 Wetland Boardwalks n = 5
Replicate no:										
Cobalt ($\mu\text{g L}^{-1}$)	< 0.8	<u>0.8 (0.9)</u>	< <u>136.0</u>	<u>10.7 (8.7)</u>	<u>3.7 (5.0)</u>	< <u>12.1</u>	< 0.5	< 1.0	< 1.7	< 1.3
Copper ($\mu\text{g L}^{-1}$)	< 7	< 5	< 10	< 2	< 6	3 (2)	< 1	< 5	< 3	4 (4)
Lead	< 0.0009	< 0.0005	< 0.0048	< 0.0002	< 0.0002	< 0.0001	< 0.0001	< 0.0002	< 0.0002	< 0.00020
Antimony	< 0.0010	< 0.0010	< 0.001	< 0.0004	< 0.0004	< 0.0003	< 0.0002	< 0.0004	< 0.0006	< 0.00060
Molybdenum	< <u>120</u>	<u>79 (49)</u>	< <u>130</u>	11 (2)	< 20	< 4	< 1	< 2	< 2	< 1
Nickel ($\mu\text{g L}^{-1}$)	< 5.6	4.7 (2.8)	< 144.0	22.3 (4.6)	11.3 (8.1)	3.6 (30.2)	1.4 (0.1)	2.3 (0.7)	2.5 (1.7)	2.5 (0.7)
Selenium ($\mu\text{g L}^{-1}$)	0.9 (0.2)	< 1.0	< 1.0	< 0.4	< 0.4	< 0.2	< 0.2	< 0.4	< <u>250.0</u>	< 0.2
Silver	< <u>0.0005</u>	< 0.00005	< 0.00005	< 0.00002	< 0.00002	< 0.00001	< 0.00001	< 0.00002	< 0.00010	< 0.00010
Arsenic ($\mu\text{g L}^{-1}$)	<u>3.9 (2.9)</u>	<u>4.9 (4.2)</u>	< <u>5</u>	1.7 (0.4)	2.1 (0.7)	1.0 (0.2)	1.0 (0.3)	1.2 (0.3)	1.1 (0.5)	0.9 (0.2)
Thallium	< <u>0.0010</u>	< 0.0002	< 0.0002	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0002	< 0.00020
Tin	< 0.007	< 0.005	< 0.005	< 0.002	< 0.002	< 0.001	< 0.001	< 0.002	< 0.001	< 0.0010
Titanium ($\mu\text{g L}^{-1}$)	6 (4)	9 (3)	10 (14)	< 1	< 1	< 1	< 1	< 1	< 2	< 1
Uranium ($\mu\text{g L}^{-1}$)	2.8 (1.5)	< 6.0	< 9.0	1.6 (0.5)	< 3.7	< 1.1	< 0.5	< 1.0	< 1.0	< 0.9
Vanadium ($\mu\text{g L}^{-1}$)	4.6 (1.7)	6.5 (1.8)	< 16	0.2 (0.1)	< 0.5	< 0.2	< 0.1	< 0.8	< 1.0	< 1.0
Zinc ($\mu\text{g L}^{-1}$)	< 10	< 8	<u>13 (10)</u>	9 (3)	11 (6)	<u>27 (36)</u>	< 1	< 3	< <u>84</u>	n.d.
Beryllium	< 0.0008	< 0.0005	< 0.0005	< 0.0002	< 0.0002	< 0.0001	< 0.0001	< 0.0002	< 0.0010	n.d.

Values are means with standard deviations in parenthesis and concentrations are in mg L^{-1} unless specified otherwise. In cases where means could not be calculated because values were below detection limits, the highest concentration observed was reported

Bolded properties indicate a guideline exceedance. Italicized underlined values represent chronic surface water quality guideline exceedances. Values with an asterisk represent acute exceedances

Fig. 3 Bar plots of dissolved anions in sub- and near-surface water at Sandhill Wetland (years 2009–2019). Error bars are standard errors. The dotted line indicates the completion of site

construction, and the switch from annual sub-surface water quality monitoring to near-surface water quality monitoring

For dissolved base cations, sodium has been dominant each year of monitoring. Similar to EC patterns, elevated sodium concentrations at the outlet in years 2013 and 2014 (means: 260 and 206 mg L⁻¹, respectively) was due to mixing of underdrain water and near-surface water. Sodium concentrations dropped precipitously at the outlet in year 2015 (mean: 105 mg L⁻¹) following closure of the underdrain system. Excluding samples collected in 2013 and 2014, sodium concentrations have increased annually by about 48 mg L⁻¹ to current levels of 344 mg L⁻¹ in year 2019. Adverse physiologic effects from prolonged sodium exposure may affect some wetland plants that initially established in an environment less concentrated with sodium. Over subsequent years, replacement of sodium-sensitive species by halophytic species may occur at Sandhill Wetland, warranting further monitoring of both water chemistry and plant community composition to capture these important successional changes (Glaeser et al. 2016). The divalent cation calcium historically has been the second most abundant cation in near-surface water, followed by magnesium. Calcium and magnesium concentrations in near-surface water exceeded

concentrations in sub-surface water. Using stable isotopes, both Biagi et al. (2019) and Vessey et al. (2019) showed annual increases in calcium and magnesium concentrations are in part due to cation exchange reactions, whereby upward movement of sodium-rich OSPW has displaced much of the calcium and magnesium previously adsorbed to the mineral clay and placed peat soil layers. Additional calcium and magnesium contents may be entering Sandhill Wetland via dust deposition and surface runoff (Wieder et al. 2016b). For years 2014 and 2015 specifically, other studies that measured calcium and magnesium across the spatial extent of Sandhill Wetland reported higher values than our observations from the outlet (Vitt et al. 2016; Biagi et al. 2019). Thus, calcium and magnesium concentrations are likely spatially variable. In contrast to sodium, calcium, and magnesium, dissolved potassium concentrations have remained quite static by comparison; perhaps serving as a limiting nutrient for plant growth.

Sulfate and bicarbonate were both dominant anions in near-surface water over the first five years (Fig. 3; Table 2). However, in years 2018–2019 sulfate concentrations markedly increased to surpass

Table 3 Organic compounds measured at Sandhill Wetland and reference wetlands

Compound	Long-term guideline (Chronic) ($\mu\text{g L}^{-1}$)	Minimum detection limit ($\mu\text{g L}^{-1}$)
F1 (C6-C10)	150	< 100
Benzene	40	< 0.40
m & p-Xylene		< 0.80
Toluene	0.5	< 0.40
Ethylbenzene		< 0.40
o-Xylene		< 0.40
F1 (C6-C10)—BTEX	150	< 100
Xylenes (Total)	30	< 0.89
B[a]P TPE Total Potency Equivalents		< 0.010
Quinoline	3.4	< 0.20
Naphthalene	1.0	< 0.10
Chrysene		< 0.0085
Benzo(k)fluoranthene		< 0.0085
Benzo(e)pyrene		< 0.050
Benzo(a)pyrene	0.015	< 0.0075
Pyrene		< 0.020
Perylene		< 0.050
Acenaphthylene	5.8	< 0.10
Indeno(1,2,3-cd)pyrene		< 0.0085
Dibenz(a,h)anthracene		< 0.0075
2-Methylnaphthalene		< 0.10
Acenaphthene		< 0.10
Fluorene	3.0	< 0.050
1-Methylnaphthalene		< 0.10
Benzo(a)anthracene		< 0.0085
Phenanthrene		< 0.050
Anthracene		< 0.010
Benzo(c)phenanthrene		< 0.050
Fluoranthene		< 0.010
Benzo(g,h,i)perylene		< 0.0085
Benzo(b&j)fluoranthene		< 0.0085
Acridine	4.4	< 0.040

bicarbonate. It is possible sulfate concentrations are spatially variable across the wetland area, which is supported by findings from Biagi et al. (2019). Thus, elevated sulfate concentrations observed in years 2018 and 2019 are potentially due to sampling additional areas beyond the outlet location. Elevated sulfate concentrations in water have been hypothesized to constrain the production of both methylmercury and methane at the site (Oswald and Carey 2016; Clark et al. 2019, respectively), therefore our sulfate water

quality data findings potentially explain and support previously reported observations of low methylmercury and methane production at Sandhill Wetland compared to natural reference sites. For the anion chloride, although concentrations were lower than sulfate and bicarbonate, chloride concentrations have exceeded those of calcium most years. Since year 2015, chloride, bicarbonate, and sulfate, concentrations have increased on average by 30, 26, and 73 mg L^{-1} each year to current levels of 246, 398, and

622 mg L⁻¹, respectively in 2019. Overall, with few exceptions we demonstrate the dominant anions and cations present in near-surface water have increased annually in a linear fashion since year 2015 (Figs. 2 and 3). These patterns by dominant ions cumulatively are responsible for annual increases in EC, total alkalinity, total hardness, and total dissolved solids (Table 2).

Similar to anion and cation patterns, closure of the underdrain system in year 2014 resulted in marked decreases in ammonium concentrations at the outlet (Table 2). From 2015 to 2019 dissolved inorganic nitrogen and phosphorus concentrations were less than 1.0 mg L⁻¹ in all years monitored. Further, for all organic compounds measured in near-surface water, concentrations were below detection limits in all years (Table 3); an important discovery as many of the substances evaluated are harmful to biota (e.g., insects and birds) at low concentrations (Barr 2009; Gentes et al. 2006; Foote 2012).

Sandhill Wetland near-surface water quality assessment

Comparing the near-surface water quality at Sandhill Wetland to the Environmental Quality Guidelines for Alberta Surface Waters for protection of aquatic life produced fewer exceedances than groundwater well samples. Moreover, in most cases near-surface water exceedances were less severe. The following substances/properties in near-surface water exceeded a long-term guideline recommendation: Total alkalinity, ammonium, sulfate, chloride, iron, boron, cobalt, selenium, and zinc (Government of Alberta 2018). Near-surface total alkalinity exceeded guidelines in all years; yet, values generally were threefold lower than sub-surface water (sub-surface T-alkalinity as CaCO₃ mean: about 860). While ammonium exceedances were detected in all years monitored, ammonium concentrations post year 2014 (following closure of the underdrain system) are approaching recommended levels (recommended guideline values for Sandhill Wetland ambient conditions = 0.41–1.91 mg L⁻¹; varies with pH and temperature). In fact, ammonium concentrations currently are within the ranges of other regional peatland systems (Graham et al. 2016; Hartsock et al. 2016, 2019). Excluding a single cobalt exceedance in year 2015 of 12.1 µg L⁻¹, cobalt and boron exceedances occurred only while the underdrain

system was in use, suggesting exceedances were likely due to mixing of sub-surface and near-surface water at the outlet. Zinc and selenium exceedances were detected in four and one water sample, respectively, out of a total of 71 near-surface water samples. The heavy metal iron exceeded guideline recommendations in ten samples total out of 71. Dissolved chloride has exceeded guideline recommendations in all years except 2015, and chloride concentrations have continued to increase annually. For dissolved sulfate, guideline exceedances occurred only in 2018. Because sulfate guidelines are influenced by ambient hardness levels, amelioration of sulfate exceedances at Sandhill Wetland are due to concurrent increases in water hardness. Recommend EC and sodium concentrations are absent from the Environmental Quality Guidelines for Alberta Surface Waters for protection of aquatic life, however, EC and sodium has increased annually in near-surface water since 2015 (SHW 2019 EC and Na⁺ means: 2560 µS cm⁻¹ and 344 mg L⁻¹, respectively) and measured levels are higher than most reference wetlands; except for the saline fens where EC and sodium concentrations were about 9000 µS cm⁻¹ and 2000 mg L⁻¹, respectively.

Sandhill Wetland vs natural wetlands

One of the central questions for the Sandhill Watershed was whether a fen could/would develop with time if the initial conditions were properly established. At the onset, initial conditions most closely mimicked a circumneutral moderate-rich fen based on site wetting with fresh lake water and a seed mix composition comprised of ~80% *Carex aquatilis* seeds (Vitt et al. 2016). Because the placed peat layer contained some material from an acidic *Sphagnum*-dominated poor fen, however, and due to anticipated interactions with OSPW, there was potential for Sandhill Wetland to develop into a variety of different wetland site types. Several reference wetlands spanning a gradient of potential successional endpoints were therefore selected for comparison against Sandhill Wetland, and for evaluating whether the site has been functioning equivalent to any type of natural site monitored. From a water chemistry standpoint, based on dominant ions present (e.g., sodium, calcium, magnesium, bicarbonate, chloride, and sulfate) and other properties (e.g., total alkalinity, total hardness, EC, pH and potassium), water chemistry at Sandhill Wetland has

Table 4 Porewater concentrations among reference wetlands

Wetland type: Replicate no:	Mb n = 5	Mf n = 6	SAL n = 15	MRF n = 19	ERF n = 7	PF n = 15
Property						
pH	7.78 (0.24)	7.12 (0.11)	7.40 (0.58)	7.06 (0.22)	7.92 (0.09)	<u>3.99 (0.26)</u>
EC ($\mu\text{S cm}^{-1}$)	717 (158)	216 (35)	8808 (5930)	134 (53)	329 (69)	38 (68)
Hardness (CaCO_3)	226 (55)	110 (23)	615 (528)	69 (23)	194 (10)	5 (4)
T-Alkalinity	<u>504 (157)</u>	<u>90 (16)</u>	<u>496 (415)</u>	<u>62 (23)</u>	<u>180 (24)</u>	< 1
TDS (calculated)	562 (145)	130 (28)	6323 (4514)	71 (25)	227 (20)	32 (34)
SAR (calculated)	4.15 (0.66)	0.43 (0.05)	37.13 (9.03)	0.21 (0.10)	0.65 (0.03)	0.36 (0.43)
Bicarbonate	616 (188)	111 (21)	613 (513)	77 (29)	220 (31)	< 1
Ammonium—N	0.11 (0.07)	0.11 (0.08)	0.40 (0.37)	0.05 (0.03)	0.06 (0.03)	0.04 (0.03)
TKN	3.50 (0.63)	3.63 (1.26)	5.65 (3.95)	0.95 (0.50)	0.77 (0.24)	0.98 (0.42)
Nitrate—N	<u>< 3.4</u>	< 0.20	< 0.26	< 1.20	< 0.17	< 2.20
Nitrite—N	0.26 (0.33)	< 0.20	< 0.18	< 0.20	< 0.010	< 0.010
Phosphorus	0.59 (0.48)	0.84 (0.41)	0.04 (0.03)	0.01 (0.00)	< 0.01	0.11 (0.11)
DOC	62 (14)	72 (26)	63 (38)	26 (7)	17 (2)	32 (9)
Sulfate	<u>616 (188)</u>	111 (21)	613 (513)	77 (29)	220 (31)	< 1
Chloride	8 (5)	4 (1)	<u>3245 (3112)*</u>	3 (2)	16 (5)	5 (11)
Sodium	144 (38)	10 (2)	1979 (1372)	4 (2)	22 (2)	2 (4)
Calcium	59 (16)	27 (6)	144 (120)	16 (6)	53 (4)	1 (1)
Magnesium	19 (4)	10 (2)	62 (56)	7 (2)	15 (1)	< 2
Potassium	4.9 (2.9)	4.9 (5.2)	2.9 (1.9)	1.3 (1.3)	1.9 (0.8)	0.7 (0.4)
Cadmium ($\mu\text{g L}^{-1}$)	< 0.020	< 0.020	< 0.040	<u>< 0.15</u>	< 0.15	<u>< 0.18*</u>
Iron	<u>0.93 (0.95)</u>	<u>3.15 (2.01)</u>	<u>< 85</u>	<u>< 0.32</u>	< 0.068	<u>< 1.1</u>
Lithium	0.06 (0.02)	< 0.04	< 0.48	< 0.020	< 0.020	< 0.020
Manganese	3.18 (2.34)	1.33 (1.11)	< 2.20	< 2.60	< 1.80	0.059 (0.061)
Strontium	0.35 (0.08)	0.23 (0.05)	4.89 (5.16)	< 0.14	0.10 (0.01)	< 0.023
Barium	0.12 (0.07)	0.04 (0.02)	< 0.60	< 0.076	0.05 (0.01)	< 0.18
Silicon	12.48 (4.23)	3.05 (1.28)	9.15 (6.49)	3.38 (0.83)	3.00 (1.58)	< 3.90
Boron	0.07 (0.01)	0.05 (0.01)	0.51 (0.17)	< 0.020	0.04 (0.01)	< 0.10
Aluminum ($\mu\text{g L}^{-1}$)	6.0 (2.0)	24.0 (15.0)	<u>30.0 (33.0)*</u>	< 11.0	< 6.8	<u>70.0 (47.0)*</u>
Chromium	< 0.0010	< 0.0010	< 0.0020	< 0.012	< 0.0010	< 0.013
Cobalt ($\mu\text{g L}^{-1}$)	<u>< 2.2</u>	<u>< 3.1</u>	< 1.3	< 0.4	< 0.3	<u>< 1.5</u>
Copper ($\mu\text{g L}^{-1}$)	< 0.23	< 0.24	< 1.6	< 3.5	< 1.2	<u>< 78*</u>
Lead	< 0.00020	< 0.00020	< 0.00069	< 0.00035	< 0.00020	< 0.00020
Antimony	< 0.00060	< 0.00060	< 0.0087	< 0.00060	< 0.00060	< 0.00060
Molybdenum ($\mu\text{g L}^{-1}$)	< 0.81	< 0.20	< 0.40	< 0.20	< 0.20	< 0.20
Nickel ($\mu\text{g L}^{-1}$)	1.9 (0.9)	2.2 (0.8)	< 2.7	< 0.8	< 2.3	<u>< 2.6*</u>
Selenium ($\mu\text{g L}^{-1}$)	< 0.44	< 0.20	<u>< 7.6</u>	< 0.20	< 0.20	< 0.20
Silver	< 0.00010	< 0.00010	< 0.00020	< 0.00010	< 0.00010	< 0.00010
Arsenic ($\mu\text{g L}^{-1}$)	1.4 (0.7)	1.0 (0.2)	0.7 (0.3)	<u>1.5 (2.2)</u>	< 0.67	<u>< 10.0</u>
Thallium	< 0.00020	< 0.00020	< 0.00040	< 0.00020	< 0.00020	< 0.00020
Tin	< 0.0010	< 0.0010	< 0.0020	< 0.0010	< 0.0022	< 0.002
Titanium	< 0.0010	< 0.0010	< 0.0035	< 0.015	< 0.0010	< 0.016
Uranium	< 0.0017	< 0.00010	< 0.00020	< 0.00010	< 0.00010	< 0.00010
Vanadium	< 0.0010	< 0.0010	< 0.0020	< 0.018	< 0.0010	< 0.018

Table 4 continued

Wetland type: Replicate no:	Mb n = 5	Mf n = 6	SAL n = 15	MRF n = 19	ERF n = 7	PF n = 15
Zinc ($\mu\text{g L}^{-1}$)	< 9.1	< 3.0	< 18.0	< 9.9	< 7.5	<u>11.1 (5.8)</u>
Beryllium	< 0.0010	< 0.0010	< 0.0020	< 0.0010	< 0.0010	< 0.0010

Values are means with standard deviations in parenthesis. In cases where means could not be calculated b/c values were below detection limit, the highest concentration observed was reported

Bolded properties indicate a guideline exceedance

Italicized underline values represent chronic surface water quality guideline exceedances. Values with an asterisk represent acute exceedances. *Mb* slightly brackish marsh, *Mf* fresh marsh, *SAL* saline fen, *MRF* moderate-rich fen, *ERF* extreme-rich fen, *PF* poor fen

clearly shared the most chemical range overlap with the slightly brackish marsh and saline fen reference sites (Tables 2 and 4). Because anion and cation concentrations have increased annually at Sandhill Wetland, water chemistry is becoming increasingly similar to saline fens with each passing year. The site overall has exhibited few likenesses with water chemistry at the other freshwater reference sites.

Reference site water quality assessment

Compared to the Environmental Quality Guidelines for Alberta Surface Waters for protection of aquatic life there were several instances of exceedances at natural sites (Table 4). The poor fens exceeded guidelines most frequently. Substances exceeding guideline recommendations at the poor fens included pH, cadmium, iron, aluminum, cobalt, copper, nickel, arsenic, zinc, and toluene (toluene exceedance = $1.30 \mu\text{g L}^{-1}$). Because recommended guideline values for select substances change considerably based on ambient site conditions, levels of a substance deemed problematic at one site may not necessary be harmful at another (Government of Alberta 2018). Due to acidic conditions characteristic of poor fens (pH ~ 4.0), recommended guideline concentrations for several substances are lower than circumneutral and alkaline reference sites. The sodic saline fens exceeded guidelines for five properties/substances that included total alkalinity, chloride, iron, aluminum, and selenium. The slightly brackish marsh exceeded guidelines for six properties/substances that included total alkalinity, nitrate, sulfate, iron, cobalt, and toluene (toluene exceedance = $19.0 \mu\text{g L}^{-1}$). Of these listed substances at the saline fens and slightly brackish marsh, seven were shown to exceed

guidelines in near-surface water at Sandhill Wetland (e.g., chloride, total alkalinity, sulfate, iron, cobalt, selenium, and zinc). Further, exceedances for total alkalinity and dissolved iron were detected across five of the six reference wetland site types, thereby suggesting several substances commonly exceed water quality guidelines in regional natural wetlands. Overall, we present fifteen examples of guideline exceedances (five of which were acute exceedances) detected in near-surface water at the natural reference sites. At Sandhill Wetland, groundwater well samples and near-surface water cumulatively exceeded guidelines for fourteen different substances/properties. The Alberta water quality guidelines note exceptions to the application of guidelines where natural water quality does not meet proposed recommendations. Although Sandhill Wetland is not a natural system, near-surface water chemistry at the site is quite representative of saline fens and slightly brackish marshes. Because the reclamation site was designed to assist succession towards a natural wetland analogue, here we provide rationale for establishing site-specific guidelines or objectives for select chemical substances and properties, namely for those that exceeded guidelines at the regional reference sites (e.g., pH, T-alkalinity, nitrate-N, sulfate, chloride, cadmium, iron, aluminum, cobalt, copper, nickel, selenium, arsenic, zinc and toluene).

Conclusions

We conclude that compared to natural reference wetlands, near-surface water chemistry at Sandhill Wetland was comparable to the slightly brackish marsh and saline fens. However, as anions and cations have increased in the wetland annually, site chemistry

is becoming increasingly similar to regional saline fen systems. In the most recent year of monitoring (year 2019), near-surface water quality at Sandhill Wetland exceeded Alberta surface water quality guidelines for three substances (dissolved chloride, total alkalinity, and iron). The saline fens also exceeded guidelines for the same substances/properties. The alkaline fen was the only site to exhibit fewer guideline exceedances than Sandhill Wetland in 2019, whereas the poor fens had up to ten exceedances, demonstrating natural environmental factors in the region can certainly account for variations in water quality. Overall, generic government issued guidelines are a good starting point, but site-specific water quality targets should be developed for Sandhill Wetland and future constructed wetlands on tailings substrates. Future studies should more thoroughly investigate water quality of natural wetlands in the OSSA to develop science-driven recommendations for setting exceptions for specific substances at appropriate concentrations, which would benefit water quality interpretations for opportunistic and constructed wetlands on mine sites.

Evaluation of surface water chemistry at Sandhill Wetland indicates freshwater systems should be carefully targeted for tailings deposit reclamation and that suitable conditions exhibited by slightly brackish marshes and saline fens may be likely endpoints. This study also documents that for most substances measured, surface water quality at Sandhill Wetland falls within the range of the results from natural sites, a good indicator of progress towards achieving equivalent wetland function. Water collected from groundwater monitoring wells generally was of poorer quality, and guideline exceedances occurred more frequently. Cumulatively these observations justify continued reclamation designs aimed at developing shallow, fresher, surface water systems that are hydraulically separated from deeper tailings OSPW affected porewater. That said, the measured and inevitable mixing of OSPW with the reclaimed area's initially fresh, meteoric sourced surface waters, has not pushed the system to an undesirable endpoint based on natural reference analogues and studies to date. Investigations should continue to understand long-term performance at Sandhill Wetland as near-surface water chemistry has yet to stabilize.

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Author contributions J.H.—Wrote the manuscript, organized the data, created graphs, and collected water samples. J.P.—Collected water samples, provided data, reviewed the manuscript, and provided comments/information regarding history about the study site. M.H.—Assisted with field work, sample collection, and provided several comments on the manuscript. D.V.—Principal investigator of the research project, and provided constructive comments on the manuscript.

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Compliance with ethical standards

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