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Water and environmental management in oil sands regions

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ABSTRACT

Study region: Oil sands regions worldwide with emphasis on rapidly developing areas of western Canada.
Study focus: This article introduces scientific contributions to the special issue paper collection focusing on water and environmental management in oil sands regions.
New hydrological insights for the region: Twenty-one new studies highlight current advances in understanding of hydrological processes relevant to oil sands regions, including: 1) regional assessments of water balance and hydrochemistry in lakes, wetlands and rivers, 2) on-lease investigations carried out at operating oil sands mines including mine circuits and reclaimed wetland and upland sites, 3) off-lease impact investigations including nitrogen emissions, lake and wetland studies, and groundwater monitoring, and 4) a paleohydrologic investigation establishing a record of water balance, chemistry, lake productivity and temperature dating back prior to industrial development. The collection emphasizes multi-disciplinary field-based approaches including use of physical, chemical and isotopic methods. Several modelling programs are also shown to be informative for specific tasks. The interplay of water quantity, water quality and vegetation characteristics is a common finding for reclamation assessments that report sensitivity of wetland vegetation to observed salinity accumulation linked to contact with buried tailings material. While all studies herein report results from the Canadian oil sands region, we posit that these investigations may provide insight into environmental challenges to be encountered worldwide, given the similar geologic settings and bitumen properties noted.

1. Introduction

Oil sands are unconventional petroleum deposits emplaced within loose or partially consolidated sandstones, distinguished from conventional crude oil by its high viscosity, high density, and elevated concentrations of some metals such as S, Ni and V (Jasechko et al., 2012; Gosselin et al., 2010). While oil sands are known to occur in many parts of the world, including Canada, Russia, Venezuela, United States, Kazakhstan, and China, commercial development since the 1960 s has largely focused on oil sands located in Canada, although recent efforts are also noted within China (Liu et al., 2019). Despite being a controversial energy source, owing to several widely publicized environmental and health issues (Gosselin et al., 2010), oil sands and other unconventional oil deposits are expected to be a key source of energy into the second half of the 21st century (Wang et al., 2015). Current global reserves of unconventional

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heavy oil and bitumen are estimated at 5.9 trillion barrels (938 billion m^3) (Bata et al., 2017), roughly 5–6 times that of conventional reserves, which are estimated at between 903 and 1242 billion barrels (143 and 197 billion m^3) (Owen et al., 2010). Oil sands alone account for 2.7 times that of conventional reserves (WEC, 2010) as will be described in more detail later on.

This special issue journal volume, which includes a collection of 21 peer-reviewed papers authored by government, academic and industry scientists, is dedicated to advances in understanding of key scientific issues that affect water resources and environmental management in oil sands regions. The Guest Editors have spent more than 20 years carrying out research in and around the Canadian oil sands region and noted that it was timely for the publication of a collection of high-quality peer-reviewed papers that highlight recent research, identify research gaps, and promote discussion of the topic within the international community. While many environmental issues related to oil sands extend beyond the traditional domain of hydrology, it is intended that this compilation of studies, based mainly on hydrologic experiences gained from the Canadian oil sands region, will encourage wider dissemination and discussion of multi-disciplinary challenges faced by resource development, and perhaps serve as examples for establishing best practices for environmental monitoring and assessment for developing oil sands regions around the world.

While regional assessment of water cycle impacts is ongoing in the Canadian oil sands region, the work included in the special issue highlights advances made along several research pathways. As an ensemble, the studies contribute to greater hydrologic and hydrochemical understanding of lakes, wetlands, rivers, and watersheds; they highlight regional variations in surface/groundwater interaction conditions and groundwater quality, and establish that natural wetland complexes are highly structured through interdependence of vegetation, water quality, and surface/subsurface hydrologic gradients. However, some specific knowledge gaps remain. Five new case studies demonstrate the primary challenges of reclamation, i.e., that engineered reclamation landscapes need to mimic natural upland-wetland complexes to recreate surface/ groundwater conditions advantageous for peat formation. Importantly, the studies also reveal that success of constructed wetlands may require vigilant management of solutes due to intolerance of peat-forming vegetation to salinity. Notably, development and refinement of new investigative tools such as hydrologic modelling platforms and isotopic tracers are also highlighted, as well as an overall need to consider the dual impacts of oil sands development under changing climate conditions.

2. World reserves of oil sands bitumen

For the purposes of this paper, oil (tar) sands are considered to be natural bitumen deposits with high viscosity (>10,000 cP) and high density (10° API gravity, API=American Petroleum Institute) which, unlike heavy oil and most extra-heavy oils, prevent it from flowing to a well bore (Kashirtsev and Hein, 2012) and/or cause it to exist in a solid state (Attanasi et al., 2010). A similar definition has been widely adopted by the World Energy Council (WEC, 2010) and others (Gosselin et al., 2010; Liu et al., 2019). Oil sands deposits differ from conventional oil deposits in that reservoirs typically occur at relatively shallow depths where the sealing capacity of cap rocks is poor, allowing oxic surface waters to penetrate the oil and permitting biodegradation, water washing, oxidation, evaporation and distillation, leading to higher density oils with typically higher sulfur content and elevated trace metals concentrations (Liu et al., 2019).

Oil sands deposits have been identified in over 70 countries worldwide (Hills, 1974), and are expected to contain more than 3328 billion barrels [529 billion m^3] (WEC, 2010, p. 140) or roughly 2.7 times the proven conventional oil reserves of the world estimated at 1240 billion barrels [197 billion m^3] (WEC, 2010, p. 56). While ~598 natural bitumen deposits have been identified worldwide, Demaison (1977) showed that just 16 of the largest oil sands deposits exceeded the conventional oil reserves at the time. Global

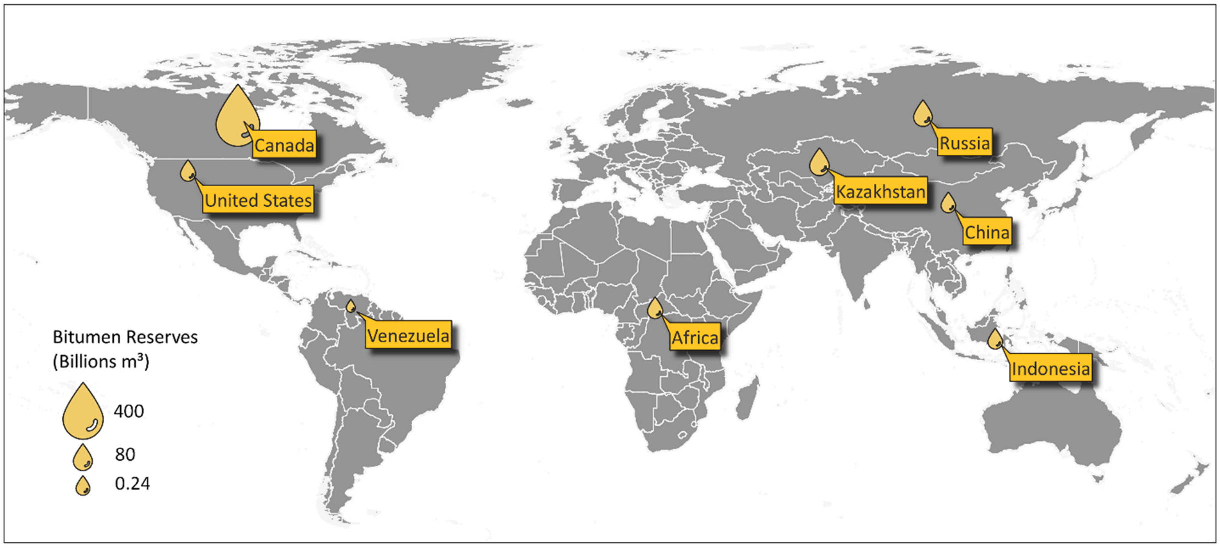

Fig. 1. Global distribution of estimated oil sands reserves (after WEC, 2010).

distribution of oil sands deposits and a summary of reserve estimates are provided in Fig. 1 and Table 1, respectively.

Formation of petroleum deposits is generally considered a multi-stage biogenic process requiring source rocks, maturation, migration pathways, reservoir rocks, traps and seals (Akramkhodzhayev and Amirkhanov, 1986). Oil sands deposits have been shown to occur most often in structural foreland basins adjacent to mountain belts. For example, the Alberta oil sands deposits, which comprise ~73 % of the world bitumen reserves (Table 1), are situated in such a setting at the northeastern margin of the Western Canada Sedimentary Basin (WCSB), which has also hosted most of Canada's conventional oil and gas deposits (Gosselin et al., 2010). In 2022, 87 % of total oil production in the province of Alberta was from oil sands. Regional structure of the WCSB is a west-dipping homocline where maturation within organic-rich marine shale source rocks and well-developed fluid transport within a thick sedimentary wedge were created due to Rocky Mountain uplift during the late Cretaceous Laramide Orogeny. Statigraphic emplacement of oil within shallow, poorly consolidated sands of the Cretaceous McMurray Formation was also aided by the presence of salt-dome collapse structures and a regional shale cap rock (Demaison, 1977). Similar foreland settings have been noted for Venezuelan Orinco deposits, the Russian and Kazakhstani deposits, and several deposits in the United States. Less common structural settings include rift settings such as Madagascar and Melville Island, Canada (Demaison, 1977). Direct radiometric dating of hydrocarbon deposits in the Western Canada Sedimentary Basin has suggested hydrocarbon ages to be 112 ± 5.3 Ma (Selby and Creaser, 2005) or Mesozoic age (252–66 million years ago) which is contemporaneous with formation of about 70 % of world reserves (Halbouty et al., 1970). In the case of oil sands, it is generally thought that biodegradation and water washing occurred post-emplacement causing light oil to become more viscous, richer in sulfur, resins, asphaltenes and metals, including nickel and vanadium (Shuqing et al., 2008; Zhou et al., 2008).

Kazakhstan has the second largest oil sands reserves in the world (12.6 %), estimated at 420 billion barrels [67 billion m^3]. The main deposits are located in West Kazakhstan in the Aktobe, Atyrau and Mangistau regions, roughly situated between or close to the Caspian and Aral Seas (Tileuberdi et al., 2015). While exploratory development of Kazakhstan's oil sands began as early as the 1980s, commercial-scale development using conventional hot water extraction techniques has been constrained by limited availability of local water resources.

Russian deposits of natural bitumen account for 10.4 % of the world reserves and are estimated at 346 billion barrels [55 billion m^3]. The main deposits include the Siberian Platform, Olenek Uplift, Eastern Siberia, and the Lena-Anabar Basin, although these deposits have not yet been brought into commercial production due to abundant conventional oil reserves as well as technical challenges associated with depth of emplacement, remoteness and subarctic climate (Liu et al., 2019; Kashirtsev and Hein, 2012).

The Faja Orinoco deposit in eastern Venezuela is the world's single largest heavy oil accumulation with an estimated 310 billion barrels [49.3 billion m^3] being technically recoverable at present with daily production estimated at 600,000 barrels/day in 2017 (Bata et al., 2017). While the deposit is primarily classified as extra-heavy oil rather than oil sands, there is at least one natural bitumen deposit, Guanoco Lake, located near the Caribbean coast on the north side of the Eastern Venezuela Basin (WEC, 2010 p. 149). Based on the survey of Liu et al. (2019) the API of the Orinoco deposits ranges from 7 to 20 API gravity so does not clearly fall into the category of oil sands, and so is not included in Table 1. A very early estimate of oil sands reserves for the region was 62 million barrels (Walters, 1974) although this estimate appears to be very conservative.

The United States oil sands deposits include commercial extraction from two principal areas, the San Joaquin Basin of central California and the North Slope of Alaska, as well as noteworthy accumulations in Alabama, Kentucky, New Mexico, Oklahoma, Texas, Utah and Wyoming. US reserves of oil sands in place are estimated at close to 54 billion barrels [8.5 billion m^3] (WEC, 2010; Schenk et al., 2006).

China's oil sands deposits include the Fengcheng oil sands in Karamay, Xinjiang, an occurrence which is transitional from heavy and light oil at greater depths. Some of the oil sands deposits are very shallow or surface occurrences (Huang et al., 2020). Currently, testing is being carried out to develop open-pit mining for shallow occurrences (<75 m) and steam-assisted gravity drainage (SAGD) or other in-situ extraction tests are targeting bitumen at greater depths (>150 m). While China has limited oil sands reserves, the national interest in global oil sands resources was clearly demonstrated in 2012 by purchase of a leading Canadian-owned insitu oil sands company, Nexen, (now CNOOC Petroleum North America).

Table 1
Rank ordered list of countries/regions by natural bitumen reserves[a].

Country/ Region	% of total original oil in place %	No. Deposits Count	Discovered original oil in place Billions m^3 (1 barrel = 0.16 m^3)	Prospective additional reserves	Total original oil in place	Cumulative Production (2010)
Canada	73.1	231	276960	112515	389475	1024
Kazakhstan	12.6	52	67310	0	67310	0
Russia	10.4	39	47265	8215	55481	2
Africa	1.9	9	2875	7419	10294	0
United States	1.6	204	5943	2614	8557	4
Indonesia	0.13	1	713	0	713	4
China	0.05	4	255	0	255	<1
Other	0.06	58	333	0	333	0
Total	100	598	401812	130764	532576[b]	1034

[a] WEC (2010, p. 139–140).
[b] This total was estimated at 582,400 billion m3 by Lui et al. (2019).

3. Oil sands extraction and environmental impacts

Open pit mining techniques have typically been used when oil sands deposits occur within 75 m depth below surface, whereas various in situ techniques, including steam-assisted gravity drainage (SAGD) or Cyclic Steam Stimulation (CSS), are used to extract oil from more deeply emplaced deposits (Birks et al., 2022). Mining, processing and upgrading of oil sands potentially involves considerable environmental disturbance and reclamation. Much can be learned from 50 years of development of the Athabasca oil sands deposit, the most extensive deposit in Canada and by far the leading development in the world.

Bitumen underlies about 1/4 of Alberta's boreal forest (142,000 km^2), although the total footprint of approved mining projects as of Dec. 31, 2020 under the Environmental Protection and Enhancement Act (EPEA) was 1599.6 km^2 (AEP, 2022). (~0.4 % of Alberta's boreal forest zone), and comparable to the area of the cities of Brisbane, Rio de Janeiro, or London (City Mayors, 2022). However, potential off-lease impacts may affect watersheds over much wider regions (Kelly et al., 2009; Culp et al., 2021; Arciszewski et al., 2022). Mining involves exploration, land clearing, road and pipeline construction, creation of large excavations and tailings ponds, and construction of infrastructure such as processing plants and upgraders. The primary environmental risks include: i) off-lease migration of oil sands processed water (OSPW) containing deleterious substances such as naphthenic acids, the potential for which was described by Ferguson et al. (2009) and Fennell and Arciszewski (2019); (ii) emissions from vehicles, upgraders and volatile contaminants outgassing from tailings ponds and mine pits, which also include greenhouse gases (Liggio et al., 2019); (iii) dewatering and well disposal of groundwater for pit development, and abstraction of river water for hot water treatment. Reclamation of mining disturbances is required in all jurisdictions under large scale development, i.e., Canada.

In situ recovery accounts for 85 % of global reserves and is expected to have a lower impact intensity than surface mining. Development of well pads and injection/production galleries, pipeline and roads, and deep well disposal are the main causes of impact. Perhaps, the principal environmental advantage of in situ methods is that bitumen is produced underground and pumped to surface, avoiding a need for tailings ponds, although thermal stimulation of aquifers is known to potentially cause mobilization of metals, organics and gases (Moncur et al., 2015). Emissions, while reduced substantially compared to open-pit mining, remain an important concern. An informed and comprehensive review of the environmental and health issues associated with oil sands industry in Canada was conducted by Gosselin et al. (2010), with subsequent syntheses of ecological and causal effects of oil sands activity impacts on river ecosystems by Culp et al. (2021) and historical overview and governance of environmental monitoring by Dubé et al. (2022). Oil sands development is a multi-decadal industrial activity where oil sands environmental challenges should be considered regionally in the context of the lifecycle of operations (Fig. 2).

The low-relief, wetland dominated landscape of the Canadian oil sands regions and cold continental climate in Alberta have presented many challenges to application of conventional hydrologic methods. Firstly, peat deposits are nearly ubiquitous across the region, and may reach up to 10 m in thickness. Peat is difficult to monitor hydrologically and has significantly different properties than mineral soil, including higher porosity, variable hydraulic conductivity, where it may vary from surface to 0.5 m by up to 5 orders of magnitude due to decomposition and compression, as well as different soil-water drainage characteristics and thermal properties (Letts

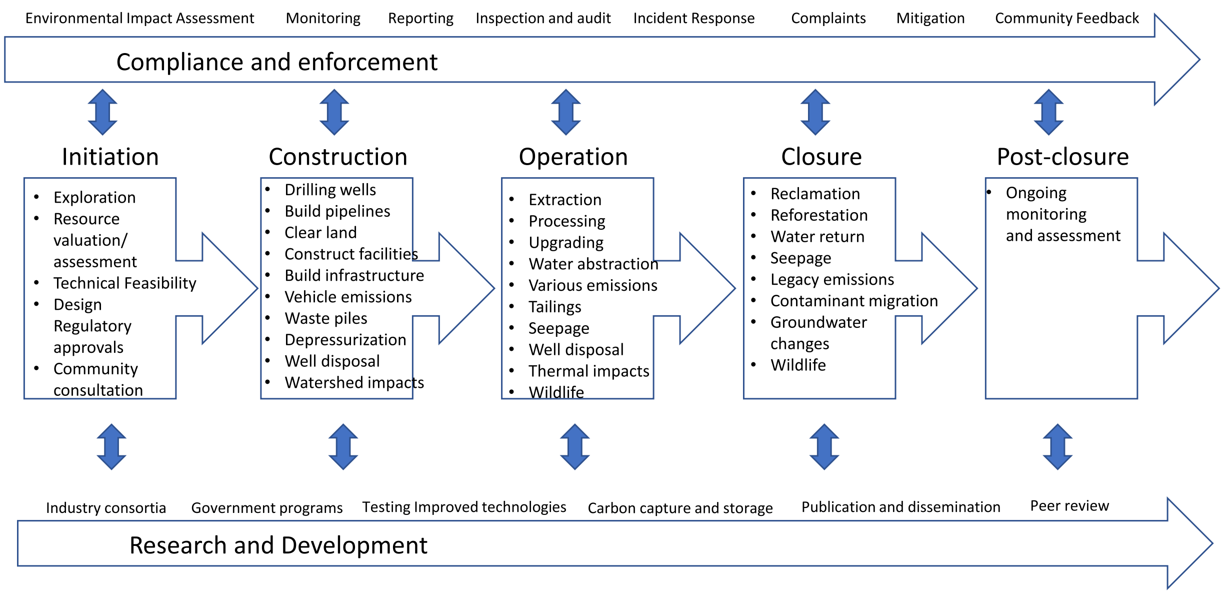

Fig. 2. Schematic showing typical lifecycle of oil sands operations and related water and environmental issues based on the Alberta, Canada example. The life cycle of an oil sands surface mine or in situ operation is expected to be several decades, although individual pits and extraction wells may be phased in and out as the grade of the deposits declines or efficiency is reduced. Water and environmental management of oil sands development is an ongoing activity from initiation to closure and beyond, although specific environmental concerns may evolve throughout the lifecycle of operations.

et al., 2000). Peatlands retain enormous reserves of water, serving to regulate low flows and floods; they also perform indirect functions such as nutrient retention, carbon storage and sediment retention, often being interconnected to form wetland complexes with distinct plant communities and hydrologic properties. Due to low relief, hydraulic gradients are challenging to measure accurately, especially owing to irregularities such as hummocks and depressions on most wetland surfaces which commonly produce fill and spill type runoff during spring melt and rainfall events.

River gauging networks across the lower Athabasca region are fairly effective at quantifying streamflow in the main river channels, but gauging of smaller tributaries and lake outflows that perennially freeze to bottom has required these gauges to operate only

Table 2
Summary of the special issue collection.

Study Category Hydrologic Focus	Contribution/ Contribution No.		Highlights	Water Quantity	Water Quality	Vegetation	Models Applied	Isotope Tracers
Regional Assessments								
Lakes	Castrillon-Munoz et al. (2022)	A	Refined hydrochemical interpretation for 50 RAMP Lakes		x		1	x
	Neary et al. (2021)	B	Lake level variation and classification in the Peace Athabasca Delta	x				
Wetlands	Vitt et al. (2022)	C	Water source control on chemistry and plant distribution in patterned fens		x	x		
	Gibson et al. (2022)	D	Alberta-wide water balance of open-water wetlands using isotope method	x				x
Rivers	Xue et al. (2022)	E	DOM as a potential tracer for source discrimination in large rivers		x			
	Ghotbizadeh et al. (2022)	F	Trace element patterns in Athabasca River and tributaries along 125 km reach		x			
	Thomas et al. (2022)	G	Control of rain events on nutrients and priority pollutants in streamflow	x	x			
Watershed	Holmes et al. (2022)	H	Sensitivity of a process-based isotope-enabled hydrologic model for Athabasca watershed	x			2	x
	Peters et al. (2022)	I	Climate and resource development impacts on runoff generation and flow	x				
On-lease Investigations								
Active mine circuit	Chad et al. (2022)	J	Water balance and isotope fingerprinting of mine water recycle circuit	x				x
Reclaimed Sites	Popović et al. (2022)	K	Carbon/water dynamics during early-development of upland-fen complex	x	x	x		
	Yang et al. (2022)	L	Salinity accumulation issues in constructed fen including vegetation impacts	x	x	x		
	Kessel et al. (2021)	M	Aquifer recharge and downstream water supply from engineered tailings uplands	x	x	x		
	Biagi and Carey (2022)	N	Hydrochemical evolution of a constructed peatland and implications for sustainability	x	x	x		x
	Nagare et al. (2022)	O	Surface-subsurface water and solute modelling of a reclaimed in-pit mine	x	x	x	3	
Off-lease impact investigations								
Athabasca Delta	Savage et al. 2022	P	Artificial substrate samplers to assess accumulation of metals of concern by flooding in Peace-Athabasca Delta Lakes	x	x			
Lower Athabasca Region	Lindenschmidt et al. (2022)	Q	Riverine mixing of sediment and vanadium along the lower Athabasca River	x	x		4	
Wetlands	Elmes et al. (2022)	R	Examination of fen hydrologic impacts due to road and pipeline construction	x		x		
Groundwater	Birks et al. (2022)	S	Spatial and temporal anomalies in water quality and implications for monitoring network design across oil sands region		x			
Atmospheric Deposition	Wieder et al. (2022)	T	Evaluation of potential for ^{15}N in lichens to be used for detecting oil sands emissions			x		x
Paleohydrologic Investigation								
Hardwater Lake	Zabel et al. (2022)	U	Paleolimnological assessment of past hydro-ecological variation extended back prior to industrial development		x	x		x

1-PHREEQC (Parkhurst and Appelo, 1999); 2 – isoWATFLOOD (Stadnyk et al., 2013); 3- HydroGeoSphere (Brunner and Simmons, 2012); 4-MESH-SED (Wheater et al., 2022) seasonally. Generally, the spring melt period is difficult to capture in these systems due to late melting of ice cover and resulting irregularity of channel configurations at this time of year. Other complications include permafrost degradation, which has been occurring across the region since the Little Ice Age. Permafrost, largely restricted to bog plateaus in the region at present, are potentially major sources of regional runoff but have been found to respond non-monotonically to climate change contributing initially to higher annual water yields which are eventually exhausted leading to an overall reduction in water yield as permafrost is completely thawed, according to the permafrost thaw cycle (Gibson et al., 2019). Abstraction of water from the Athabasca River, pumping of groundwater for pit dewatering or in situ water supply, and deep well disposal have also played a role in altered surface and groundwater systems.

Hydrogeological complexities also contribute to the challenge of working in Canada's oil sands region, as several generations of glacial till and an extensive network of buried channels occur above and incised within bedrock. Additional features such as saline springs, found along river channels, are widely attributed to glaciogenic waters that have originated from injection and westward migration of subglacial meltwater under kilometers-thick ice sheets at the margins of the WCSB, leading to dissolution of evaporitic beds, and subsequent reflux of water once ice sheets melted, leading to eastward and upward migration of these waters (Grasby and Chen, 2008; Birks et al., 2018, 2019). In addition, baseline conditions prior to development have been difficult to establish due to a 50 + year history of resource development in the region, including cutting of seismic lines for petroleum exploration and early development of natural gas which have both contributed to alteration of the natural state of surface runoff and groundwater levels.

Reclamation, the process of returning land used for oil sands mining back to its original, natural state, is another challenge of the oil sands industry in Alberta where all mines are required to be post-operationally restored, and this task has only just begun in the last decade; by 2020, only ~74 km^2 of terrestrial and ~13 km^2 wetlands/aquatics landscape were permanently reclaimed (AEP, 2022). The main challenge, according to several of the studies presented herein, has been to construct wetlands that are both sustainable and peat forming, without mobilization or concentration of salinity that is present in residual tailings material, and which is harmful to wetland vegetation.

As for other oil sands regions, it is likely that the environmental challenges may take on completely different forms. In Kazakhstan, for example, commercial scale development using conventional hot-water extraction techniques is not possible due to long distances to water sources, making in situ approaches using solvent extraction a more attractive option.

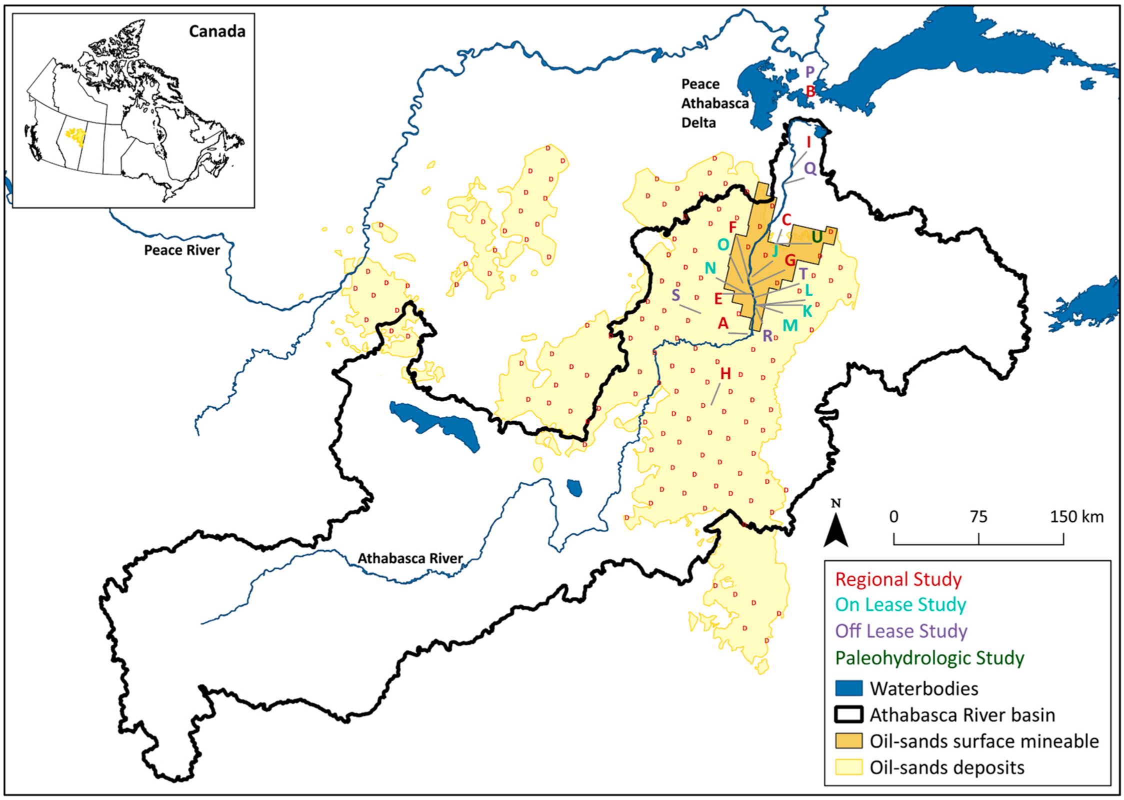

Fig. 3. Map of the Canadian oil sands region illustrating the spatial distribution of study locations from this compilation, colour coded by study category, and lettered according to contribution number (see Table 2). Inset shows position of oil sands region within Alberta, Canada.

4. Content of the water and environmental management collection

The special issue includes 21 water and environmental case studies in four general topical areas: (1) regional assessments, (2) on-lease investigations, (3) off-lease impact investigations, and (4) paleohydrology. As noted in Table 2 below, the studies contained in this special issue have addressed many of the issues described in the preceding sections, and in many cases have integrated multi-disciplinary approaches to address water quantity, water quality and vegetation issues related to oil sands resource extraction activities. Several of the studies have been directly or indirectly funded by industry and/or by government. Notably, much of the research was initiated in response to public and environmental concerns, and/or executed as part of the Joint Oil Sands Monitoring (JOSM) Plan developed by the Government of Canada and the Province of Alberta. The main purpose of JOSM (which has since transitioned to Oil Sands Monitoring, OSM) is to provide risk-based assessments of impacts from oil sands activity on environmental health and to examine cause–effect relationships (Environment Canada and Alberta Environment, 2011a, 2011b). An important distinction is made in our classification of studies between those conducted in on-lease locations, which reflect active or decommissioned mine sites with obvious development impacts versus off-lease locations, which are more likely to reflect natural systems or to have indirect impacts. On-lease investigations often reflect research carried out under regulatory requirements of the Alberta Energy Regulator or through initiatives of individual operators or consortia such as Canadian Oil Sands Innovation Alliance (COSIA). A brief description of the contributions to the collection follows. A map of the Canadian oil sands region illustrates the regional extent of the oil sands deposits and the spatial distribution of the study locations described in this collection (Fig. 3).

4.1. Regional assessments

4.1.1. Lakes

Castrillon-Munoz et al. (2022) assess geochemical processes contributing to pH increase in local lakes, including carbonate dissolution and organic matter uptake, and provide support for the hypothesis that permafrost thaw processes are releasing carbon to the lakes and alteration of lake ice characteristics may be affecting CO_2 dissolution. pH increase was unexpected when observed as lakes were anticipated to acidify in response to increased acid deposition in the oil sands region.

Downstream of the oil sands development, Neary et al. (2021) provided new insight into hydrological processes that cause of lake level variation within the Peace-Athabasca Delta (PAD) floodplains, a Ramsar Wetland of International importance. Based on ice-free period water levels in ~50 sites, the study develops a description and classification scheme which allows for differentiation of sites which may be more influenced by ice-jam flooding and river flooding versus precipitation-fed sites which are likely to be affected by wet/dry deposition. This information will be helpful in addressing impacts due to river regulation, climate change, as well as potential contaminant migration from both riverine and airborne pathways that have been suggested in prior work.

4.1.2. Wetlands

Vitt et al. (2022) investigate the interplay between plant community distributions and water chemistry in a patterned rich fen located adjacent to a planned open-pit oil sands mine and apply these characteristics, including string/flark size and orientation, to delineate water source regions that support the fen. The study is significant as it offers a practical basis for understanding the important source areas that support the patterned fen, which despite its proximity to open-pit mine development, is required by the energy regulator to be preserved.

Gibson et al. (2022) report on an isotope mass balance study carried out on 1022 open-water wetlands that are widely distributed across Alberta, including the oil sands regions. The survey, which spans Grassland, Parkland, Foothills, Mountains, and Boreal regions was applied to quantify water balance and to classify and map sites according to degree of reliance on groundwater and other factors. For the 3 Alberta oil sands regions (Peace, Athabasca and Cold Lake), the survey suggested that between 20 % and 40 % of wetlands within the bitumen zones are detectably groundwater reliant compared to 35–50 % in the wider vicinity of the deposits. Such approaches are expected to provide tools for designing and monitoring wetland water balance and enable the identification of potential impacts related to development activities versus other factors.

4.1.3. Rivers

Sources, properties and transport of dissolved organic matter (DOM) in the lower Athabasca River was investigated by Xue et al. (2022), providing significant new information on natural variations along an important reach with abundant oil-sands development. Tributaries were found to be major sources of dissolved organic carbon (DOC) with trends towards greater degrees of humification and aromaticity downstream. The study also examined river mixing in detail and concluded that DOM may be applied as a conservative tracer of riverine mixing for some applications.

Ghotbizadeh et al. (2022) examined trace element distributions along a similar 125-km reach of the lower Athabasca River with abundant oil-sands development. A PCA analysis was also used to identify specific tributary contributions to the Athabasca River. Although a wide variety of natural and anthropogenic inputs were anticipated, average trace element concentrations were found to be below the Canadian surface water quality guidelines (CCME, 2022).

Thomas et al. (2022) measured discharge and water quality parameters in select tributaries to the lower Athabasca River to evaluate the importance of rain events in controlling nutrients and priority pollutants. The study found that average daily loads were highly sensitive to changes occurring during rain events but overall, that such perturbations during rain events had little effect on annual loadings calculations.

4.1.4. Watersheds

Holmes et al. (2022) provide an analysis of hydrological processes influencing streamflow volume and timing in the Athabasca River watershed by testing sensitivity to flow and isotopic performance metrics within an isotope-enabled distributed hydrological model. Interestingly, isotopic metrics were found to be more useful that flow metrics for improving the model representation of subsurface hydrological processes.

Peters et al. (2022) applied the Cold-regions Hydrological Indicators of Change framework to examine the geography of flow generation to and within the lower Athabasca River watershed. A combined flow magnitude and relative flow contributions analysis yielded new insights: open water low flows emanated from the upper regions and experienced a generally increasing tendency from the lower regions; Peak summer flows generally experienced decreases from the upper portions of the basin, while contrary increasing tendencies emerged for the east bank of the lower Athabasca River mainstem. Climate, landscape and geology were considered as potential causal factors for the observed divergent runoff generation responses, while contrast between east bank and west bank responses is consistent with prior streamflow assessments (Gibson et al., 2016; Bickerton et al., 2018).

4.2. On-lease investigations

4.2.1. Mine water circuits

Chad et al. (2022) provide a water balance and isotope labelling study of recycle water circuit at a mine comprising open pit excavation of bituminous sands at two sites (Mildred Lake and Aurora North), with a single hot-water extraction circuit connecting extraction plants at each mine. Importantly, the study identified unique evaporative effects of cooling towers, and in addition provided the most recent precipitation data update, used to refine the local meteoric water line of Baer et al. (2016).

4.2.2. Reclamation studies

Several contributions to the special issue present research carried out on pilot scale experimental wetland reclamation projects: the Nikanotee Fen Watershed (32 ha) Sandhill Fen (52 ha) are designed to guide decisions and strategies for commercial-scale fen reclamation in the future (Ketcheson and Price, 2016); the Nikanotee Fen was constructed on an overburden dump, and; the Sandhill Fen was built upon sand-capped soft tailings which are highly saline.

Popović et al. (2022) evaluated the initial performance of the Nikanotee Fen Watershed using a functional-based, ecosystem-scale approach focused on carbon dynamics and water use efficiency (WUE). The study is fairly optimistic in that it suggests overall that conditions during early-development are evolving towards a self-sustaining, carbon-accumulating, functional ecosystem. Also working at the Nikanotee Fen Watershed, Yang et al. (2022) described how elevated sodium ($Na+$) in the porewater of mine-waste materials has been shown to migrate to the fen through groundwater, likely influencing fen vegetation health and, in particular, impacting the rooting zone. They suggest that salt-tolerant vegetation may be required to maintain carbon accumulation in such constructed systems. Kessel et al. (2021) report on the role of recharge basins for maintaining sufficient water availability at the Nikanotee Fen. They showed that such basins enhance recharge within engineered landscapes, and provide a consistent and focused supply of water to upland aquifers, and importantly, serve to supply relatively fresh groundwater to downgradient ecosystems.

Biagi and Carey (2022) report on 6 years of hydrochemical and isotopic studies carried out at the Sandhill Fen Watershed which were used to evaluate salinity and ion patterns and provide insight on the fen's trajectory. Based on these findings, a shift in design strategy is recommended (replicating saline instead of freshwater peatlands) to increase the success of these systems.

Nagare et al. (2022) describe use of an integrated surface-subsurface water and solute modeling to evaluate conditions of a reclaimed in-pit oil sands mine including freezing and thawing impacts. Transient simulations of wet and dry climate cycles suggest that the reclaimed landform will shed water only during wet years.

4.3. Off-lease impact investigations

A number of offsite investigations examined potential impacts of oil sands operations beyond the operators lease boundaries. Savage et al. (2022) quantify enrichment of eight metals (Be, Cd, Cr, Cu, Ni, Pb, V, Zn) in aquatic biota, relative to sediment-based pre-industrial baselines in >40 lakes. Potential for downstream delivery of contaminants via Athabasca River floodwaters to lakes of the PAD has raised local to international concern. The study, extending to 40 lakes, showed that absence of marked metal enrichment in flooded delta lakes, as well as the lack of difference in enrichment among lakes of different flood status, provided evidence that oil sands industrial metal pollution is not detectable at the base of food webs in lakes of the downstream delta.

Elmes et al. (2022) describe impacts to hydrologic function of a channel fen following placement of an access road and below ground pipeline. One of the important findings was that, if possible, pipelines should be oriented parallel to wetland flow direction and located along the central axis of the wetlands to minimize overall impacts.

Lindenschmidt et al. (2022) developed and applied a novel, quasi-two-dimensional surface water-quality modelling approach to simulate sediment and vanadium transport along the lower Athabasca River where it traverses the oil sands region. Their conclusion regarding observed vanadium distributions was that it derives mainly from surficial aquifers and is present in muskeg dewatering water from the mine sites, and possibly also enters the river via dust deposition and bank erosion. Based on their analysis, contaminated sediment and/or tailings water seepage do not seem as likely based on the available evidence.

Wieder et al. (2022) test the hypothesis that ^{15}N in lichens from bogs can resolve the extent to which nitrogen deposition from oil sands may have affected the nitrogen cycle in area ecosystems. Their study concluded that at present a paucity of data on $\delta^{15}N$ signatures of oil sands related N sources precluded definitive interpretation of $\delta^{15}N$ in plant or lichen tissues with respect to oil sands N emissions.

Birks et al. (2022) describe an assessment of groundwater monitoring near oil sands development based on 546 water quality parameters measured in 5118 wells differentiated by hydrostratigraphic unit over the period 1958–2015. Regionally, baseline water quality conditions were found to vary significantly in the various subsurface units, with wide ranges in total dissolved solids and geochemical facies, reflecting variable lithology and geochemical processes. Data gaps and a number of spatial and temporal anomalies were identified, described and recommendations for follow-up.

4.4. Paleohydrology study

Zabel et al. (2022) describe a paleolimnological assessment of McClelland Lake, a shallow hardwater lake situated adjacent to an oil sands mine site under current development. Their study is particularly interesting as it establishes a record of water balance, lake chemistry, lake productivity and temperature dating prior to industrial development. The study provides an approach to characterize natural range of variability of ecosystem conditions over extended time periods as compared to conventional monitoring.

5. Summary

To date, oil sands have reached an advanced stage of commercial-scale development in Canada, although the large world reserves of oil sands bitumen, which exceed current known conventional petroleum reserves by almost three times, suggest that these deposits will form a significant component of the future energy profile of leading economies such as China, Russia, and the Americas. While regional assessment of water cycle impacts is ongoing in the Canadian oil sands region, studies highlighted in the special issue provide new information, novel tools and methods that may assist in strategic planning for future environmental investigations worldwide. In particular, the examples drawn from these case studies illustrate the importance of surface/groundwater interaction and salinity management for successful reclamation of peat-forming wetlands. A wholistic approach considering that oil sands development is occurring under changing climate conditions is also shown to be required for improved hydrologic prediction. This compilation is the result of the collective efforts of a large multidisciplinary group of researchers and experts from academia, government, and industry.

CRediT authorship contribution statement

John Gibson, Daniel Peters: Conceptualization, Investigation, Writing – Original draft, review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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