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Groundwater vulnerability in the Athabasca and Cold Lake oil sands regions: gaps, opportunties, and challenges

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Abstract

Oil sands development in the Athabasca and Cold Lake oil sands regions of Alberta has raised concerns about potential impacts to groundwater and groundwater dependent ecosystems. This review summarizes the current state of understanding as to how oil sands mining and in situ activities can affect groundwater systems using a stressor-mechanism-response framework. Specific oil sands activities and practices are reviewed, and where possible, described in terms of how they can impact hydraulic head, the hydraulic properties of aquifers, recharge and transport of constituents of concern and linked to observed or potential impacts to groundwater quantity and quality. Groundwater is an important component of the water balance in boreal ecosystems, and specific vulnerabilities related to development are reviewed, including water use, landscape disturbance, groundwater withdrawals, tailings pond seepage, deep well disposal and thermal impacts. Knowledge gaps include lack of baseline data and monitoring of the quantity and quality of groundwater discharge to rivers, lakes and wetlands. One key monitoring challenge is attribution of hydrogeologic responses to specific oil sands stressors given the range of other natural and anthropogenic factors contributing to their variability. Quantitative groundwater exchange mapping, regional-scale isotope mass balance assessment, and broader incorporation of isotopic and geochemical tracers for fingerprinting water sources and incorporation of Indigenous Knowledge appear promising for improved effectiveness of monitoring.

Key words: groundwater, surface water, impacts, oil sands, mining, in situ development

1. Introduction

Groundwater is a critical component of the hydrological cycle; it is an essential source of water to maintain the hydrological and geochemical conditions for groundwater dependent ecosystems such as rivers, lakes, wetlands and riparian zones. In the Athabasca Oil Sands Region (AOSR), groundwater has been shown to contribute greater than 40% of the input to tributaries of the lower Athabasca River (e.g., Steepbank, Muskeg and Firebag Rivers; Gibson et al. 2016), between 5% and 20% of input to small headwaters lakes (e.g., Schmidt et al. 2010), and is known to be the dominant water source for more than 50% of wetlands in the region (e.g., those classified as groundwater dependent fens; see Volik et al. 2020). Groundwater is also a determinant of the health of aquatic ecosystems, controlling temperature, salinity, and vegetation, and influencing seasonal and long-term water levels and water level fluctuations (Eamus et al. 2016) that are required to maintain the habitat for the organisms that live in and rely on these groundwater-dependent ecosystems (GDEs) (Link et al. 2023; Rhodes et al. 2024; Saccò et al. 2023). Impacts to the availability and quality of groundwater have the potential to affect not only the health of groundwater dependent terrestrial and aquatic ecosystems, but also the health of Indigenous Communities that harvest and use resources such as fish, waterfowl, berries, plants, and mammals, may affect traditional ways as hunting, fishing and gathering, and hinder the use of rivers as pathways for seasonal travelling. Differences in the geological setting of oil sands resources in the Athabasca and Cold Lake regions have led to the use of different extraction methods (i.e., surface mining and in situ) and as a result there are different types of potential stressors to groundwater and groundwater dependent ecosystems.

This paper reviews Environmental Impacts Assessments (EIAs) and peer-reviewed literature, and builds on previous reviews (Hrudy et al. 2010; King and Yetter 2011; Miall 2013) to provide an overview of the current state of understanding of the processes by which oil sands activities (mining and in situ operations) can impact groundwater resources and groundwater receptors, using a stressor-mechanism-response framework based on an adaptive monitoring design (Arciszewski

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and Munkittrick 2015). Knowledge gaps, opportunities for improvement, and challenges are discussed to stimulate wider discussion on sustainability of oil sands development, and to promote better understanding of related issues among the scientific community, decision makers, and the public.

1.1. Hydrogeological setting

Alberta has three main oil sands regions, Peace, Athabasca and Cold Lake (Fig. 1), where Cretaceous Formations contain bitumen-ore grades suitable for economic recovery using current technologies. This review focuses on the Athabasca and Cold Lake regions where oil sands activities have been most extensive to date. A thorough review of the hydrogeological settings can be found in Hackbarth and Nastasa (1979), Bachu and Underschultz, (1993); Barson et al. (2001); Lemay et al. (2005); and Parks et al. (2005). The depth of the bitumen zone and the presence of vertical connectivity features are aspects of the hydrogeological setting with the greatest relevance for development of the conceptual models of impacts to groundwater. The depth of the bitumen zone dictates the type of oil sands extraction technique that can be used, the extent to which shallow or deep groundwater flow systems are affected, and whether organics and salinity will be present naturally in near surface waters. The occurence of vertical connectivity features, such as buried channels, faults, karst or fractures introduced by collapse features, will determine whether preferential pathways for groundwater flow are present, and the degree to which stressors to groundwater at depth can affect near surface aquifers and surface water bodies and vice versa.

The Athabasca and Cold Lake Regions are situated near the eastern margin of the Western Canada Sedimentary Basin (WCSB) on a low-relief, peatland-rich, boreal plain with numerous lakes and bog-dominated plateaus containing zones of thawing permafrost. Bedrock units are comprised mainly of lower Cretaceous sandstones and shales resting unconformably on upper Devonian carbonates, sandstones and evaporites, and are overlain by Quaternary/Neogene drift. In the AOSR, bitumen is present and can be economically extracted from the McMurray-Wabiskaw Formation, but in the Cold Lake region the primary bitumen reservoirs are in the Grand Rapids and Clearwater Formations. The entire sequence dips to the southwest so that in the northern portions of the Athabasca Oil Sands (NAOS) Region the bitumen ore is at or near the surface, whereas in the southern portion of the AOSR (SAOS) and in the Cold Lake Region, the bitumen reservoirs are present at much greater depth. In the NAOS area (north of Fort McMurray), bitumen is sufficiently close to the surface (<75 m) so that surface mining operations are a practical approach for bitumen recovery, whereas in the SAOS and in the Cold Lake regions, the bitumen zones are deeper and require in situ extraction techniques such as Steam Assisted Gravity Drainage (SAGD), or cyclic steaming stimulation (CSS). It should be noted that there are some areas in the NAOS where the bitumen is present at about the 75 m limit of mining where both types of oil sands extraction methods are being used.

The proximity of deep regional flow systems near the land surface in northern areas of the AOSR is evident from the presence of saline springs along river channels, (Mahood et al. 2012; Gue et al. 2015), saline water emerging from the hyporheic zone of the Athabasca River and its tributaries (Gibson et al. 2013; Birks et al. 2018), and occurrence of variably saline lakes and fens (Volik et al. 2021). Identification of potential migration of oil sands constituents of concern into the ambient environment is complicated in the NAOS region because natural bitumen-saturated sediments, and high salinity groundwater are present near the surface, and many rivers in the region are incised directly into these deposits.

Cretaceous formations are overlain by Quaternary and Neogene sediments consisting of deposits of glacial till, outwash sands and gravels, and buried channel sediments deposited during various advancing and retreating phases of the Laurentide ice sheet that covered the region during the Quaternary Period. The buried channel networks (Andriashek 2003; Andriashek and Atkinson 2007) are important hydrogeological features in the region since they can provide vertical connectivity between the surface and underlying Cretaceous and Devonian formations, and depending on the channel fill, can be important water supply aquifers.

Faults, karst or fractures introduced by collapse features associated with dissolution of the Prairie Evaporite Formation have also created local areas of vertical hydraulic connectivity (Broughton 2015) and are co-located with areas of very high TDS water in the McMurray Formation (Cowie et al. 2015; Birks et al. 2022). Another important regional feature is the Colorado Group shale, an extensive aquitard present in the western NAOS (underlying the Birch Mountains) and in the SAOS (underlying the Stony Mountains) as well as the Cold Lake Region which is found to limit recharge and surface-groundwater interaction. In locations where it is thin or absent, especially to the west of the erosional bitumen edge, greater mixing of shallow groundwater with the underlying formations is often evident (Birks et al. 2022).

Conceptual and numerical groundwater flow models generally agree that the region can best be represented by a nested, hierarchical flow system, consisting of regional flow in the Cretaceous and Devonian formations of the WCSB, overlain by intermediate and shallow flow systems (Barson et al. 2001). The intermediate and shallow flow systems are generally considered to be topographically controlled, but in the shallowest flow systems occurring in widespread areas with thick, glaciated deposits, topography may have limited influence on water table position (Devito et al. 2005, 2012; Hokanson et al. 2019, 2020). Wetlands account for ∼54% of the land surface in the AOSR (Volik et al. 2020) and form the uppermost layer of shallow flow systems that are often the conduit of water between landscape units (Devito et al. 2005, 2012) and between groundwater and surface waters (Volik et al. 2023). A comprehensive review of the role wetlands have in groundwater surface water interactions in the AOSR is presented in Volik et al. (2023).

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Fig. 1. Map showing the three main oil sands areas in Alberta (see inset). The Athabasca Oil Sands Region (AOSR) includes the North Athabasca Oil Sands (NAOS) north of Fort McMurray and the Southern Athabasca Oil Sands (SAOS) south of Fort McMurray. All data provided by the Government of Alberta under the Alberta Open Data License (2024), Coordinate System: NAD 1983 10TM AEP Forest.

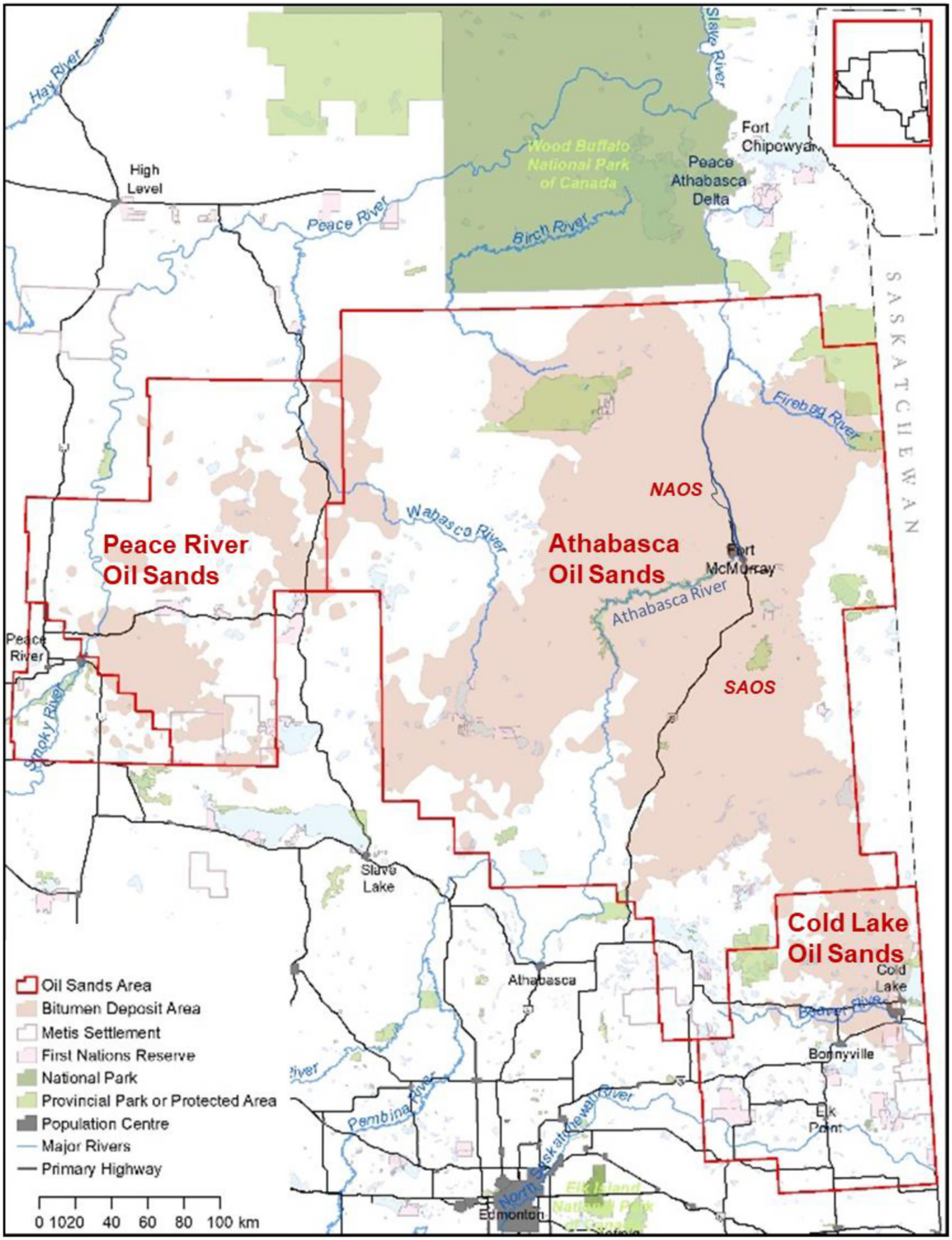

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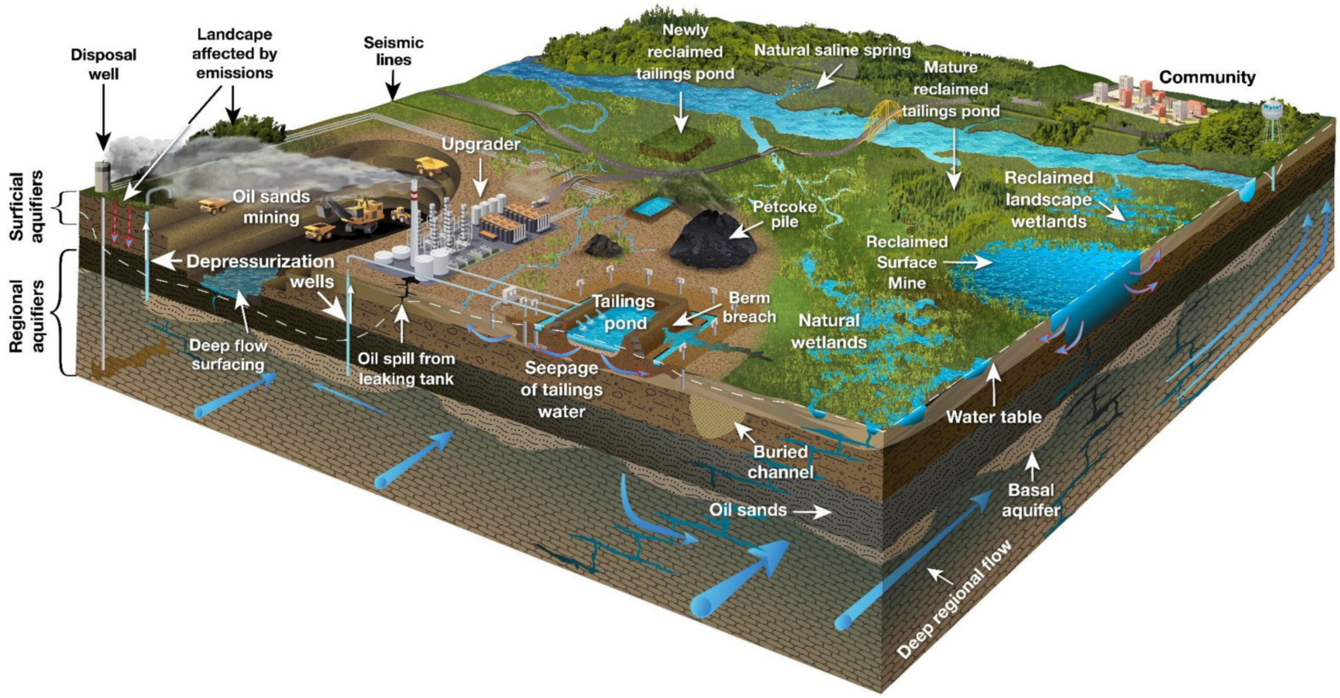
Fig. 2. Schematic showing the activities associated with oil sands surface mining operations and the potential stressors to groundwater. Mining operations occur in the NAOS where the McMurray Formation is < 75 m from the surface.



2. Stressor–mechanism–response framework

A review of Environmental Impact Assessments (EIAs, available at ftp://ftp.gov.ab.ca/env/fs/EIA/, see Supplemental Information S1 for full list), peer-reviewed publications and selected grey literature was used to develop a stressor–mechanism–response framework for impacts to groundwater from oil sands activities similar to what has been developed for other environmental media (Horb et al. 2021; Roberts et al. 2021; Arciszewski et al. 2021; Beausoleil et al. 2021; Lima and Wrona 2019). Since activities associated with surface mining are different from those associated with in situ operations, separate conceptual models outlining the potential stressors, mechanisms, responses and effects were developed (Figs. 2 and 3, for mining operations and Figs. 4 and 5 for in situ operations). We designate broad categories of oil-sands related activities as "pressures" within which more specific "stressors" include oil sands activities that can alter hydrogeological "mechanisms", leading to "responses" such as changes in the quantity and quality of groundwater present in aquifers, or changes in aquifer discharge to surface water, whereas "effects" are the resulting environmental or societal impacts. Within this framework, the term "mechanism" is used with the intention to identify modes of hydrogeological changes that result directly from a "stressor" and that have the potential to change the quantity or quality of groundwater, or groundwater discharge. Flow charts are used to illustrate proposed frameworks for mining operations (Fig. 3) and in situ operations (Fig. 5). The response to a stressor will occur initially within an aquifer but depending on the hydrogeological setting the response could eventually include a change in the quantity or quality of groundwater discharge (green boxes in Figs. 3 and 5). The hydrogeological setting (light blue boxes in Figs. 3 and 5) will determine whether a change in the quality or quantity of groundwater in an aquifer will be propagated to a groundwater discharge zone, where it has the potential to affect aquatic or terrestrial ecosystems, Indigenous community health and traditional ways. Ideally Indigenous Knowledge is braided with western science to identify regional pressures, stressors, mechanisms, responses, and linkages to culturally significant resources in the oil sands region (grey boxes in Figs. 3 and 5).

In the NAOS area the bitumen is present at <75 m depth so surface mining occurs and the pressures to groundwater are from construction and operation of the mine, the storage of mine waste in tailings ponds and eventually reclamation of the site (Fig. 3). In the SAOS and Cold Lake areas bitumen is present at depths > 75 m so in situ extraction techniques are required and the pressures to groundwater are from construction and operation of the central processing facility, injection of steam (Fig. 5), and in some operations the co-injection of solvent (see Supplemental Material S3.8). The stressors identified in the conceptual models include some that are present at all types of operations that have a high probability of occurring (e.g., small spills and leaks), and others which can be considered catastrophic hazards with a very low probability of occurring (e.g., berm failure). Many of the stressors that are thought to operate on relatively small spatial and temporal scales are covered by onsite operational groundwater and surface water monitoring required under provincial legislation. The OSM Groundwater Technical

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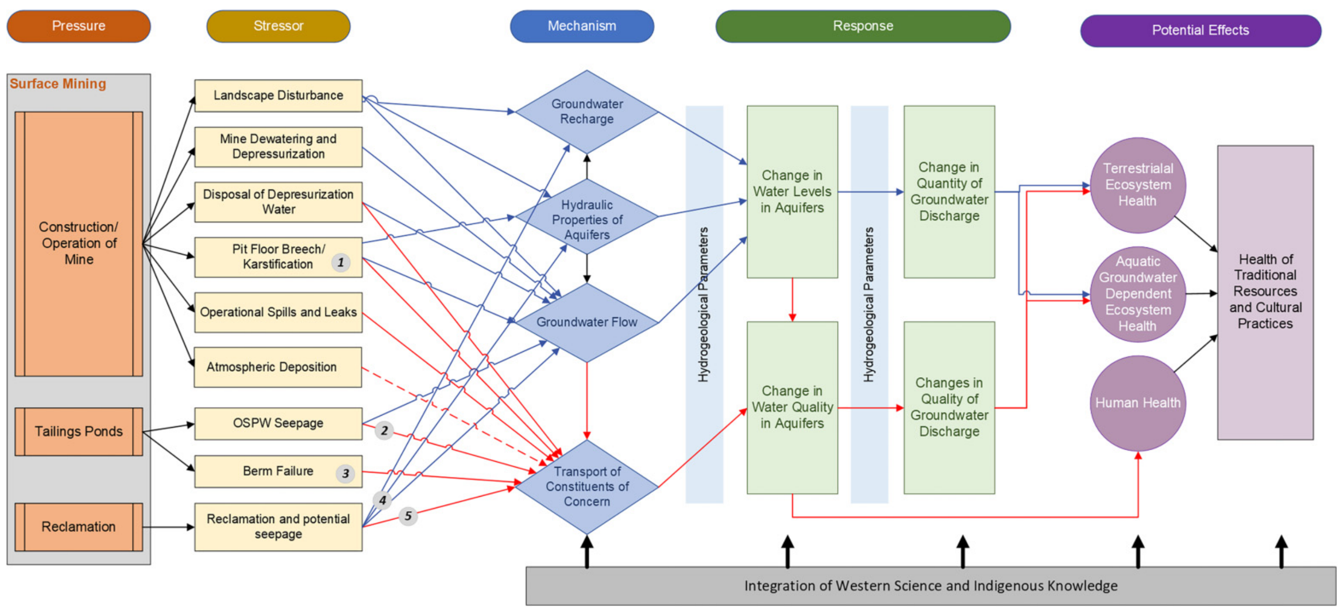
Fig. 3. Conceptual model of groundwater stressors, mechanisms, responses and potential effects for oil sands surface mining operations. Blue arrows indicate potential impacts to water quantity, and red arrows indicate potential impacts to water quality. Number labels indicate relevant investigations listed below: **Pit Floor Breech**[1] AER 2013; **OSPW Seepage**[2] Ahad et al. 2013; Ahad et al. 2020; Fennell and Arciszewski 2019; Ferguson et al. 2009; Gervais 2004; Hunter 2001; Oiffer et al. 2009; Savard et al. 2012; Yasuda et al. 2010; **Berm Failure**[3] Dibike et al. 2018; Mahdi et al. 2020; **Reclamation**[4] Biagi et al. 2019; Dompierre and Barbour 2016; Little-Devito et al. 2019; Lukenbach et al. 2019; Sutton and Price 2020*a* and 2020*b*, Vessey et al. 2019, **Reclamation**[5]. Hartsock et al. 2019; Kessel et al. 2018; Li et al. 2020; Nagare et al. 2018; Nagare et al. 2022; Nesbitt et al. 2018; Nesbitt and Lindsay 2017; Robertson et al. 2019; Vander Muelen et al. 2021).



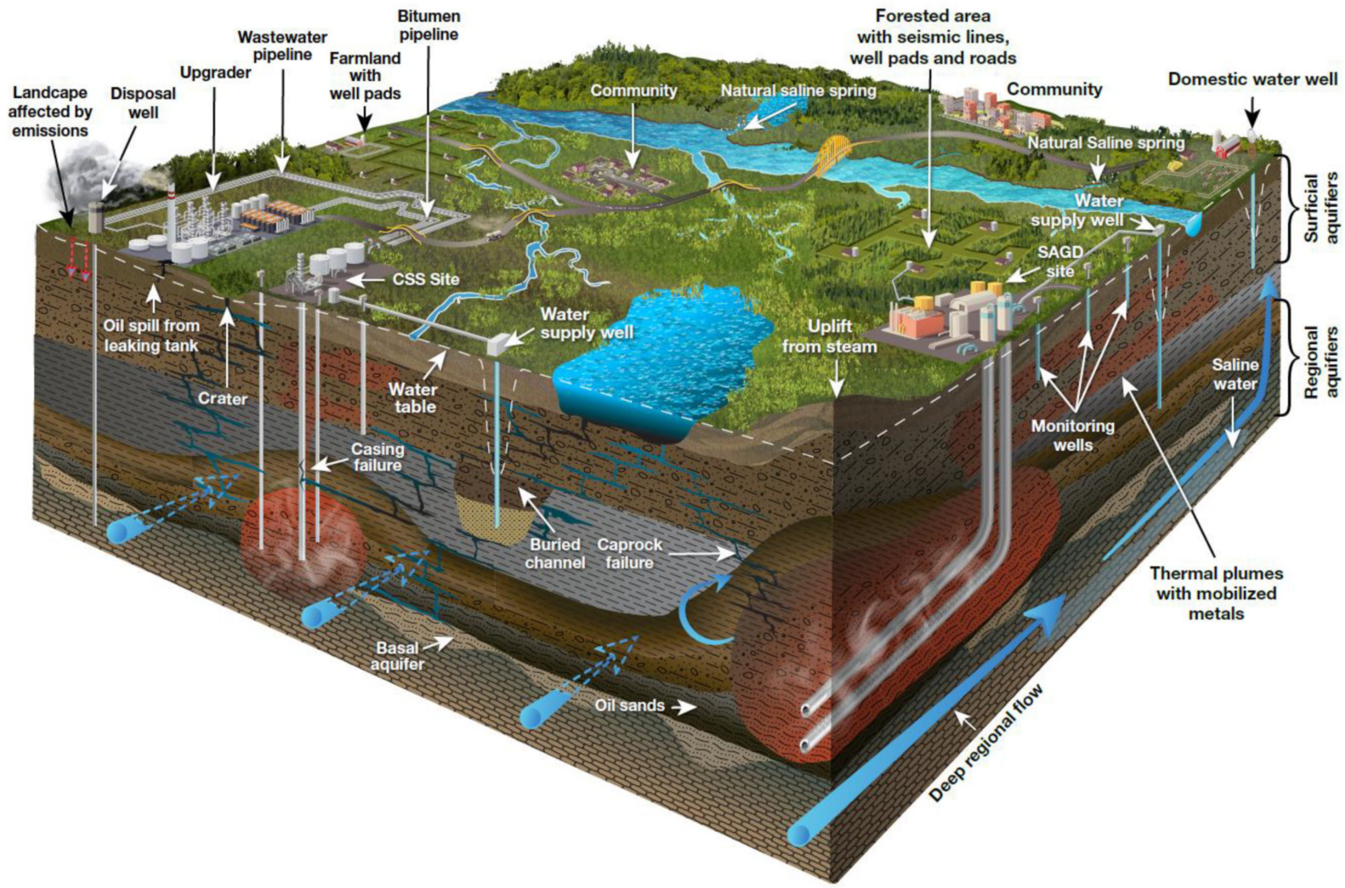
Advisory Committee (TAC), comprised of representatives from government, industry and stakeholders, identified a subset of oil sands stressors with the greatest perceived risk or knowledge gaps. The priority groundwater stressors for surface mining were identified as: landscape disturbance, groundwater withdrawals, Oil Sands Process-affected Water (OSPW) seepage and reclamation, and for in-situ operations as follows: groundwater withdrawals, thermal contaminant mobilization, and injection of wastewater into deep saline formations. Selection of priority stressors was based on public concern about impacts to groundwater from the stressor, or the potential for the stressor to have cumulative effects on temporal or spatial scales not covered by on-lease monitoring. A comprehensive description of the major and minor stressors for both mining and in situ extraction are provided in Sections 2.1 and 2.2 and in the Supplementary Material.

Four fundamental hydrogeological mechanisms were identified as modes of change that could be altered as a result of oil sands stressors: groundwater recharge, hydraulic properties of the aquifer, groundwater flow (due to changes in hydraulic head), and the transport of constituents of concern. These mechanisms are often co-dependent, with the hydraulic properties of the aquifer exerting influence on recharge rates and hydraulic heads, which in turn, can influence the transport of constituents of concern.

Changes in groundwater mechanisms have the potential to elicit two main groundwater responses: (i) changes in water levels (hydraulic head) in aquifers, and (ii) changes in water quality in aquifers (Figs. 3 and 5). The hydrogeological setting determines whether a change in a groundwater mechanism will result in a response within an aquifer, and whether that response will eventually lead to a response in groundwater discharge to a groundwater-dependent ecosystem (Figs. 3 and 5). Differentiating between responses in groundwater and responses in groundwater discharge is important because changes in groundwater discharge have the greatest potential to directly impact aquatic and terrestrial receptors. The permeability of the aquifers and the distribution of hydraulic heads determine the temporal and spatial scale of groundwater movement, as well as the time frame and spatial extent of potential groundwater contamination from transport of constituents of concern. These properties will determine if the groundwater response will be short-lived and local, or permanent and regional, making them important components of a site-specific groundwater conceptual model.

If the initial responses within aquifers result in changes in the quantity and quality of groundwater discharge to surface waters, impacts to groundwater dependent ecosystems (e.g., fens, springs, rivers, lakes) may eventually occur (Culp et al. 2020). Terrestrial ecosystems (e.g., riparian zones) may also be directly impacted due to changes in groundwater availability and quality, or indirectly affected by disruptions in food webs and bioaccumulation of contaminants. Human health can be directly affected in cases when groundwater serves as a drinking water source (e.g., Quaternary and Neogene aquifers in some areas of the Cold Lake

Fig. 4. Schematic showing the main activities associated with in situ oil sands mining and potential stressors to groundwater, representative of areas in the SAOS and Cold Lake Regions. In situ operations are used when the target bitumen formations are > 75 m below the surface.



region), or when aquatic and terrestrial ecosystem components are harvested or used for cultural practices by Indigenous communities. The quantity and quality of groundwater discharge to rivers and lakes will affect navigability, can alter thermal regimes impacting fish habitats and can lead to transport of constituents of concern, potentially impacting the quality of wild foods. Naturally occurring and anthropogenic PAHs and metals have been detected in some wild foods in the in the region, but these have not been attributed to oil sands activities (Baker 2018; Bigstone Cree Nation 2016).

2.1. Priority surface mining stressors and mechanisms

The potential stressors to groundwater quantity and quality from surface mining include those associated with the construction and operation of the mine (e.g., landscape disturbance to expose the bitumen, dewatering and depressurization of the pit, pit floor breach), as well as those related to the storage of Oil Sands Process-affected Water (OSPW) in tailings ponds (e.g., tailing pond seepage, berm failure) and reclamation (e.g., seepage from construction material used in reclaimed landscapes) (see Supplemental Information Section 2 for additional information) (Figs. 2 and 3).

During construction of the mine, overburden materials such as muskeg or glacial sediment present above the McMurray Formation are removed, the water table is lowered, and the McMurray is depressurized to allow for excavation of the oil sands from the pit. The removal of surficial material and other mining landscape disturbances, such as rerouting surface drainage, construction of tailings ponds, and development of infrastructure for processing and storage (i.e., fuel and chemical tank farms, various non-tailings storage ponds, petcoke stockpiles, roads, and pipelines) (Fig. 2), alters the permeability and infiltration capacity of the shallow overburden, affecting the hydraulic properties of the surface, groundwater recharge, and shallow groundwater flow systems and runoff behavior within the disturbed area (Fig. 3). Lowering the water table and depressurizing the McMurray Formation, creates changes in the hydraulic head distribution around the mine which will alter groundwater flow and potentially affect the quality and quantity of groundwater discharge to the surface. Depressurization water can be saline and may require disposal via deep well disposal or removed off-site. The drawdown cones around dewatering activities are typically small in spatial extent and limited to the lease area in unconfined aquifers, but can extend beyond mine lease boundaries when dewatering or depressurization occurs in confined aquifers.

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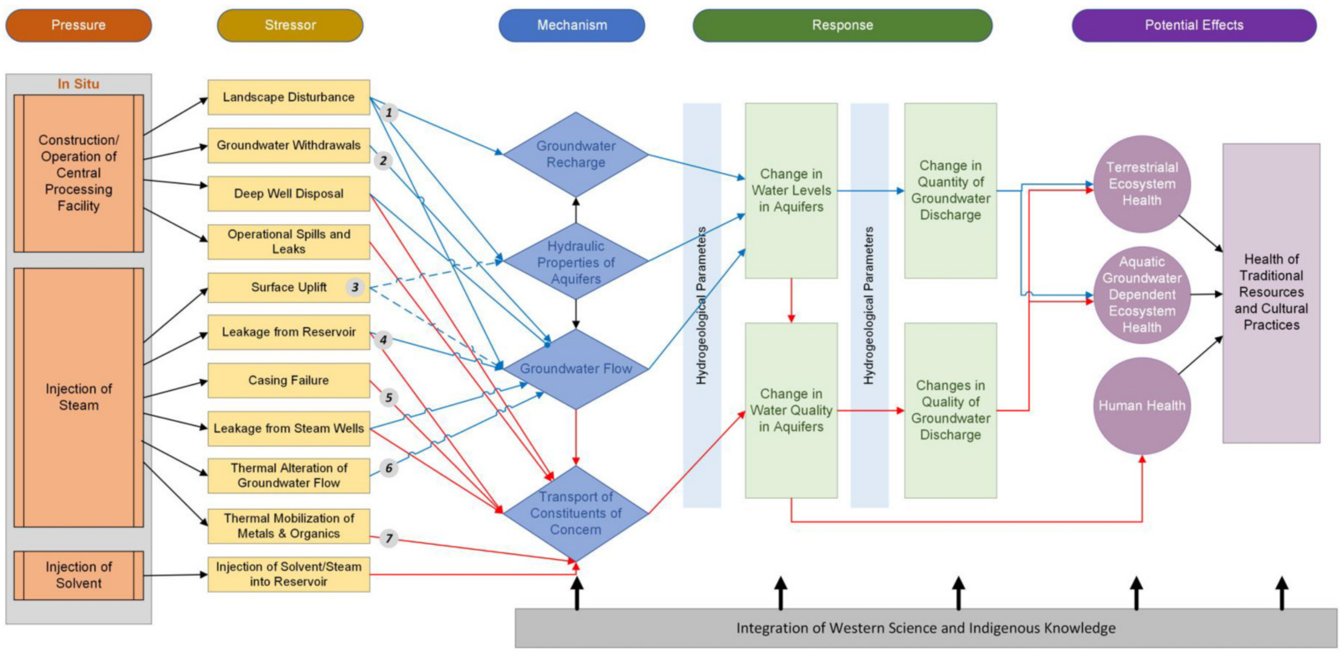
Fig. 5. Conceptual model of groundwater stressors, mechanisms, responses and potential effects for in situ oil sands operations. Blue arrows indicate potential impacts to water quantity, and red arrows indicate potential impacts to water quality. Number labels indicate relevant investigations: **Landscape Disturbance[1]** Elmes et al. 2021; **Groundwater Withdrawals[2]** EIAs: e.g., Devon NEC Corporation 2012; Matrix 2013; **Surface Uplift[3]** Collins et al. Pearse et al. 2014; Samsonov and Czarnogorska 2014; Samsonov 2017; Shen et al. 2014; **Leakage from Reservoir[4]** Mohammadi et al. 2021; **Casing Failure[5]** AER 2016; CNRL 2014; ERCB 2010; Hein 2010; **Thermal Alteration of Groundwater Flow[6]**, Fennell 2008; Liu et al. 2011; Giraldo and MacMillan 2016; **Thermal Mobilization of Metals and Organics[7]** AEP 2018; Craig et al. 2021; Fennell 2008; Javed and Siddique 2016; Moncur et al. 2015*a*. **Injection of Solvent[8]** AER 2018*a* and 2018*b*.



In the EIAs reviewed the predicted extend extent of a 1 m water table drawdown cone around the mine pit ranged from 0 km (no expected drawdown due to low hydraulic conductivity of overburden material; Joslyn North Mine) to 5 km (Shell, Pierre River Mine, 2007) with an average distance of about 1.6 km from the mine. The drawdown cones from dewatering and depressurization will be present while the mine is operating, during which time groundwater discharge to wetlands and rivers within this zone may be altered.

Storage of the by-products of bitumen ore processing (i.e., petroleum coke, OSPW, tailings) are the main groundwater quality stressors for surface mining (Fig. 3). Bitumen ore is processed using Clark Hot Water treatment to separate the oil from sands and fines creating large volumes of tailings and OSPW that will need to be recycled or stored in tailings ponds. To promote further separation of residual bitumen from the fine tailings the remaining tailings mixture may be treated with caustic chemicals, like sodium hydroxide or sodium carbonate, to raise the pH and alter electrical charge characteristics of the solids and the bitumen to facilitate separation. The tailings produced from these steps are stored in basins called tailings ponds, which allow the solids to settle. Upgraders convert the bitumen to synthetic crude oil using a coking process that uses thermal cracking of long-chain hydrocarbons (Masliyah et al. 2008) with petroleum coke as a byproduct of upgrading. This carbonaceous material is enriched in sulfur and metals present in the bitumen ore and it is often stored on site (Nesbitt and Lindsay 2017; Nesbitt et al. 2018; Zubot et al. 2012).

Seepage of OSPW from tailings ponds was identified as a priority stressor to groundwater quality and has been an active area of research (Fig. 3). OSPW typically has elevated concentrations of constituents originally present in the bitumen ore (e.g., naphthenic acids, inorganic ions, dissolved metals such as V and Mo), and constituents related to the presence of some unrecovered bitumen such as asphaltenes, and solvents added during the extraction process (e.g., polar hydrocarbons, PAHs, benzene, phenols, toluene); (Allen 2008; Madill et al. 2001). Naphthenic acids have been identified as the main source of toxicity in OSPW (Morandi et al. 2015), with inorganics such as metals and salts also of concern (Bauer et al. 2019). Tailings ponds containing OSPW can be classified as: in-pit ponds (located in previously mined open pit), and external (out-of-pit) ponds (constructed dyked areas built above ground) (Fennell and Arciszewski 2019) (Fig. 6). Both types of ponds are typically located or constructed with low permeability material at the base and sides, but some out-of-pit ponds are situated on more permeable, granular deposits, and as a result may have a higher potential to impact adjacent groundwater and surface water bodies. OSPW plumes have been identified in groundwater (Gervais 2004; Holden et al. 2011; Hunter 2001; Oiffer et al. 2009; Savard et al. 2012; Yasuda et al. 2010), but discharge of these plumes to surface waters have not been identified. Despite evidence that

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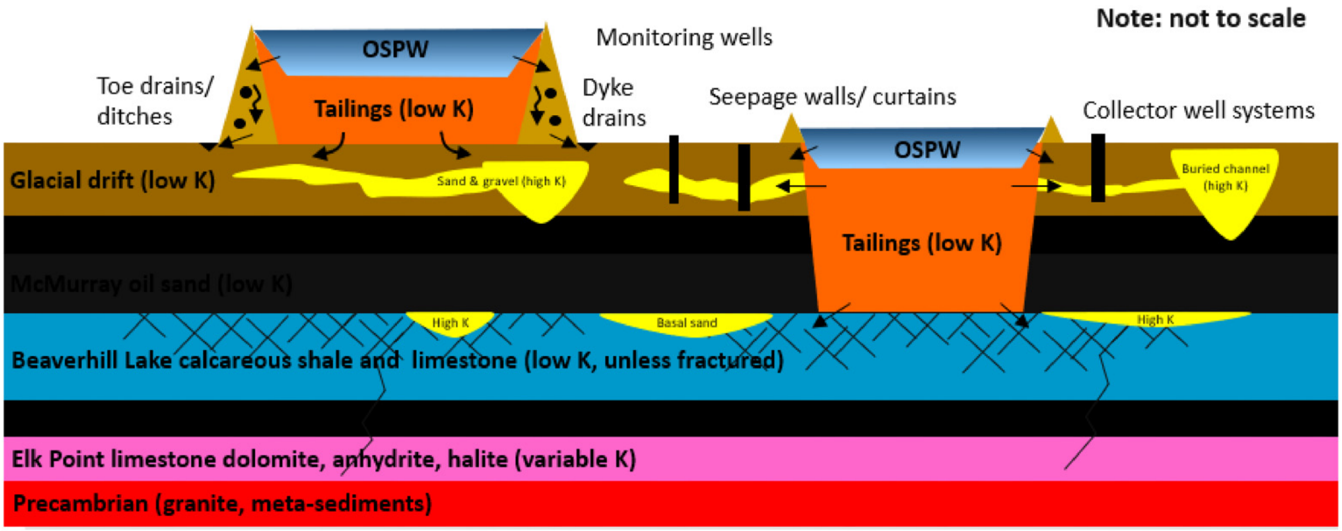
Fig. 6. Conceptual diagram showing the difference between out-of-pit tailings ponds (left) and in-pit tailings ponds (right). Also shown are the typical types of collection/interception/barrier systems and monitoring conducted around these impoundments.



any impacts to surface water ecosystems from OSPW-affected groundwater are likely limited and local in scale (e.g., Roy et al. 2016; Fennell and Arciszewski 2019; Culp et al. 2020), the suggestion in several prominent studies (e.g., Timoney and Lee 2009; Kelly et al. 2010) that tailings seepage is a source of contaminants in the Athabasca River likely contributes to the public's concern regarding OSPW seepage.

Oil sands reclamation programs aim to return the landscape to a natural state and involve creating new terrestrial and aquatic landscape features out of materials available on site. These changes in the nature and distribution of overburden materials and drainage patterns, have the potential to alter groundwater recharge, hydraulic properties of the local aquifers, groundwater flowpaths (Biagi et al. 2021, Kessel et al. 2018; Ketcheson et al. 2017; Lukenbach et al. 2019; Sutton and Price 2020*a* and 2020*b*; Volik et al. 2023) and depending on what materials are used (e.g., coarse tailings, petroleum coke), may include transport of constituents of concern (e.g., naphthenic acids, salts, metals) (Kessel et al. 2018; Hartsock et al. 2019; Nesbitt et al. 2018; Nesbitt and Lindsay 2017; Robertson et al. 2019).

2.2. Priority in situ stressors and mechanisms

In the SAOS and Cold Lake Regions, bitumen is extracted using in situ thermal recovery methods (e.g., Steam Assisted Gravity Drainage, SAGD; Cyclic Steam Stimulation, CSS) where steam is injected below ground to heat the bitumen in situ so that its viscosity is lowered allowing it to be pumped to the surface. Stressors which can impact groundwater quality and quantity at in situ operations include those associated with the construction and operation of the central processing facility (i.e., landscape disturbance, groundwater withdrawals, deep well disposal), stressors related to the injection of steam (i.e., surface uplift, leakage from the reservoir, casing or injectors wells, thermal impacts to groundwater flow, and thermal mobilization of metals and organics) or in some operations stressors related to the use of solvent (Figs. 4 and 5) (see Supplemental Material Section 3 for additional information). In SAGD operations, a dual-pair of horizontal wells are used with steam injected into the top, injector well, heating the surrounding bitumen and reducing the viscosity. Bitumen then drains by gravity to the underlying producing well, where it is pumped to the surface for further refinement (Fig. 5). For CSS operations, high pressure steam is injected in a single well drilled through the bitumen reservoir and heated for several weeks, after which the well is reversed to allow pumping of the bitumen to surface (Fig. 4). Steam is injected into reservoirs that are typically 150 m to 450 m below ground surface, but the heated injector well can result in heating of the overlying sediment.

Groundwater withdrawals from Cretaceous and buried channel aquifers are often used to supplement recycled water for steam generation at in situ operations, and this stressor will lower the hydraulic head in the target aquifer and may affect overlying or underlying aquifers (Fig. 4). The degree to which groundwater withdrawals impact adjacent groundwater and surface water resources will depend on the hydraulic properties of the aquifer, and the location and rate of the withdrawals. Groundwater model simulations of the cumulative impacts of groundwater withdrawals by all in situ operations at their maximum groundwater allocation and withdrawal rates predict drawdown in the Lower Grand Rapids of 21% to 43% of baseline (or between 10 and 150 m) with drawdown cones that extend well beyond lease boundaries (e.g., Devon NEC Corporation 2012; Matrix 2013). Drawdown in deep Cretaceous aquifers is mainly of concern in areas where there is vertical connectivity with overlying formations, where lowering of water levels at depth could alter groundwater discharge to groundwater dependent ecosystems. Numerical groundwater modelling to predict the cumulative impacts of groundwater withdrawals for all in situ operations predict much smaller drawdown in

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the Quaternary and Neogene channel aquifers (between 1 and 10 m) (Matrix 2013), but it isn't clear if the simplified representation of surficial geology used in the numerical model is capturing all the vertical connectivity (i.e., buried channels) present. Comparisons of model simulations with field data are needed (Brinsky et al. 2023), particularly in areas where the distribution of geochemical and isotopic tracers indicates potential vertical connectivity between Cretaceous aquifers and the surface (Birks et al. 2019).

A potential impact to groundwater quality related to in situ development is leakage from disposal wells that are used to dispose liquid waste streams generated during SAGD and CCS production (Fig. 4). Obtaining a license for a disposal well requires demonstrating that the target aquifer is hydraulically isolated and that the disposal rates will not result in migration of wastewater to non-saline aquifers or aquatic environments. Geologically isolated, saline, bedrock formations like the McMurray Formation, or saline areas of the Grand Rapids are common targets for disposal and maximum limits for disposal are set under Directive 081 (AER 2019). Increases in hydraulic heads that occur during disposal (i.e., mounding) are in many cases balanced by groundwater withdrawals, since there is a lot of water sourcing from the Basal McMurray and Lower Grand Rapids aquifers.

During thermal bitumen recovery, the sediments and groundwater adjacent to the injector wells are heated, which can result in the release constituents of concern, such as metals and organics, present naturally in the sediment (Fennell 2008; Moncur et al. 2015*a*, 2015*b*; Javed and Siddique 2016; AEP 2018; Craig et al. 2021) which can result in transport of constituents of concern and impacts to groundwater quality. There is extensive on-site monitoring of groundwater quality in the vicinity of in situ operations as required by the directive "Assessment of Thermally-Mobilized Constituents in Groundwater for Thermal In-situ Operations" (AEP 2018) and the results from these programs can be used to evaluate the temporal and spatial scale for thermal groundwater plumes.

3. Groundwater response: baseline conditions and change detection

Knowledge of the potential stressors and mechanisms helps identify what types of groundwater responses to expect, but clearly identifying a groundwater response and attributing it to a stressor is challenging and has some associated knowledge gaps. A successful groundwater monitoring program must be able to detect changes in groundwater conditions that are outside the range of natural variability and be able to attribute the change to a cause (e.g., oil sands operations versus climate change), or, at least, to determine if there is high concomitance with plausible sources of impacts and observed changes. Identifying a significant groundwater response is based on having good characterization of baseline conditions for the quantity and quality of both groundwater and groundwater discharge as well as an understanding of their natural variability and this is an area where there are significant data (Table 1) and knowledge gaps.

3.1. Baseline groundwater quantity and quality data availability and change detection

Data on groundwater quantity and quality for the major hydrostratigraphic units in the AOSR and Cold Lake Regions are fairly comprehensive and have benefitted from the baseline groundwater data collected on the site-scale prior to oil sand mine development as well as data from on-going regional groundwater monitoring programs. There have been numerous efforts to synthesize groundwater quantity and quality data on the subregional scale (e.g., NAOS, SAOS, Cold Lake) (Table 1). The most recent synthesis of regional groundwater quality used data from these previous baseline groundwater quality characterization efforts, updated with updated using publicly available from, EIAs, provincial monitoring programs, and was summarized for the entire AOSR (Birks et al. 2022; Manchuk et al. 2021), to establish typical conditions and stable values for each of the hydrostratigraphic units. This synthesis established ranges for water quality parameters for the major aquifers in the region and revealed naturally high concentrations of solutes and some organics in many aquifers. The average concentrations of indicator parameters in some aquifers exceed the concentrations used as interim triggers showing the challenge of characterizing baseline groundwater quality in complex hydrogeological settings, with large contrasts in natural water quality and the importance of establishing baseline conditions when setting of water quality triggers, limits and management strategies. The updated groundwater quality database was used to identify areas with a potential groundwater quality response, using statistically significant temporal trends in select groundwater quality parameters (Birks et al. 2022).

Data on baseline groundwater flow conditions (e.g., hydraulic head) have been synthesized at the site-scale for EIAs, and for sub-regions to develop maps of groundwater flow as part of development of Groundwater Management Frameworks (Table 1) (Parks et al. 2005; Worley Parsons 2010, 2012). The most recent groundwater hydraulic head compilation and synthesis established pre-development hydraulic head and total dissolved solids (TDS) distributions in the Cretaceous aquifers (Grand Rapids, Clearwater and McMurray Formations) (Nakevska 2020*a*, 2020*b*; Singh and Lemay 2021; Nakevska and Lemay 2021; Brinsky et al. 2023). These pre-development baseline datasets are being used for change detection studies to see if there have been groundwater responses to oil sands development that are outside of the predicted effects (Brinsky et al. 2023). Establishing baseline conditions in the Quaternary and Neogene aquifers is more challenging because of smaller more isolated shallow systems and lack of water level monitoring data.

3.2. Baseline groundwater discharge quantity and quality data availability and change detection

Groundwater-surface water interactions were identified in both the original joint federal-provincial Oil Sands Monitoring plan (JOSM; 2012–2015) and the renewed OSM (2018-present) program as a critical component for integrating the

Table 1. Summary of previous work that have contributed to our understanding of the quality and quantity of groundwater and groundwater discharge in the AOSR and Cold Lake Region and whether changes relative to baseline have been assessed.

		Baseline characterization	Response: change detection
Groundwater	Quantity	**Sub-Region**: Hackbarth and Nastasa 1979; Ozoray 1974; Ozoray et al. 1980; Bachu and Undershcultz 1993; Worley Parsons 2010, 2012; Parks et al. 2005.	
		Regional- Cretaceous Aquifers: Nakevska 2020*a*; Nakevska and Lemay 2021; Brinsky et al. 2023	**Regional- Cretaceous Aquifers**, Brinsky et al. 2023
	Quality	**Sub- Region**: Birks et al. 2019; Cowie et al. 2015; Hackbarth and Nastasa 1979; Lemay et al. 2005; Manchuk et al. 2021; Ozoray 1974; Ozoray et al. 1980; Parks et al. 2005; Worley Parsons 2010, 2012.	
		Regional: Birks et al. 2022; Nakevska 2020*b*; Manchuk et al. 2021; Nakevska 2020*b*; Singh and Lemay 2021	**Regional**- Manchuk et al. 2021; Birks et al. 2022.
Groundwater Discharge	Quantity	**Rivers**: Bickerton et al. 2018; Jasechko et al. 2012; Ellis and Jasechko 2018; Gibson et al. 2015, 2016; Hwang et al. 2023.	**Rivers Regional**- Baseflow in selected rivers in Murray et al. 2023
		Wetlands: Elmes and Price 2019; Gibson et al. 2022; Hokanson et al. 2019; Hokanson et al. 2020	
		Lakes: Schmidt et al. 2010; Gibson et al. 2010, 2015, 2019*a*, 2019*b*	
	Quality	**Rivers**: Birks et al. 2018; Gibson et al. 2013; Grasby and Chen 2005; Gue et al. 2015.	–
		Wetlands: Wells and Price 2015	

Note: Regional refers to datasets that include the entire AOSR and Cold Lake Region.

role of groundwater into the monitoring and assessment of cumulative effects on aquatic ecosystems in the AOSR. Despite its importance, the quantity and quality of groundwater discharge to surface have not been routinely described at the site-scale in EIAs or assessed regionally as part of any historical monitoring program. There are some data available on the quantity of groundwater discharge for selected rivers, lakes and wetlands from surface water datasets or from site-specific studies, but regional synthesis of groundwater discharge data to establish baseline conditions are limited, particularly for wetlands, and change detection studies have only recently been conducted for rivers (Murray et al. 2023) (Table 1). Data on the quality of groundwater discharge to rivers, lakes and wetlands is even more scarce and has only included characterizing water quality in springs and wetlands and specific groundwater discharge zones in rivers.

3.2.1. River groundwater discharge data

Estimates of the quantity of groundwater discharging to rivers in the AOSR and Cold Lake areas are available using traditional hydrograph separation techniques based on stream discharge data (Murray et al. 2023), field studies using differential flow gauging (Bickerton et al. 2018), tracer-based streamflow partitioning (Ellis and Jasechko 2018; Gibson et al. 2016; Gue et al. 2015; Jasechko et al. 2012) and have been estimated from integrated groundwater surface water models (Hwang et al. 2023). These individual studies were mainly conducted on the mainstem of the Athabasca River and tributaries present in the NAOS, and the only estimates of groundwater discharge to rivers outside of the NAOS are from stream discharge hydrograph separation technique (Murray et al. 2023) and from integrated groundwater surface water model simulations (Hwang et al. 2023). Groundwater-river interactions can be complex and occur at a variety of scales, including groundwater-fed springs, seepage from riverbanks, and baseflow from deep regional aquifers (see Brunner et al. 2017). The methods that can be used to quantify groundwater discharge can provide estimates based on different spatial and temporal scales and, depending on the tracers selected, can quantify different end-members (i.e., saline groundwater discharge, vs total groundwater discharge). Chloride and chlorine isotope mass balance methods estimated saline groundwater contributions from Cretaceous or Devonian formations are less than 3% of monthly flow in the Athabasca River north of Fort McMurray (Gue et al. 2015; Jasechko et al. 2012). Hydrograph separation studies using stable isotopes of water for the same river reach estimated groundwater contributions at between 31% and 41% of flow (Gibson et al. 2016). The difference between the groundwater contributions for saline and total groundwater inputs, implies a preponderance of fresh rather than saline groundwater inputs along the mainstem and show the value of multi-tracer approach. While much of the fresh fraction of groundwater is likely inherited from tributaries, fresh inputs may be dominated by shallow groundwater flows from aquifers above the bituminous McMurray Formation (e.g., baseflow from shallow aquifers, riverbank seepage, discharge via connected wetlands), which serves as an aquitard. The only source of groundwater discharge data with sufficient length of record to do statistically significant trend analyses are based on stream discharge data (Murray et al. 2023).

3.2.2. Lake groundwater discharge data

Lake hydrology investigations in the oil sands region have not typically focused on determining the role of groundwater, but rather on general features of the overall lake water

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balance including evaporation, and connectivity or throughput. There have been a number of regional lake surveys (e.g., 50 lakes in the Regional Aquatic Monitoring Program, RAMP; Gibson et al. 2010 and 2019*a*; 128 lakes in the SAOS area Gibson et al. 2019*b*) that have provided information about lake water balance conditions, such as the ratio of evaporation to inflows, where inflows include both surface water and groundwater contributions. Repeat sampling of the lakes can be used to generate time-series of isotope-mass-balance assessments of lake water balance status which can be used to identify trends in evaporation to inflow ratios and catchment yield. A 16-year record of isotope mass balance estimates of evaporation to inflow and water yield for the 50 RAMP Lakes identified trends water yield that were related to climate, wetland type, lake watershed configuration and permafrost (Gibson et al. 2019*a*). Groundwater contributions to a subset of the RAMP lakes were estimated using radon-222, a radioactive gas widely distributed in rocks and soils has been found to be useful for partitioning surface and groundwater exchanges with lakes (Schmidt et al. 2010). Due to its short half-life (3.8 days), presence of radon-222 in a surface water body is strong evidence that the water body is receiving active groundwater discharge from silicate bearing aquifers within the past 16 days (∼4 half-lives). Radon estimates of groundwater inflow to 37 RAMP lakes in 2009 suggested that groundwater forms less than 20% of the annual water yield to the lakes, and that water yield has been shown to be enhanced by permafrost thaw, and likely affects the degree of groundwater surface water interaction for lakes.

Combining the results from isotope mass balance assessments of lake hydrology with tracers of groundwater contributions show promise for being able to better distinguish the groundwater contribution to the total inflows (surface and groundwater) estimated using the isotope mass balance approach. Combined evidence from radon and TDS has been applied preliminarily to test tracing capabilities for characterizing degree of groundwater surface water interactions while differentiating fresh and saline water sources. Survey data from lakes in surface mining and in situ regions of the Athabasca oil sands region (Gibson et al. 2019*b*) compared to selected rivers and groundwaters (Fig. 7), reveal low but variable radon concentrations in lakes, intermediate values in river water, and relatively high levels in groundwater, which shows potential for differentiation of mixing with different groundwater sources.

Combining information from isotope mass balance modelling with geochemical indicators of groundwater contributions such as TDS and strontium appear promising for identifying lakes with increased connectivity with groundwater discharge. Regional mapping of water yield from isotope mass balance modelling on lakes in the SAOS has identified that spatial variations in runoff amount may be pronounced due to capture of runoff by incised and buried channels in some areas and presence of Colorado Shale, (Gibson et al. 2019*b*) (Fig. 8). The higher TDS and strontium concentrations in lakes situated where the Colorado Shales are not present is consistent with greater connectivity with Cretaceous and Devonian aquifers in this area.

3.2.3. Wetland groundwater discharge data

The type, magnitude, and frequency of hydrological linkages between different wetland classes and adjacent landscape units vary by wetland type, but generally depend on surficial geology, topography, and climate (Devito et al. 2005*a*, 2017; Hokanson et al. 2019, 2020). Defining baseline conditions for wetland state is particularly challenging because baselines need to be developed for each type of wetland spanning spatial and temporal ranges (Mahoney et al. 2023).

With the exceptions of bogs, which are fed by precipitation, and wetlands underlain by low permeability substrates, most wetland types in the AOSR are reliant on groundwater discharge for their water balance (Volik et al. 2020; Devito et al. 2012). The most abundant wetlands are fens, which can be connected to regional-scale groundwater flow systems at topographic lows where coarse-grained sediments are sufficiently thick (Smerdon et al. 2005; Devito et al. 2012), and connected to local-scale groundwater flow systems in other hydrogeological settings, rendering them more susceptible to water level fluctuations from changes in precipitation-driven recharge (Elmes and Price 2019). Up to 50% of wetlands in an area that roughly corresponds with the NAOS were disturbed by anthropogenic effects, with the highest proportional disturbance occurring within fens (Chasmer et al. 2021).

There is a regional dataset of wetland water balance data collected from 509 shallow open water wetlands from the AOSR and Cold Lake areas between 2009 and 2018, conducted in co-operation with the Alberta Biological Monitoring Institute (ABMI) (Gibson et al. 2022). Isotope mass balance classifications for those open water wetlands show a range of water balance conditions and sensitivities to seasonal volume changes, degree of groundwater reliance and throughput (Gibson et al. 2022). Reduced groundwater inputs, identified in wetlands above the bitumen zone compared to the larger reference areas, is consistent with the presence of impermeable Cretaceous shales and bitumen impregnated rock reducing connectivity with underlying aquifers (Barson et al. 2001; Birks et al. 2019). Similar to lakes, repeat sampling of wetlands can be used to identify changes in wetland water balance using isotope mass balance techniques, but approaches to better identify the contributions of groundwater discharge to the water balance of the wetland still need to be evaluated. Numerical models can be used to evaluate the role wetlands play in the overall water balance boreal hydrology on the watershed (Kompanizare et al. 2018) and basin scales (Hwang et al. 2018).

4. Gaps, opportunities, and challenges

The preceding summary of our current understanding of the stressors, mechanisms, and the current ability to identify groundwater and groundwater discharge response relative to baseline has highlighted some knowledge and data gaps, opportunities and challenges for oil sands groundwater research and monitoring programs.

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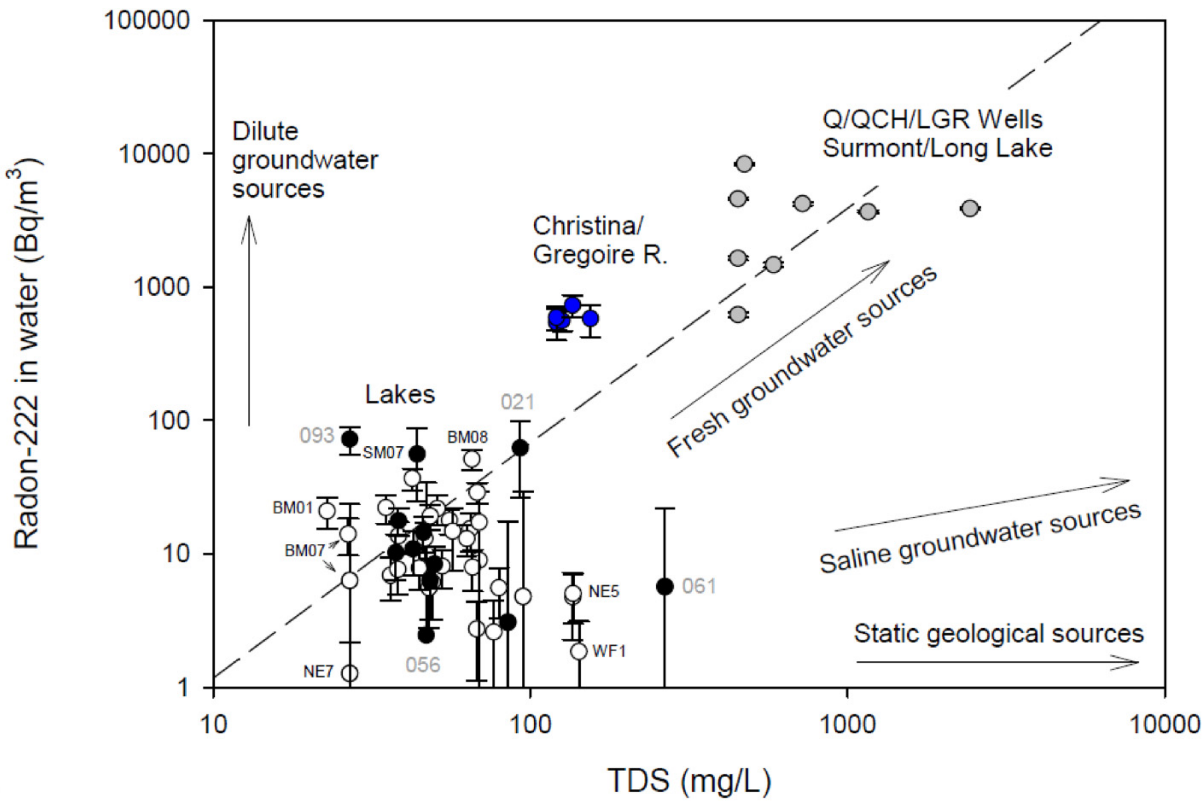
Fig. 7. Radon-222 and TDS relationships for selected RAMP lakes, south Athabasca oil sands survey lakes and the Christina/Gregoire R. and groundwater sampled near the Surmont and Long Lake leases from Quaternary (Q) and Lower Grand Rapids (LGR) wells (Data compiled from Schmidt et al. 2010; Birks et al. 2019 and unpublished data, InnoTech Alberta). Arrows indicate mxing trajectories expected for lakes compared to various radon/TDS sources.



4.1. Knowledge gaps related to stressors and mechanisms

From our review of EIAs, published literature and grey literature we have identified some stressors where there is insufficient understanding of the groundwater mechanisms to be able to determine what the temporal and spatial extent of groundwater response will be. Identifying the monitoring needs and assessing the potential risks to groundwater from these stressors are limited without this information.

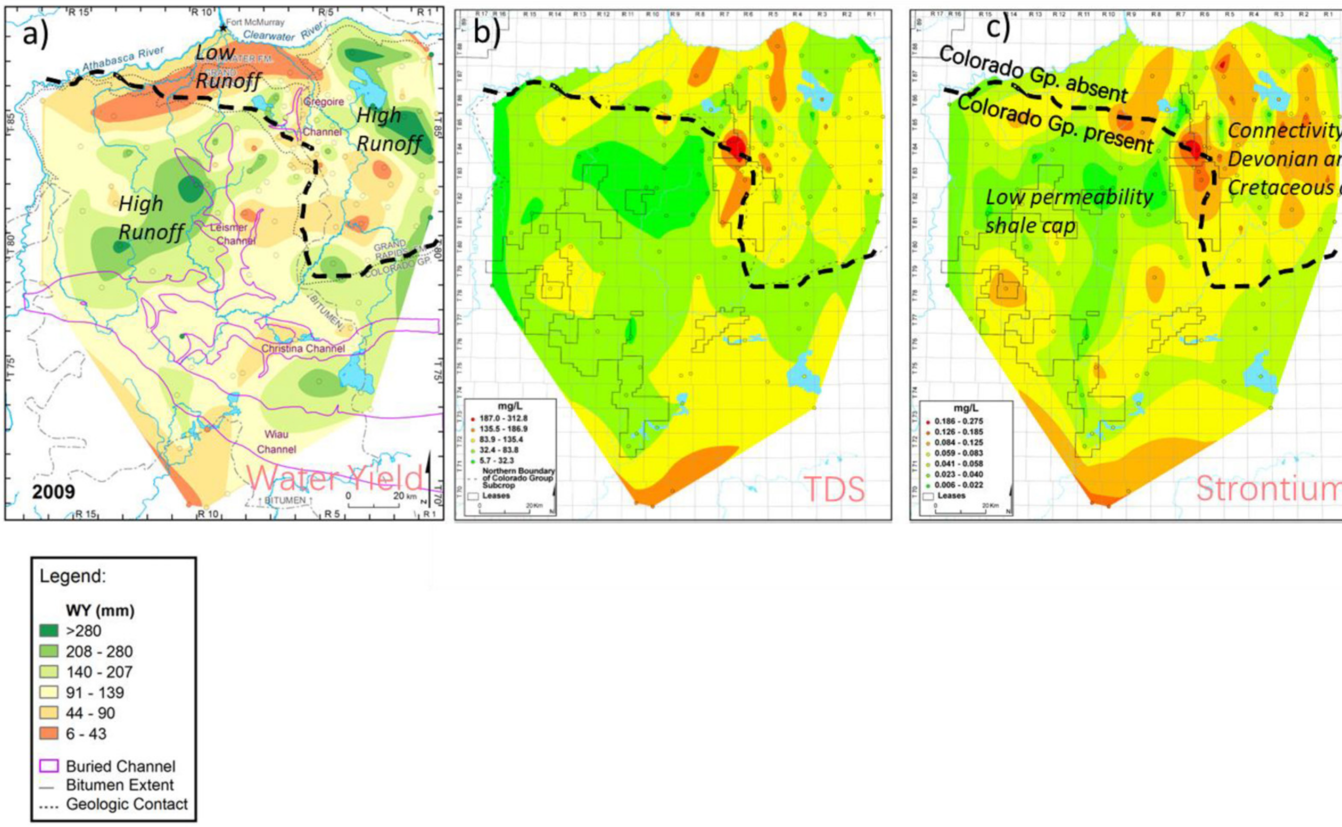
4.1.1. Surface uplift due to thermal operations

Surface uplift wasn't identified as a priority groundwater stressor based on perceived risk but is one where there is not much data available on the associated groundwater mechanisms, particularly whether there will be changes in the hydraulic properties of aquifers due to the short- and long-term uplift and subsidence cycles associated with thermal operations. Surface uplift, or ground deformation, has been detected above the steam chamber in the vicinity of CSS and SAGD operations, (Collins 2007) and near injector wellheads (Pearse et al. 2014). The uplift is typically more pronounced at CSS operations where thermal expansion and high injection pressures create uplift, compared to SAGD operations where thermal expansion is the main cause (Pearse et al. 2014). At both types of operations surface uplift is expected to last for the duration of active steaming; after which net subsidence is expected once the reservoir cools (Pearse et al. 2014). The measurements of surface uplift currently available indicate relatively small displacement, <30 cm (Stancliffe and van der Kooij 2001). Ground deformation data in the vicinity of thermal operations can be used to infer changes in subsurface integrity but assessing changes in subsurface integrity over the duration of CSS operation has been limited by the lack of pre-development ground deformation data for the older operations with the greatest uplift (Samsonov 2017). Developing time-series of subsurface integrity estimates, or field measurements of hydraulic conductivity pre-and post-development are needed to evaluate the potential changes to groundwater flow system.

4.1.2. Thermal effects on groundwater flow and quality

Research opportunities in this area are mainly related to temporal and spatial extent of heat dissipation and geochemical effects. The geochemical processes leading to the release of naturally occurring metals such as arsenic during aquifer heating are fairly well understood, but the controls on release of organics and gases (Moncur et al. 2015*a*), and the reversibility of metal sorption when elevated temperatures decline to ambient conditions (Van Breukelen and Bonte 2016) are not as well known. Conductive heat transfer primarily impacts the area adjacent to injector wells causing alterations

Fig. 8. Contour maps based on kriging of lake isotope mass balance results and geochemistry for SAOS lakes sampled in 2009. Selected results are shown including: (*a*) water yield to lakes (mm/yr), (*b*) TDS (mg/L) and (*c*) strontium (mg/L) (modified from Gibson et al. 2019*b*, unpublished data, InnoTech Alberta).



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in flow (e.g., convective effect due to transfer of heat and density gradient) and potentially altering our ability to predict plume migration and design effective monitoring within that vicinity (Additional information in Supplemental Information S3.6). The effects seem to decrease further downgradient where groundwater temperatures decrease and where intervening clay units and aquitards are present. Better understanding of spatial and temporal extent of effects within formations typically affected by heating will improve predictions about the fate and transport of constituents of concern which can be used to design improved monitoring networks and improve evaluation of environmental risk. There will be an opportunity to evaluate the site-scale groundwater temperature and quality monitoring data generated by the directive (Assessment of Thermally-Mobilized Constituents in Groundwater for Thermal In Situ Operations, AEP 2018) across the AOSR to assess the potential for regional cumulative effects on aquifers used as domestic water sources as well as on downgradient aquatic ecosystems.

4.1.3. Cumulative effects of landscape disturbance and reclamation

The life cycle of a surface mining operation includes the initial removal of muskeg and surficial aquifers, pit construction and operation of the mine, followed by construction of the reclaimed landscape. Widespread alteration of topography and hydraulic properties of the surficial aquifers are expected over the lifecycle of the mine, which can alter recharge, groundwater flow and the discharge of groundwater to wetlands and surface waters. The cumulative effects of this series of landscape disturbances on the quantity and quality of groundwater and groundwater discharge are not known and represent a significant knowledge gap and research opportunity.

Predicting shallow groundwater flow in heterogeneous landscapes with abundant peat has unique challenges due to its compressibility and depth- and moisture-dependent properties compared to common porous media (Waddington et al. 2015; Volik et al. 2020). However, understanding flow in peatlands is important for understanding the watershed scale impacts of land disturbances and for designing reclamation landscapes. Peatlands, which form 50% to 60% of the AOSR (Vitt et al. 2000; Rooney et al. 2012) have been shown to limit subsurface flow and water table drawdown, allowing stabilization of water table depths even in moisture limited settings. Other influential properties include peat deformation (Morris et al. 2011), moss surface resistance (e.g., Price et al. 2009), and moss productivity (e.g., Thompson and Waddington, 2008), which tend to provide negative feedback on water level variations.

Recent soil moisture modelling has shown how local-scale variability in material properties influences recharge (Sutton and Price 2020*a*, 2020*b*). The implications of local-scale

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variability in material properties on groundwater recharge and subsequent translation to larger spatial scales still needs to be assessed. Volik et al. (2020) noted the limited number of studies that address the potential long-term changes to groundwater recharge in watershed in the AOSR (Hwang et al. 2018), with respect to fens connected only to local groundwater flow systems, but this knowledge gap is also a limitation in our ability to predict the potential impacts to the water balance of other groundwater dependent ecosystems. Upscaling from site to regional scale for hydrological analysis and cumulative effects assessment, is one of the major challenges for wetland hydrology in Canada. The role that wetlands play in the overall water balance of boreal watersheds has been addressed in groundwater surface water modelling studies on watershed (Kompanizare et al. 2018) and basin scales (Hwang et al. 2018) but the cumulative effects of changing the proportion, type and distribution of wetlands through the lifecycle of oil sands mine development and closure have not been modelled. There is opportunity to make better use of the advances in numerical modelling to help predict how the cumulative impacts of oil sands activities may impact groundwater and groundwater discharge to aquatic ecosystems and to use remote sensing products (Chasmer et al. 2020*a*, 2020*b*) to improve understanding and monitoring of the cumulative impacts of landscape disturbance.

4.2. Challenges and opportunities in identifying groundwater response

4.2.1. Monitoring approaches for groundwater discharge quantity and quality

By far the largest monitoring and knowledge gaps and opportunity areas are related to improved characterization of the quantity and quality of groundwater discharge, including the location of groundwater discharge areas, and their relevance to receiving ecosystems. Measuring groundwater discharge to lakes, rivers and wetlands is challenging to execute due to temporal and spatial heterogeneity of discharge. Depending on the depth to which the river is incised they can intercept groundwater discharge from shallow and deep groundwater flow systems, and can include groundwater-fed springs, seepage from riverbanks, seepage from adjacent wetland areas as well as baseflow from aquifers (Brunner et al. 2017). Methods to identify groundwater discharge to rivers such as terrain conductivity surveys (i.e., EM31), reach water balance, geochemical and isotope hydrograph separation techniques and radon surveys have not yet been applied systematically across the region. Isotope-based hydrograph separations have been conducted on data from the Athabasca River, and some tributaries in the NAOS, providing watershed-scale estimates of groundwater contributions (Gibson et al. 2016*a*). However, similar discharge and isotope datasets are not available for rivers in other parts of the AOSR or Cold Lake Region. Refinements in integrated groundwater surface water numerical models have improved our ability to predict how changes in climate and groundwater withdrawals might affect groundwater flow, and groundwater discharge to terrestrial and aquatic ecosystems (EarthFX 2016; Hwang et al. 2018). The limited temporal and spatial availability of groundwater discharge quantity and quality data has made establishing baseline and its variability challenging. A combination of hydrometric, thermal imaging (Conant 2004), and tracer techniques for characterizing saline groundwater (i.e., terrain conductivity, geochemical signatures), and non-saline groundwater contributions, such as radon-222 (Cartwright and Gilfedder 2015), that also incorporates Indigenous Knowledge would provide a more comprehensive assessment of groundwater discharge contributions. Synthesizing data from the many sub-regional scale investigations on groundwater discharge to lakes, rivers and wetlands (Table 1) into regional maps of groundwater dependent ecosystems would help better facilitate monitoring of these areas as has been done in other jurisdictions (Australia; Doody et al. 2017; Nevada; Nature Conservancy Nevada 2019; California; Klausmeyer et al. 2018; Rhode et al. 2024).

An important opportunity area is using the growing availability of remote sensing products to improve our ability to monitor shallow groundwater and groundwater discharge as a step towards regionalizing monitoring of shallow groundwater resources. This is particularly true for scaling up wetland data, where remote sensing data have been able to map wetland area and abundance, vegetation characteristics, climate variables (Mahoney et al. 2023) and the water table (Rahman et al. 2017). The many field investigations that have been conducted in boreal catchments have contributed to growing understanding of the mechanisms controlling the quantity and quality of groundwater discharge to wetlands, lakes, and rivers, but monitoring to establish baseline conditions and obtaining data for change detection is challenging because of the scale of the region, and because of the potential for cumulative water balance effects to occur downgradient of the stressor. Data from the Gravity Recovery and Climate Experiment (GRACE) has been evaluated as a tool to estimate groundwater storage in Alberta (Huang et al. 2016; Bhanja et al. 2018). The GRACE data had good correlation with measured water levels in the southern portions of Alberta, but there was poor correlation between measured groundwater level data and the predicted groundwater storage in the AOSR, indicating a need for improved land surface modelling for boreal terrains (Huang et al. 2016). Multi-date synthetic aperture radar (SAR) imagery, combined with LiDAR-derived topography have been used to estimate water level variations in wetlands to improve wetland characterization (LaRocque et al. 2020), and this approach combined with thermal imaging may be useful for monitoring changes in groundwater discharge to wetlands.

4.2.2. Methods to identify OSPW Constituents in receiving environments

Definitive detection of OSPW derived constituents of concern in surface waters remains a major research challenge owing to high dilution factors and confounding signals from natural sources of bitumen present near surface, but it is becoming evident that no individual mass spectrometry-based analytical method can be used to unequivocally

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identify OSPW. Field studies at sites where OSPW plumes have been identified in groundwater (Gervais 2004; Holden et al. 2011; Hunter 2001; Oiffer et al. 2009; Savard et al. 2012; Yasuda et al. 2010), pilot experimental tailings ponds (Abolfazlzadehdoshanbehbazari et al. 2013), and laboratory experiments (Holden et al. 2011, 2012 and 2013) have provided understanding of the geochemical processes that will control the fate and transport of many OSPW constituents of concern in groundwater, but there are still knowledge gaps related to the transport and conservativeness of organic acids present in OSPW. Laboratory and field studies have shown that biodegradation of naphthenic acids can occur in groundwater environments (Ahad et al. 2018, 2020; Lv et al. 2020), but resampling of naphthenic acid in groundwater plumes has not identified significant decreases in naphthenic acid concentrations that can be attributed to biodegradation (e.g., MLSB plume Oiffer et al. 2009 and Hewitt et al. 2020). Monitoring the migration and composition of known OSPW plumes over time would provide better understanding of the long-term fate and transport of naphthenic acids and other constituents of concern and may help better identify the compounds that would be expected in OSPW discharging to receiving environments.

The most promising areas of research for OSPW identification and tracking appears to be a multi-tracer approach that combines high resolution profiling of the organic components with geochemical and isotopic measurements, and incorporates information about the hydrogeological setting, and site history (e.g., spatial and temporal characterization of both OSPW, groundwater, and surface water) (CEC 2020).

4.3. Community-based monitoring and braiding western science and indigenous knowledge

A key component to understanding environmental changes in oil sands regions is to develop a comprehensive evidence-based monitoring approach that incorporates Indigenous Knowledge, along with western science to identify potential impacts to groundwater from oil sands activities, particularly those that are of concern for Indigenous Communities. Traditional land use and Indigenous Knowledge can be a valuable source of information on predevelopment groundwater and groundwater discharge conditions. Given the long-time scales over which groundwater flow systems operate, there is a potential for Indigenous Knowledge to include intergenerational observations that can extend our estimates of baseline conditions beyond existing data and provide information about of its variability. A pilot program to inventory Indigenous Knowledge in the MacKay River Watershed identified many traditional land use activities and Indigenous Knowledge that could be used to provide qualitative or quantitative information about groundwater including: observations about surface water levels (e.g., recreation and navigation routes), indicators of groundwater discharge (e.g., salt licks, saline sloughs, bitumen outcrops, wetlands, surface waters that remain unfrozen, fish habitats) (Birks et al. 2021). In other jurisdictions groundwater Indigenous Knowledge and community-based monitoring has been very successful in providing reliable data on groundwater levels across broad regions lacking in western science monitoring locations (e.g., Clark and Brake 2009; Lightfoot 2012; Shemsanga et al. 2018). Indigenous Knowledge and community-based monitoring have been incorporated into the Mackenzie River Basin monitoring program that includes the Athabasca River (Parlee et al. 2021) and has demonstrated the usefulness of participatory community-based monitoring using indicators based on Indigenous Knowledge. There appear to be rich datasets of Indigenous Knowledge related to groundwater discharge that can be incorporated with western science results to improve our understanding of predevelopment conditions, variability for groundwater discharge quantity and quality and identify changes.

4.4. Separating climate change and other non–oil sands effects

Many of the potential oil sands stressor groundwater responses can also occur as a result of non–oil sands and natural stressors. For example, non–oil sands landscape disturbances cover ∼15% of the oil sands region and oil sands disturbances cover ∼1% (ABMI 2024). Forest fires are a natural stressor common in the region and they are expected to be more frequent in boreal regions with future climate warming (de Groote et al. 2013; Walker et al. 2019). Forest fires can result in changes in some hydraulic properties of organic soils, such as water repellency, infiltration and evapotranspiration (Elmes et al. 2019; Ireson et al. 2015) which can affect the post-fire hydrology (Lukenbach et al. 2017). Whether these changes are reversible is not yet clear, but they appear to depend on oil properties, hydrogeological and hydrometeorological conditions and type of fire and thus can be very site-specific (Kettridge et al. 2021; Volik et al. 2023). Comparison of pre- and post-fire groundwater contributions to streamflow in non-boreal regions have found that forest fires cause significant changes to shallow groundwater discharge (Rey et al. 2023). Improved understanding of forest fire impacts to groundwater recharge, flowpaths, and consequences for the quality and quantity of groundwater contributions to streamflow are needed for boreal regions.

Better understanding of how climate change will impact recharge, groundwater flow, and groundwater discharge is needed so that impacts to groundwater from oil sands activities can be separated from those expected due to changes in temperature, precipitation (timing and amount) and evapotranspiration due to climate change. Regional scale groundwater surface water modelling has identified the importance of peatlands in controlling water availability to surface water systems by reducing the water loss through evapotranspiration (Hwang et al. 2018). This modelling used a range of accepted climate forcing scenarios and predicted that the region will experience generally wetter conditions, but that increases in actual evapotranspiration will result in shallower water tables (Hwang et al. 2023). Despite decreases in the groundwater contributions to streamflow, the model predicts that streamflow changes will be offset by increases in precipitation and surface runoff (Hwang et al. 2023), which may complicate efforts to identify impacts to ground-

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water and groundwater discharge from oil sands activities. On the watershed scale, the effects of climate change on the hydrological connectivity in the surface mining area have also been evaluated using a semi distributed surface water groundwater model (GSFLOW) which predicted that under warmer wetter climate scenarios the growing season ratio of precipitation to actual evapotranspiration will not change significantly as increases in precipitation are offset by increased evapotranspiration (Kompanizare et al. 2018).

Areas within the northern portion of the AOSR are undergoing active permafrost degradation (Vitt et al. 2000) and the contribution of permafrost thaw has been identified as a significant source of water to some headwater, boreal lakes (Gibson et al. 2015). This degradation will be accelerated under a changing climate and will potentially amplify predicted changes in landscape (e.g., loss of forested lands, increases in long-term net organic matter accumulation). There are challenges in quantifying permafrost extent but using the Pawley and Utting (2018) permafrost dataset areas of discontinuous permafrost were mostly found in scattered areas of the NAOS, with a few HUC8 watersheds having >2% of the land identified as permafrost. Eventual depletion of permafrost stores is expected to result in reduced surface runoff (potentially increasing local groundwater recharge), more negative water balances for wetlands, lakes and rivers, and significant changes in water quality and acidification potential for regional water resources in general. Bog and fen collapse due to permafrost thaw are also associated with enhanced groundwater interaction, which may also lead to mobilization of large stores of carbon and nutrients to nearby waterbodies through increased hydrologic connectivity (Gibson et al. 2019*a*). Such factors have likely impacted geochemistry of lakes and may be contributing to recently observed pH increases (Castrillon-Munoz et al. 2022).

5. Conclusions

The conceptual models relating groundwater stressors to potential groundwater responses from oil sands surface mining and in situ activities (Figs. 3 and 5) have provided a framework for categorizing our current state of understanding on the potential risks to groundwater and perspective on future research and monitoring needs in the oil sands regions of Alberta, Canada. There are some stressors where a lack of mechanistic understanding limits our ability to predict temporal and spatial scale of potential groundwater responses, and all of the potential cumulative impacts arising from these activities. For example, surface uplift in the vicinity of in situ thermal operations has been observed, and most of the literature on this topic has been on methods to identify this stressor, but little is known about how uplift may impact hydraulic properties of aquifers, recharge and runoff characteristics. Similarly, recent advances in understanding wetland hydrology in peatlands have provided better understanding of the role reclamation design plays in the hydrology of the landscape and transfer of solutes between landscape units. However, long-term predictions on how the water balance of catchments will evolve through the entire lifecycle of exploration, development, mining, reclamation and closure and whether the materials used to construct the new landscapes will affect groundwater quality are still knowledge gaps. Currently there are no unequivocal methods for detecting bioaccumulation, bioamplification and transmission of oil sands related contaminants through ecological receptors and the identification and location of groundwater dependent ecosystems is still in a preliminary stage.

Identifying shifts in the state of quantity and quality of groundwater and groundwater discharge requires long-term monitoring of the appropriate indicators at relevant locations to inform understanding of baseline conditions and variability. Baseline conditions for groundwater quantity and quality are well established at individual oil sands operations, but there is a need for an equivalent understanding of baseline conditions for the quantity and quality of groundwater discharge to surface waters. The spatial and temporal variations in groundwater discharge makes these parameters challenging to monitor on relevant scales, and there is a need for systematic compilation of existing data, as well as greater use of remote sensing products and integrated groundwater surface water models as a step towards regionalizing monitoring of shallow groundwater resources. Data compilation and synthesis at a regional scale complemented with Indigenous Knowledge and indirect methods to infer groundwater discharge to surface waters that have been piloted at local scales (e.g., integrated groundwater surface water models, remote sensing, hydrograph separation, geochemical and isotopic indicators of groundwater discharge) may assist in delineating potential groundwater discharge areas and dependent ecosystems for future confirmation.

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Data availability

This review was based on data from the peer-viewed literature as well as review of Environmental Impact Assessments which are publicly available at: ftp://ftp.gov.ab.ca/env/fs/EIA/.

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Competing interests

The authors declare there are no competing interests.

Supplementary material

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