Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Groundwater monitoring near oil sands development: Insights from regional water quality datasets in the Alberta Oil Sands Region (AOSR)

S. Jean Birks[a,f,*], John Manchuk[c], Yi Yi[d,g], Cynthia N. McClain[e,f], Michael C. Moncur[a,h], John J. Gibson[b,g], Clayton V. Deutsch[c], Emily B. Taylor[a], Guy Bayegnak[d]

[a] *InnoTech Alberta, Calgary, AB, Canada*
[b] *University of Victoria, Victoria, BC, Canada*
[c] *Centre for Computational Geostatistics, University of Alberta, Edmonton, AB, Canada*
[d] *Alberta Environment and Parks, Edmonton, AB, Canada*
[e] *Alberta Environment and Parks, Calgary, AB, Canada*
[f] *University of Calgary, Calgary, AB, Canada*
[g] *InnoTech Alberta, Victoria, BC, Canada*
[h] *University of Saskatchewan, Saskatoon, AB, Canada*

ARTICLE INFO

Keywords:
Groundwater quality
Oil sands
Temporal anomalies
Groundwater monitoring
Geochemistry

ABSTRACT

Study region: This study is carried out across a 142,000 km^2 area within the Alberta Oil Sands Region (AOSR), Alberta, Canada.
Study focus: Groundwater quality data for the AOSR are compiled and interpreted to provide information on regional water quality to inform groundwater monitoring and land use planning. A database of 546 water quality parameters measured between 1958 and 2015 from 5118 water wells is compiled, cleaned, and analyzed by hydrostratigraphic unit (HSU).
New hydrologic insights for the region: Baseline water quality conditions were found to vary in the 12 main HSU's, with wide ranges in total dissolved solids and geochemical facies, reflecting variable lithology and geochemical processes. Median concentrations for multiple parameters exceeded "interim trigger values" under consideration by government regulators. Statistically significant temporal changes in water quality were detected in the 2000's in isolated areas of Surficial Sands aquifer, the Cretaceous and Devonian formations in the North Athabasca Oil Sands, and in Quaternary aquifers in the South Athabasca Oil Sands and Cold Lake Beaver River. Temporal anomalies occur in areas with enhanced vertical connectivity due to the presence of buried channels, incised rivers, or where the Colorado Group is thin or completely absent. The compiled dataset highlights the role of geochemical data in identifying aquifer connectivity and monitoring priority. Lack of publicly available data for key aquifers near some mining areas are noted.

* Corresponding author at: InnoTech Alberta, Calgary, AB, Canada.
E-mail address: jean.birks@innotechalberta.ca (S.J. Birks).

https://doi.org/10.1016/j.ejrh.2022.101079
Received 30 November 2021; Received in revised form 8 March 2022; Accepted 4 April 2022

1. Introduction

The Alberta Oil Sands Region (AOSR), which comprises an area of 142,000 km^2 located in the boreal forest of northeastern Alberta, constitutes the largest energy reserve in Canada and third largest in the world, with over 165 billion barrels of proven bitumen reserves (Canadian Association of Petroleum Producers (CAPP), 2018). The AOSR is comprised of three regulatory districts established by the Alberta Energy Regulator (AER), including Athabasca, Cold Lake - Beaver River (CLBR), and Peace River regions. While a significant energy resource for the country, there is a recognized need to ensure that current and future development of the petroleum resources do not pose significant risk to surface and groundwater quantity or quality. As a critical component of the hydrological cycle, groundwater supports a variety of ecosystems, called groundwater dependent ecosystems (GDEs), such as wetland fens, i.e., the dominant land cover type in the AOSR (Volik et al., 2020), rivers, i.e., groundwater provides > 40% of flow to tributaries on the east bank of the lower Athabasca River (Gibson et al., 2016), lakes, i.e., groundwater provides 5–20% of input to small headwater lakes (Schmidt et al., 2010), and riparian zones. Groundwater also directly affects the health of humans in the AOSR where it is used for domestic water supply, and indirectly through human reliance on fish, waterfowl, berries, plants, and mammals harvested from GDEs.

As part of Alberta's efforts to ensure more sustainable development of oil sands resources, Groundwater Management Frameworks (GWMF) have been developed under the Lower Athabasca Regional Plan (LARP) for three sub-regions, North Athabasca Oil Sands (NAOS), South Athabasca Oil Sands (SAOS) and Cold Lake Beaver River (CLBR) (Fig. 1), with an overall objective to understand groundwater conditions in the oil sand regions and facilitate the evaluation of cumulative effects of development (Alberta Environment and Parks (AEP), 2013a, 2013b, 2013c, see also WorleyParsons, 2010a; WorleyParsons, 2009a). The importance of monitoring, evaluating, and reporting on potential impacts of oil sands development has prompted formation of a provincial-federal Oil Sands Monitoring (OSM) program funded by industry, and jointly designed, implemented and overseen by Environment and Climate Change

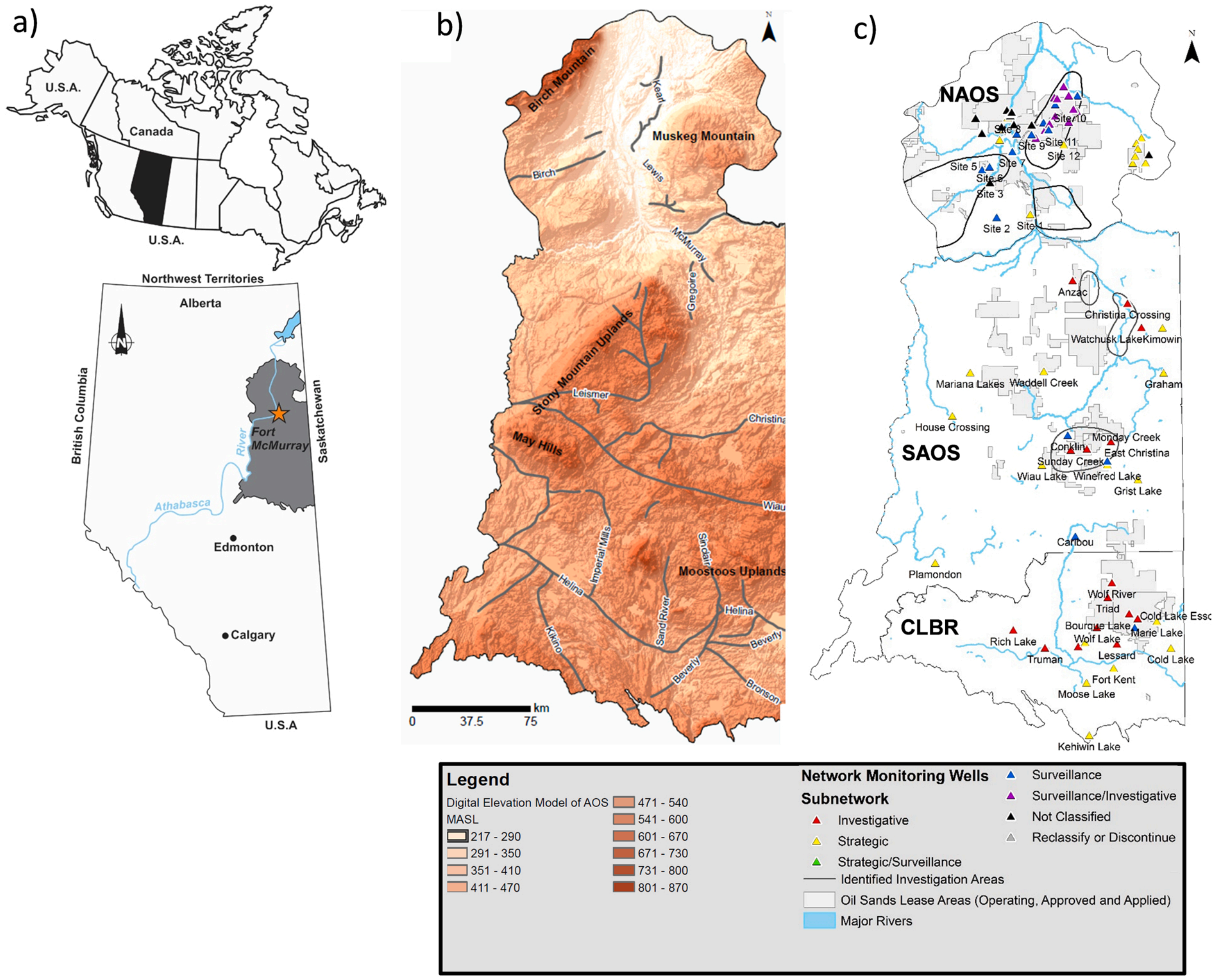

Fig. 1. a) The AOSR (grey shaded area) is located in northeastern Alberta. b) Topography of the AOSR, with thalwegs of buried valleys shown. C) Outlines of operating approved and applied-for oil sands lease areas, with existing oil sands monitoring wells (MWs). MW are color coded to indicate whether they are investigative, strategic or surveillance. Boundaries for the North Athabasca Oil Sands (NAOS), South Athabasca Oil Sands (SAOS) and Cold Lake Beaver River (CLBR) areas are shown. Peace River region is not shown.

Canada and Alberta Environment and Parks. The program is mandated to include integrated reporting and regular assessment of environment condition to inform ongoing policy and management decisions (Government of Alberta, 2017). One of the aims of OSM was to implement an adaptive management strategy by developing a perspective of baseline conditions based on water quality indicators and establishing a set of decision-making triggers and limits that could be acted upon in cases where deleterious changes to the natural system are detected (see Nie and Shultz, 2012).

The first phase of comprehensive groundwater monitoring in the oil sands region was initiated in 2009 and has proceeded annually,

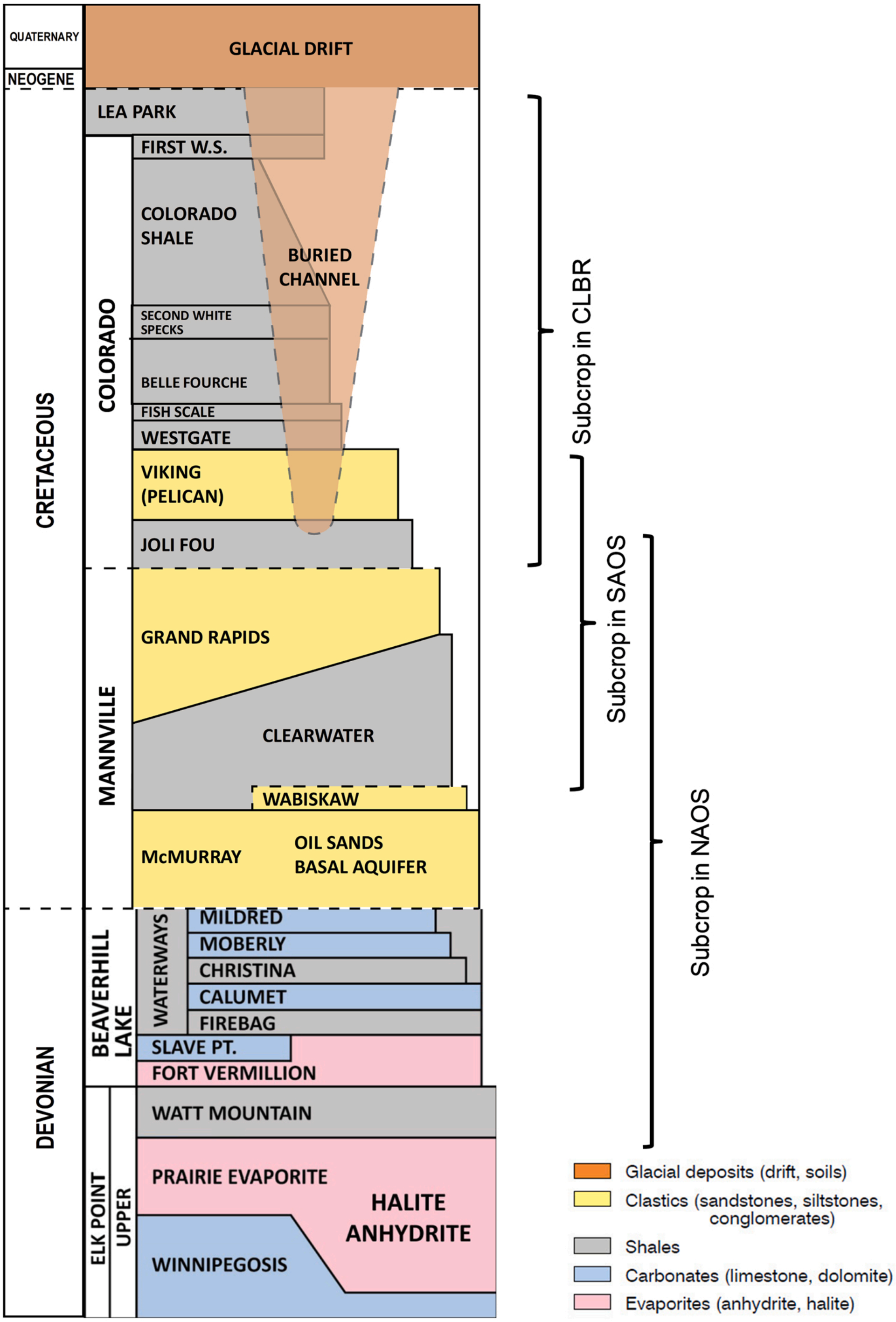

Fig. 2. Simplified stratigraphic column showing the entire sedimentary sequence present in the AOSR with text indicating the subcrop in each of the three major oil sands regions.

amassing a significant monitoring dataset from monitoring wells (MWs) situated in the various sub-regions (WorleyParsons, 2010c; WorleyParsons Canada Ltd, 2011; Integrated Sustainability, 2013a; Matrix Solutions Inc (Matrix), 2014b, 2015a, 2013, 2014a, 2015b). As recommended in a 2015 scientific review (GW Solutions, 2015), compiling these datasets to form a regional dataset accompanied by an improved interpretation of regional groundwater quality were recognized as important steps to advance the current understanding of groundwater characteristics, variability, and vulnerability across the AOSR. Specific recommendations of the scientific review included: interpretation of existing data in the context of proximity to development, hydrogeological setting, and natural variability, to facilitate a rigorous evaluation of the monitoring plan, and to make recommendations for future monitoring. Prior studies have been motivated by specific interests such as: (i) developing conceptual models of groundwater flow and vertical connectivity (Birks et al., 2019; Hackbarth and Nastasa, 1979; Ozoray, 1974;), (ii) establishing baseline water quality values for different management areas (NAOS; WorleyParsons, 2010a; Alberta Environment and Parks (AEP), 2013a; SAOS: WorleyParsons, 2009; Alberta Environment and Parks (AEP), 2013b; CLBR: Lemay et al., 2005; Alberta Environment and Parks (AEP), 2013c), (iii) investigation of specific water quality concerns (e.g. arsenic, Moncur et al., 2015a), and (iv) synthesis of springs and groundwater discharge water quality (Grasby and Chen, 2005; Birks et al., 2018; Gibson et al., 2013; Gue et al., 2015; Ellis and Jasechko, 2018). However, a regional synthesis of water quality data from aquifers spanning the entire region has yet to be conducted.

The objective of this study was to compile groundwater quality data available for CLBR, NAOS, and SAOS into a combined AOSR dataset, to interpret the new dataset in the context of conceptual hydrogeological models that describe potential impacts from mining and in situ oil sands activities across the region, and to use the new combined AOSR groundwater quality dataset to evaluate the efficacy of the current groundwater monitoring program. The groundwater quality dataset was compiled and is used for the following purposes: (i) to characterize the geochemical composition of each of the hydrostratigraphic units to better understand the variability of parameters across the AOSR, (ii) to compare the range and variability of parameters in the hydrostratigraphic units to interim triggers proposed by GWMF LARP, and (iii) to assess whether baseline results identify geochemical anomalies indicating vertical connectivity between aquifers that might require additional monitoring efforts. The new regional dataset arising from our analysis is found to have many potential applications for water management in the region. As we show, it can be used to improve conceptual hydrogeological models for the area, and demonstrates approaches to augment traditional groundwater monitoring in data-sparse areas through statistical methods and using geochemical data to identify potential aquifer vulnerability.

2. Study area

2.1. Oil sands activities

Economic bitumen deposits are largely emplaced within the Cretaceous McMurray Formation, situated at the base of Mannville Group strata (Fig. 2). Depth to the bitumen layer is the main determinant of whether surface mining or in situ methods are used, the latter being required at depths below surface of greater than 75 m. A range of specific impacts are associated with each type of extraction (see S1. Supplementary material). Mining impacts within the NAOS include dewatering of overburden, depressurization of the basal McMurray aquifer around the mine pits, storage of tailings, and disturbance to the landscape during development, and eventually during reclamation. Depressurization of the basal McMurray aquifer is needed for mine stability during excavation and reductions in hydraulic head in the McMurray and overlying Quaternary aquifers (Fig. 2) may result in decreased groundwater contributions to some wetlands, tributaries and the main stem of the Athabasca River during the operational period. These changes in hydraulic head could also alter groundwater flowpaths which could impact groundwater quality by changing the mixing between fresh and saline aquifers. Numerical groundwater modeling of the hydraulic head response in aquifers adjacent to surface mining over the duration of mine development, operation and reclamation predict recovery to pre-development levels after pumping for dewatering and depressurization is stopped (e.g. Frontier Project; Teck, 2011). Potential leakage of contaminated process water containing elevated organic contaminants and metals from tailings ponds is another potential threat to groundwater quality. Water supplies for surface water operations are primarily obtained from the lower Athabasca River although some basal McMurray dewatering sources are also in use.

In-situ extraction methods are typically used in areas where the McMurray Formation is present at greater than 75 m depth, including parts of the NAOS, and across the SAOS and CLBR areas (Fig. 2). Bitumen is immobile at reservoir temperatures, however when heated to 200 °C, it approaches the viscosity of water. Enhanced thermal recovery methods (e.g., steam assisted gravity drainage, SAGD or cyclic steam stimulation, CSS) are used to increase the temperature of the bitumen to decrease its viscosity. Where oil sands are extracted using steam injection, groundwater is used for steam production, typically 0.4–0.5 m^3 of water per m^3 of bitumen produced (Hrudy et al., 2010). The majority of this water is withdrawn from permeable Cretaceous sandstone formations (Fig. 2), with supplementary quantities taken from relatively deep unconsolidated sand and gravel deposits (Matrix, 2012). Heating of aquifer sediment adjacent to the injector wells can result in the release of metals and organics present naturally in the sediment, both of which have the potential to affect groundwater quality in the immediate vicinity of operations.

2.2. Geological and hydrogeological setting

The terrain of the AOSR region is characterized by low-lying plains (~ 550 masl) and adjacent broad, rolling uplands (~ 700 masl) (Andriashek, 2003) (Fig. 1a). In this boreal forest ecosystem where > 50% of land cover is wetlands, and the majority of those wetlands are fens that are sustained by groundwater (Alberta Environment and Parks (AEP), 2018), large accumulations of peat and recent soils (formed since the final retreat of the continental ice sheets around 10,000–15,000 years ago) make up the region's surficial deposits.

Surficial unconsolidated sediments, also known as drift, are comprised of tills, lacustrine clays, and fluvial sands and gravels of glacial and pre-glacial origin, typically ranging from 10 to 30 m thick. Note that drift deposits can exceed 100 m or more in deeply incised pre-glacial and glacial channels eroded into bedrock (Fig. 1a) (Andriashek, 2003). The thickness of the Quaternary aquifers increases towards the south, and in the SAOS and CLBR there are thick sequences of Neogene and Quaternary sediments. The Quaternary aquifers in the CLBR are well characterized across this region include alternating aquifer and aquitard units intersected by a network of pre-glacial and glacial buried channels (Parks et al., 2005). In the CLBR, the following Quaternary HSU's are used for domestic supply: Grand Centre, Sand River, Marie Creek, Ethel Lake, Bonnyville, Muriel Lake, and Empress (Parks et al., 2005).

Bedrock units are comprised mainly of lower Cretaceous formations resting unconformably on upper Devonian-aged units (Fig. 2). The sedimentary sequence dips to the southwest so the depth to the McMurray Formation becomes progressively deeper towards the southern portion of the study area and the subcropping units differ between the three oil sands sub-regions (Fig. 2). Thus, rivers within incised river valleys of the AOSR have the potential for diffuse or localized (e.g., springs) interaction with groundwater from formations with different water quality along the river's course. Shale-dominated formations of the Colorado Group cap the aquifers of the Cretaceous Mannville Group, which include, in descending order, the Grand Rapids, McMurray, and Clearwater Formations. These Manville Group aquifers are of particular interest since they are used as industrial, low quality water sources.

The dissolution edge of the deeper Prairie Evaporite Formation of Middle Devonian age forms a prominent structural feature in the AOSR (Broughton, 2013, 2015; Schneider and Cotterill, 2017). Soluble salts (e.g., halite and anhydrite) have been removed in that interval which has led to formation collapse, a reversal in the usual south-west dip on the overlying Mannville Group formations creating a north-easterly dip, and formation of a structural trap for hydrocarbons. These collapse features provide vertical connectivity between the Devonian and the overlying McMurray Formation and are co-located with areas of very high TDS water in the McMurray (Birks et al., 2019; Cowie et al., 2015). The degree of connectivity is influenced by low permeability bitumen deposits in the McMurray Formation, which can act as effective aquitards. Removing this bitumen barrier during operations can increase the potential for saline Devonian groundwater to enter the mine pit (Walker et al., 2017). The potential for cross-formational groundwater flow also occurs near buried channels (Fig. 1b) eroded into, and, in one area through, the underlying bedrock formations as deep as the upper Devonian (Andriashek, 2003).

In general, groundwater flows across the AOSR are topographically controlled, with more localized shallow groundwater flows originating from regional uplands such as the Birch, Muskeg and Stony Mountains and flowing to adjacent lowlands, incised channels and river valleys (Bachu, 1996; Bachu et al., 1993). Regional flow of deep groundwaters within Cretaceous and older strata include deep basin brines, originating at depth within the Western Canada Sedimentary Basin, or glaciogenic brines, originating from glacial waters undergoing pressurized recharge under the ice sheet (Grasby and Chen, 2005). The latter are commonly encountered in springs or seeps along the Athabasca and Clearwater Rivers (see S2. Supplementary material).

2.3. Groundwater monitoring

Groundwater monitoring of various forms has been a recurring activity for decades in the oil sands region (see S3 Supplementary material), although geochemical parameters and operational details have varied somewhat over time. Regional provincial groundwater monitoring efforts unrelated to oil sands development, has included surveys conducted by the Alberta Geological Survey (AGS) and routine water quality monitoring conducted by the Government of Alberta's Groundwater Observation Well Network (GOWN), that was initiated in the 1970s, and continued until the mid-1990s. There was a monitoring hiatus for the GOWN that continued until resumption of surveys in 2008 (CLBR), 2009 (NAOS), and 2012 (SAOS). Groundwater quality data are still available for the hiatus due to site-specific monitoring of groundwater conditions on and adjacent to active leases that oil sands operators were required to conduct to meet Environmental Protection and Enhancement Act (EPEA) conditions. In the CLBR area groundwater is widely used as a source of domestic drinking water so comprehensive groundwater quality data are available from Alberta Health (AH) assessments focused on drinking water quality (Government of Alberta, 2014). However, each of the agencies involved in groundwater monitoring within the oil sands areas (AEP, AER, AH) have operated according to their respective mandates and jurisdictions, and monitoring decisions were generally made to satisfy the specific agencies' own objectives.

Table 1
Summary table of primary, secondary and tertiary water quality indicators as outlines in the GWMF.

Indicators for Mining Operations		
Quality	Primary	pH, redox, total dissolved solids, sodium, chloride, arsenic, ammonia, naphthenic acids.
	Secondary	All other major ions + remaining trace elements, fluoride, dissolved organic carbon, BTEX, phenols, Low Molecular Weight PAHs.
	Tertiary	Stable and radiogenic isotopes
Indicators for In situ Operations		
Quality	Primary	Temperature, redox, total dissolved solids, chloride, silica, arsenic, boron, phenols.
	Secondary	All other major ions + remaining trace elements, naphthenic acids, BTEX, PHC F1 and F2, Low Molecular Weight PAHs.
	Tertiary	Stable and radiogenic isotopes.
Indicators for Other Influences		
Quality	Primary	pH, TDS, chloride, nitrate, BTEX.
	Secondary	All other major ions, trace elements, pesticides, Low Molecular Weight PAHs.
	Tertiary	Stable and radiogenic isotopes.

2.4. Water quality indicators

The types of water quality impacts expected from oil sands activities differs between mining and in situ operations, so the GMWF identified different primary, secondary and tertiary water quality indicators for each region (Table 1). Primary and secondary indicators are measured on all groundwater samples, whereas tertiary indicators are parameters that may be measured as part of investigations to determine the cause of water quality changes. The GMWFs did not recommend specific stable or radiogenic isotopes but $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$ -DIC, $\delta^{34}S$ -SO_4 and $\delta^{18}O$-SO_4, ^{3}H and ^{14}C have been measured on selected oil sands monitoring wells to provide information about the sources and ages of water and solutes. The GMWF identifies two types of thresholds for detecting changes in water quality: triggers, which are early warning signs of negative change from the natural variability in aquifer conditions and limits which are conditions beyond which the potential for impacts is considered unacceptable.

Interim regional groundwater quality triggers were developed for each aquifer in the GWMF using oil sands monitoring well and baseline groundwater data to define upper and lower control triggers for the range of natural variability within each aquifer (Alberta Environment and Parks (AEP, 2012). In addition to these regional triggers and limits, as a part of the GWMF's management system temporal trend analysis on data from individual wells can be used to detect changes in groundwater quality that might occur without exceeding regional triggers or limits. The spatial variability of water quality parameters across each aquifer or aquifer management unit makes selection of a single trigger value for each aquifer challenging (Matrix Solutions Inc (Matrix), 2014a). For this reason, final trigger values and selection of the appropriate approach for establishing these limits (e.g. aquifer-wide limits vs limits for individual wells, or clusters of wells) has been postponed pending improved characterization of baseline conditions for each aquifer.

3. Methods

3.1. Data sources

This study includes compilation and interpretation of two types of groundwater data:

- Oil Sands "Monitoring Well (MW)" data: These data are from groundwater wells that were selected to be part of AEP's Oil Sands regional groundwater monitoring network to support the OSM Program and LARP GWMF. This monitoring network included groundwater wells installed specifically for regional groundwater assessments and oil sands monitoring as well as data from groundwater wells owned by industry who sample and provide the data to AEP.
- "Baseline" groundwater data: This category of data included all other groundwater quality data from groundwater wells located in each of the regions, which were installed and monitored to serve a wide range of applications (e.g., industrial water supply wells, domestic groundwater wells, industry and government owned monitoring wells installed for non-oil sands monitoring programs, data from Environmental Impact Assessments (EIAs), see S4 Supplementary material). For this study, the term baseline refers to the regional AOSR dataset extending from 1958 to 2015, recognizing that some of these data do not represent conditions prior to development.

The Baseline data compiled here were used to evaluate the range of natural variability in hydrostratigraphic units across the region, to represent the current state of regional groundwater quality against which future changes can be evaluated, and to compare against the data from the oil sands groundwater monitoring wells. Note that hydrostratigraphic assignments that were adopted to intercompare all three sub-regions are provided in S5 Supplementary material.

The oil sands MW data were obtained for each of the three regions from AEP and included groundwater wells identified as oil sands monitoring wells in the NAOS and SAOS, and from a *de facto* network consisting of GOWN wells already undergoing monitoring in the CLBR.

The baseline dataset included water quality databases assembled during development of the GWMFs for the three regions (Alberta Environment and Parks (AEP), 2013a, 2013b, 2013c) (Table 2) and were updated with water quality data available from EIAs (see S4 Supplementary material for full list) and other publicly available datasets (e.g., Alberta Health).

These baseline databases included previous provincial monitoring well data, and water supply well data submitted as part of

Table 2
Summary of original baseline databases made available by AEP originally used in the development of the GWMFs for the three regions.

	NAOS Baseline Database (Alberta Environment and Parks (AEP), 2013a)	SAOS Baseline Database (Alberta Environment and Parks (AEP), 2013b)	CLBR Baseline Database (Alberta Environment and Parks (AEP), 2013c)
# of Water Quality Measurements	120,839	235,026	677,118
# of Entries with Location	112,921	235,025	540,213
# of Entries with Aquifer completion	112,056	84,261	Not reported
# of wells	1479	35,529	13,434
# of wells with Aquifer completions	1366	8610	1483

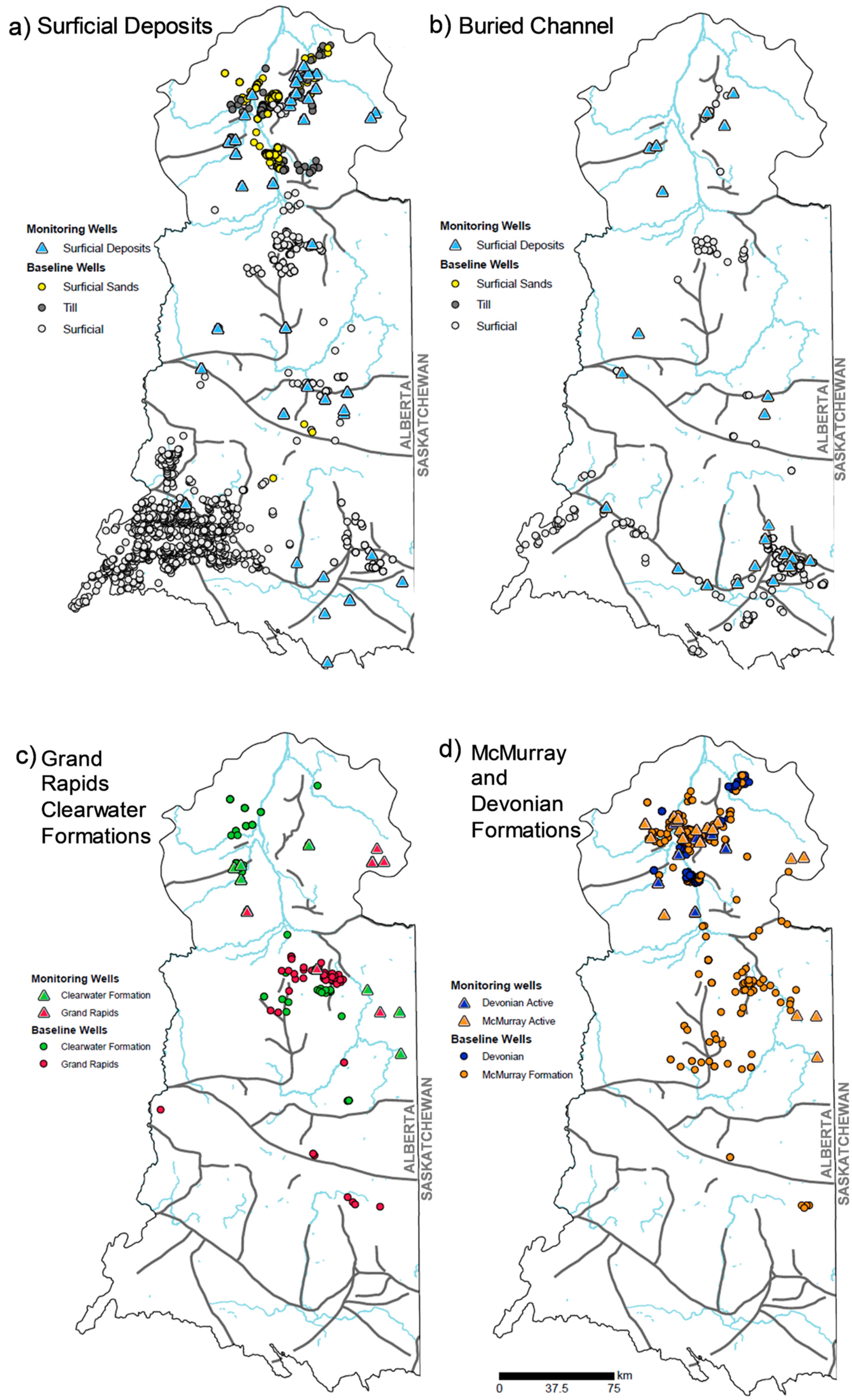

Fig. 3. Distribution of oil sands Monitoring Wells (MW) (triangles) and Baseline data (circles) for the main hydrostratigraphic units in the region a) surficial deposits, b) buried channels, c) Grand Rapids, and d) McMurray Formation. Surficial deposits include all Quaternary and Neogene formations including the Surficial Sands and undifferentiated overburden, while Channel wells show wells specifically identified as being in channel deposits.

industrial and private well reporting, however we should note that annual compliance data (EPEA reporting) were not available or included.

3.2. Field methods, water quality QA/QC and statistical treatment

The MW and Baseline water quality datasets were from a variety of programs each of which followed standard groundwater sampling protocols and used accredited laboratories, but there was undoubtedly some variations in methods used between programs and over time. The data were initially screened to remove data without sufficient metadata related to hydrostratigraphic formation or location and were then screened using quality assurance/quality control criteria prior to inclusion in the current analysis. Out of the ~ 27,000 groundwater samples available with water quality data, approximately 15,000 met the QA/QC criteria and were kept in the database. After data cleaning of the geochemical parameters reported in the various databases, fifteen of the primary and secondary indicator parameters were selected for statistical analysis (Na, Cl, SO_4, TDS, NO_3, NH_3, DOC, TOC, As, B, Si, naphthelene, pyrene, naphthenic acids, and temperature). Statistical treatment of the compiled dataset included use of probabilistic bootstrap technique (described in Manchuk et al., 2021) to model stable values, quantify variance and uncertainty and identify temporal anomalies for selected water quality parameters. The smoothed bootstrap approach was used to provide an estimate of the stable value of selected water quality parameters that was representative of a specified time interval. Such values are referred to as "stable" measured values, since the smoothed bootstrap approach filters noise and mitigates outliers. For each variable and monitoring well, the five most recently available data points were used in the smoothed bootstrap approach to estimate the mean over the resulting window of time and to specify confidence intervals. The statistical analysis determined stable values and temporal anomalies for fifteen indicator parameters for each hydrostratigraphic unit that were represented spatially using global ordinary Kriging (see S6–S8 Supplementary material).

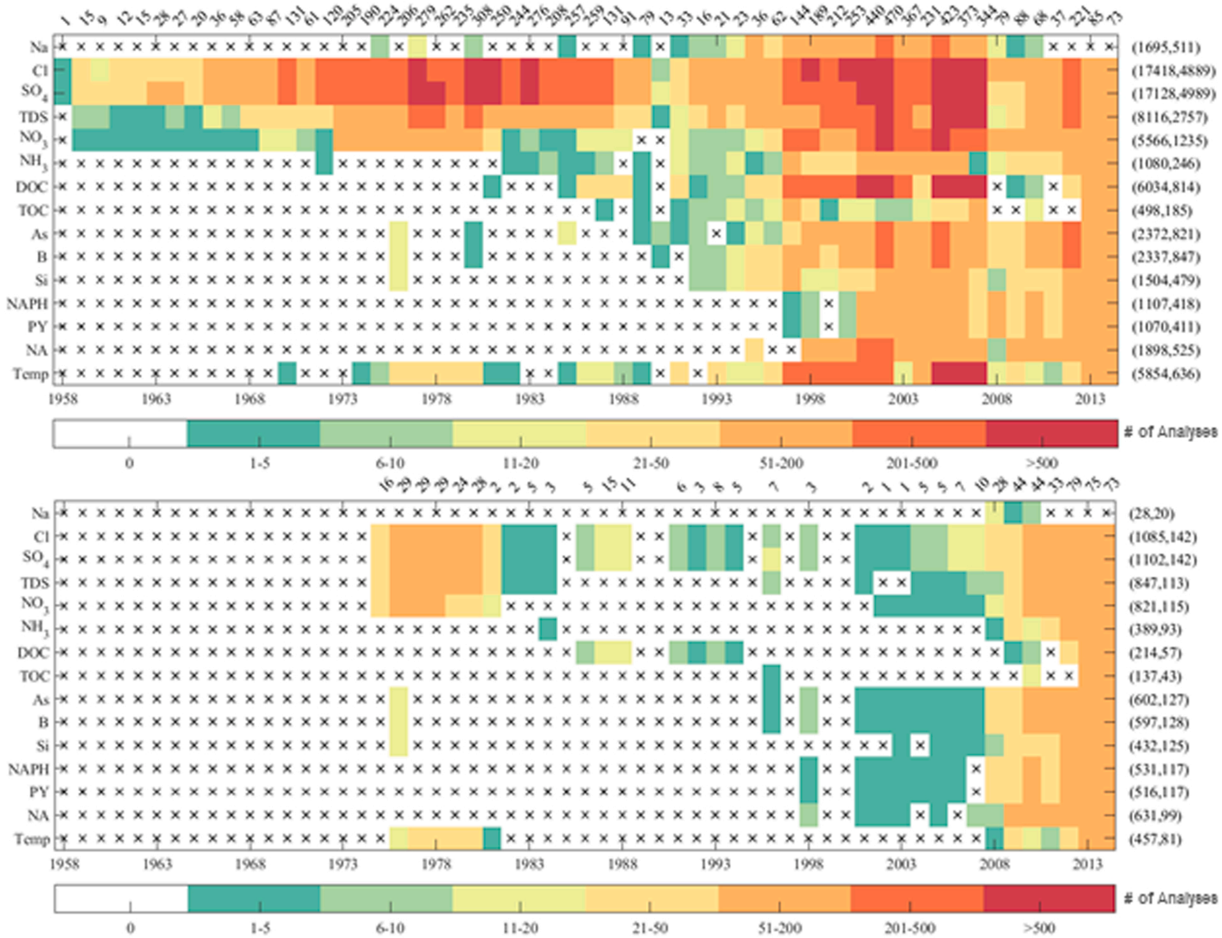

Fig. 4. Timeline of data density from 1958–2014 for all wells (Baseline + MW) (top) and only the oil sands MW network (bottom). An x indicates no samples. Numbers along the top axis indicate wells sampled in that year for all variables combined. Numbers at the right indicate (total samples, total wells) sampled for each indicator over the time span (modified from Manchuk et al., 2021).

4. Results

The combined MW and Baseline database included data from the main hydrostratigraphic units used by the oil sands industry (Fig. 3) and covers 1958–2014 (Fig. 4). Data from the surficial deposits, channel deposits, the Grand Rapids and McMurray Formation, are presented here to represent key water supply aquifers for oil sands activities (Grand Rapids and some Channel deposits), the formation where the majority of oil sands activities are occurring (McMurray Formation), and the aquifers that could be acting as conduits between the surface and deeper formations (Channel deposits) (Figs. 5–7).

4.1. Data density

The spatial and temporal data density in the compiled dataset of oil sands MW and Baseline data highlights differences in groundwater data availability in the main aquifers across the three main oil sands regions (Fig. 3) and variations in monitoring effort that occurred over the programs history (Fig. 4). There is a high density of Baseline groundwater quality data available for surficial aquifers in the CLBR due to the large numbers of domestic water supply wells in the southwestern portion of the study area (Fig. 3a). Routine water quality parameters are available from the entire monitoring period but metals and organics were included in the analyzes in the more recent data (Fig. 4). The availability of groundwater quality data from MWs coincide with various provincial monitoring initiatives, with increased efforts towards groundwater quality monitoring from the 2008 onwards.

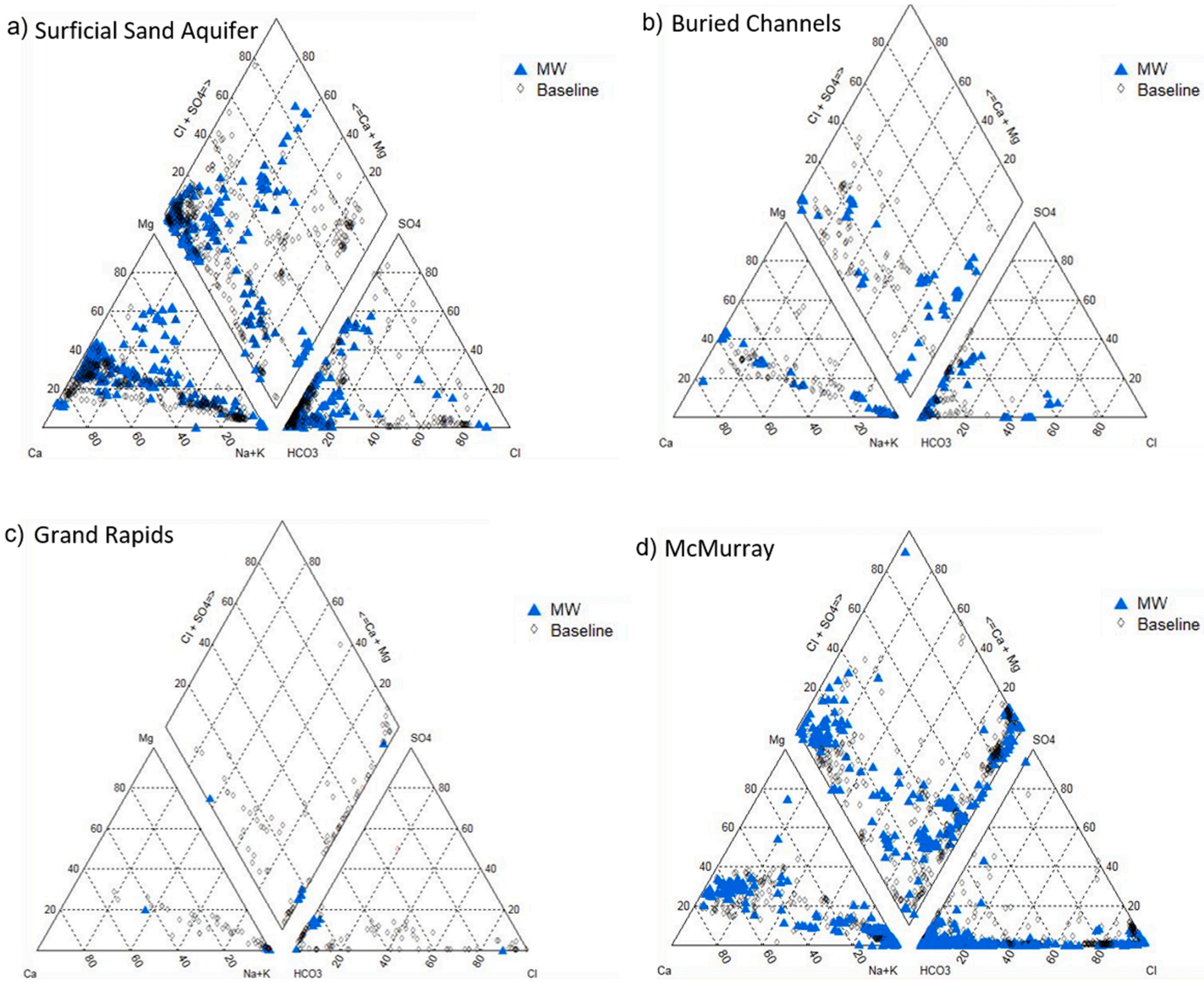

Fig. 5. Piper plots showing major ion geochemistry of groundwaters sampled from key stratigraphic units a) Surficial Sand aquifer, b) buried channels, c) Grand Rapids, and d) McMurray Formation. Data from the network of oil sands MWs are differentiated from the Baseline data by their symbols.

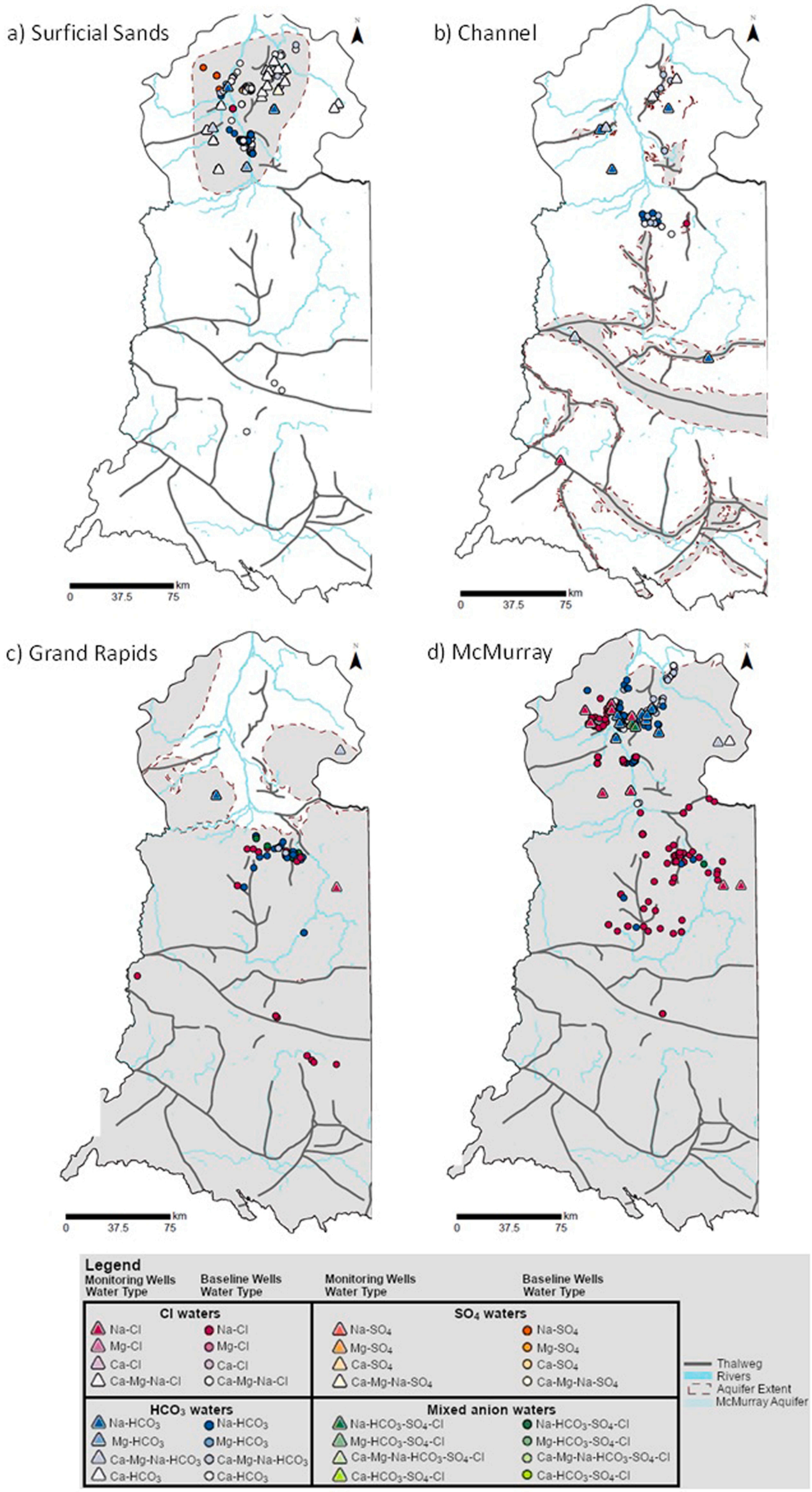

Fig. 6. Spatial distribution of major ion water types determined for Baseline (circles) and oil sands MWs (triangles) located in a) Surficial Sands, b) channel aquifers, c) Grand Rapids Formation, and d) McMurray Formation. Symbols are color-coded by dominant anion type. Grey shading shows the spatial extent of each of the aquifers.

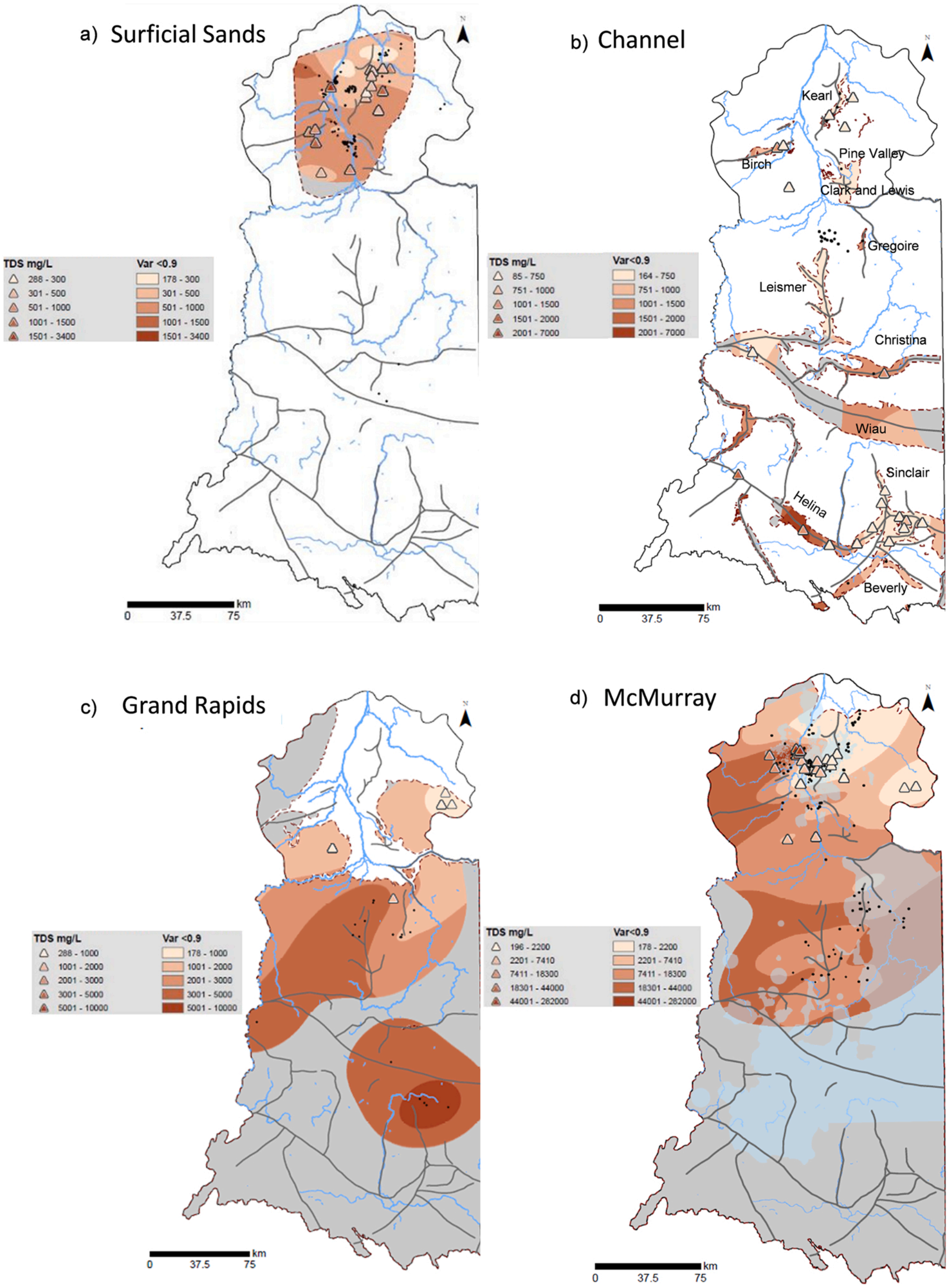

Fig. 7. Modeled stable TDS concentrations and MW data for a) the Surficial Sands aquifer, b) channel aquifers, c) the Grand Rapids Formation and d) the McMurray Formation. Modeled stable TDS concentrations were only shaded for areas with < 0.9 variance in the modeled values (see S8 Supplemental material). Control points for the model are shown as black dots, the MW TDS concentrations are shown as shaded triangles.

4.2. Geochemical facies

The major ion geochemical facies can be used to evaluate the degree of water rock interaction, which can be used to infer information about the geochemical evolution and history of the groundwater (Figs. 5 and 6). Groundwater typically evolves geochemically along a flowpath from low TDS, $Ca\text{-}HCO_3$ type composition near recharge areas, towards $Na\text{-}HCO_3$ or SO_4-dominated types in deeper aquifers with greater water-rock interaction time, and eventually to deep basin brines where the Cl anion often dominates (see Freeze and Cherry, 1979, p. 241–247). Shifts in the dominant cations occur due to ion exchange, and precipitation dissolution reactions that are dependent on the mineralogy of aquifer material along the flowpath.

In shallow aquifers, the more soluble minerals have typically been removed from the shallow zone, and only mineral phases with lower solubilities remain. Deeper into the flow system, more soluble mineral phases may be present, and dissolution of these phases can be influential in determining dominant ions. Quaternary hydrostratigraphic units showed a wide variety in major ion type classifications (Fig. 5a, b).

For the Surficial Sand aquifer, Baseline data show primarily mixed cation bicarbonate waters consistent with recent recharge; however, there were some wells with Na-Cl (Baseline wells), or $-SO_4$ type waters (Baseline and MW) which are more typical in deeper flow systems (Fig. 5a). The Na-Cl type waters were sampled from wells in the northwestern portion of the Surficial Sands aquifer, west of the Athabasca River (Fig. 6a). None of the oil sands monitoring wells completed within Quaternary units had Na-Cl type compositions, even though Na-Cl type waters were identified in the Baseline dataset.

The channel groundwater samples had fewer-mixed cations type waters than the Surficial Sands, and were dominated by Ca to Na, consistent with ion exchange (Fig. 5b). There were isolated locations with Na-Cl type waters in Baseline samples along the Gregoire Channel in the SAOS and Helina Channel in the CLBR which may indicate mixing with deeper formation waters where channels are incised into underlying Cretaceous formations (Fig. 6b).

Grand Rapids Formation groundwaters had a Ca-Na-HCO_3 to Na-Cl composition (Fig. 5c). This aquifer dips to the southwest and as a result has been eroded away completely in many areas of the NAOS, and is present at increasing depths in the southwest. The Na-Cl type waters were found in the SAOS and CLBR, where the overlying Colorado Group aquitard has been removed (north of the Wiau channel or west of the Christina River) (Fig. 6c). Ca-Mg-HCO_3 type waters tend to occur in the northern extent of the aquifer and also had lower TDS concentrations, consistent with a shallower flow system (Fig. 7c). The wide range of geochemical facies in the McMurray Formation aquifer (Fig. 5d) are consistent with previous studies that have hypothesized that vertical connectivity between the McMurray Formation and the underlying saline Devonian formations has resulted in widely varying salinity and water type (Cowie et al., 2015; Birks et al., 2019). The McMurray Formation groundwaters range from Ca-HCO_3 type waters, more consistent with shallow flow systems in the northern portion of the study region (Fig. 6d), to Na-Cl waters sampled in some areas in the NAOS west of the Athabasca River and in the SAOS. In the SAOS there were isolated samples from the McMurray Formation with HCO_3 type waters (Fig. 5d). In most cases these samples were from groundwater wells located near the thalwegs of buried channels or near river valleys where there may be greater connectivity to shallow flow systems. However, methanogenesis and/or bacterially mediated sulfate reduction can also lead to increased HCO_3 concentrations, and a shift towards this water type.

4.3. Distribution of stable TDS baseline values relative to oil sands MW data

The estimated stable measured values that represent the most recently available samples taken from all MW and Baseline wells combined are used as a best estimate of the stable values for each water quality parameter based on the combined oil sands groundwater database. The modeled distribution of stable TDS values provides a useful baseline (with outliers and noise removed) that can be applied to interpret the current distribution of oil sands MW values. Kriged stable values for TDS (shading on Fig. 7) are shown with control points used for the model indicated by circles, and monitoring well data indicated by triangles. Maps are shown for the Surficial Sands, channel aquifers, Grand Rapids and McMurray Formations, but similar maps were developed for each of the hydrostratigraphic units listed in Table 2. The shading was only extended to areas with an estimation variance less than 0.9 to highlight areas with sufficient data to infer stable values. The distribution of MW and baseline data across the Surficial Sands aquifer was sufficient to estimate stable values for most of the aquifer; only a small portion of this aquifer did not have sufficient data to model stable TDS concentrations (Fig. 7a). This aquifer had a fairly narrow range of TDS concentrations (176 mg/L to 3400 mg/L) compared to deeper units. The northwest area of this aquifer contained the highest stable TDS values according to the model, and was where most of the Na-Cl type waters were detected (Fig. 6a).

The channel aquifers had a wider range of modeled TDS values ranging from 164 mg/L in buried channel aquifers in the NAOS, to values approaching 7000 mg/L in some deeper buried channel aquifers in the CLBR area. This aquifer category incorporates a wide range of depths (e.g. drift thickness: Gregoire 100 m, Leismer Channel, 240 m, Kearl Channel 25–70 m, Helina 50–100 m) (Parks et al., 2005; Andriashek and Atkinson, 2007), and the wider range in TDS appear to reflect depth of the various channel aquifers, as well as TDS in adjacent formations. Highest TDS values were measured in groundwater wells in the Helina Channel (Fig. 7b). In contrast, low TDS in the NAOS channel aquifers and in the SAOS Leismer Channel are consistent with shallower occurrences where greater influence of recently recharged meteoric water would be expected.

Large areas of the Grand Rapids Formation had insufficient baseline data to model stable TDS values (Fig. 7c). These areas were typically located away from oil sands development. The lack of control points and oil sands monitoring well data available at the time of compilation (2015) indicate a need for improved characterization of this important water supply aquifer. Where data are available, a trend of higher TDS in the southern portion of this aquifer compared to the northern extent is evident (Fig. 7c). The wells with Na-Cl type waters identified in Fig. 6c, occurred in the SAOS and CLBR areas where TDS concentrations were higher.

The modeled stable TDS values for the McMurray Formation show some limitations of kriging (Fig. 7d) related to the sparse distribution of data away from the central portion of the map. The modeled stable TDS values capture the higher TDS values in the McMurray Formation west of the Athabasca River in the NAOS, compared to on the eastern side, similar to patterns identified by both Cowie et al. (2015) and Birks et al. (2019). However, the bootstrapping and variance criteria resulted in omission of some of the high TDS groundwater data coinciding with the Prairie Evaporite Dissolution scarp (Broughton, 2013). This highlights one of the challenges in establishing baseline water quality distributions in a region with a high degree of spatial variability due to complex, discontinuous geological features. In such cases, secondary information relating to geochemical sources would need to be included in the kriging equations as a drift term, as an additional variable for cokriging, or as a locally varying mean. For example, proximity to the dissolution scarp may be a valid secondary variable if it is found to have sufficient correlation with TDS. Differences between the MW TDS shading

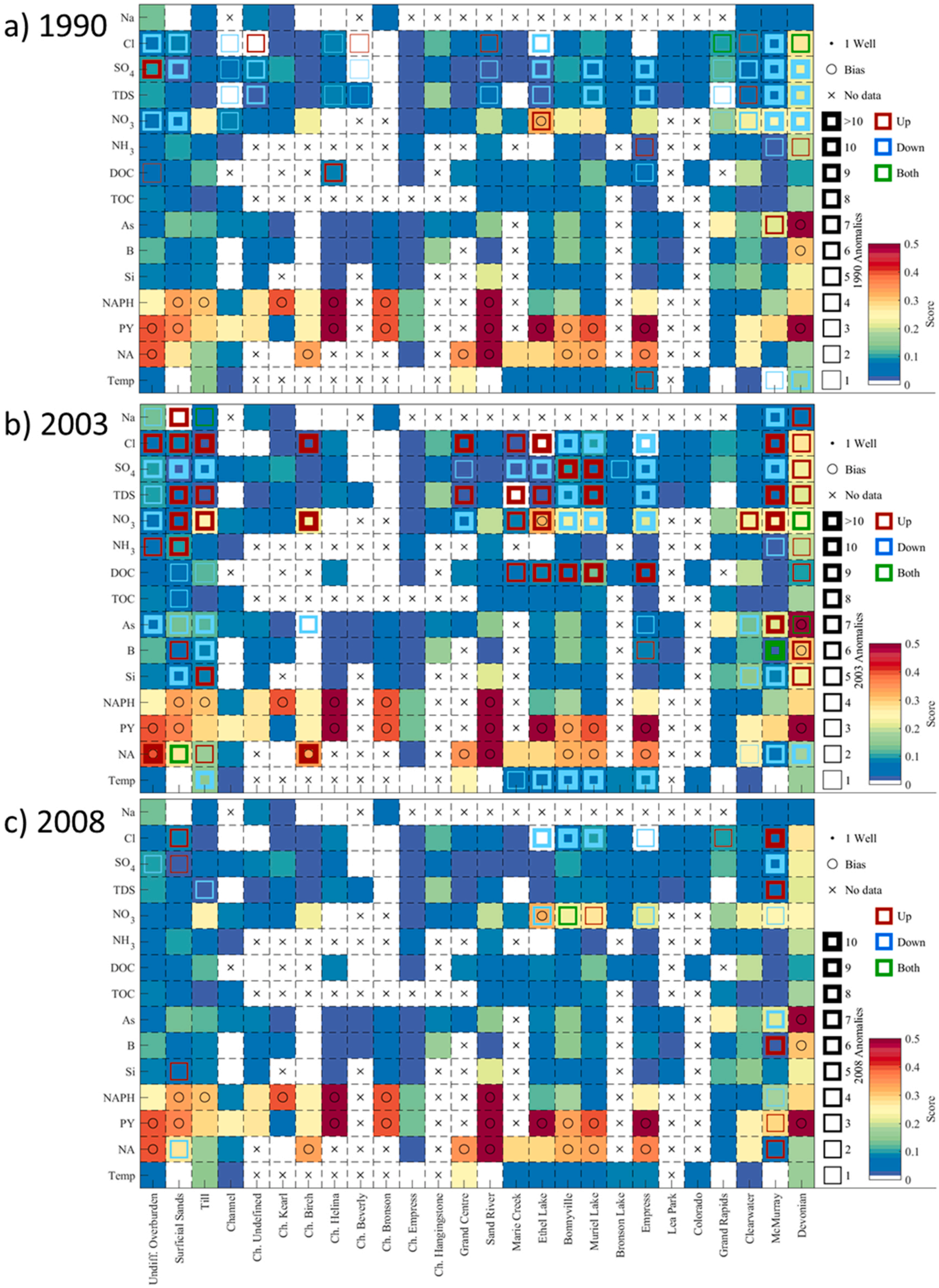

Fig. 8. Sampling scores and time anomaly occurrence for a) 1990, b) 2003 and c) 2008 for oil sands MW and Baseline by formation and for the indicators of interest. Shading indicates sampling score and outlines show significance of the trends (weight of outline) and whether the anomalies indicate increasing, decreasing or variable concentrations between data before and after each time period are compared.

and the modeled stable values also highlight the challenge of working with water quality data that can be heterogeneous in some aquifers and hydrogeological settings within the region.

4.4. Spatial anomalies

Considering typical patterns for geochemical evolution of groundwater from recharge to discharge along flowpaths in sedimentary basins, some geochemical indicators of vertical connectivity can be identified in the combined AOSR database (i.e. influence of shallow aquifer recharge at depth, or indicators of discharge of deep groundwater sources in shallow aquifers). In the Surficial Sands aquifer, groundwater with anomalously high concentrations of TDS and Na-Cl water type were found near the confluence of the McKay and Athabasca Rivers in the NAOS, likely indicating deeper more saline groundwater may be discharging at this location. Several anomalous groundwater compositions were encountered in the vicinity of buried channel aquifers, including; higher TDS and Na-Cl

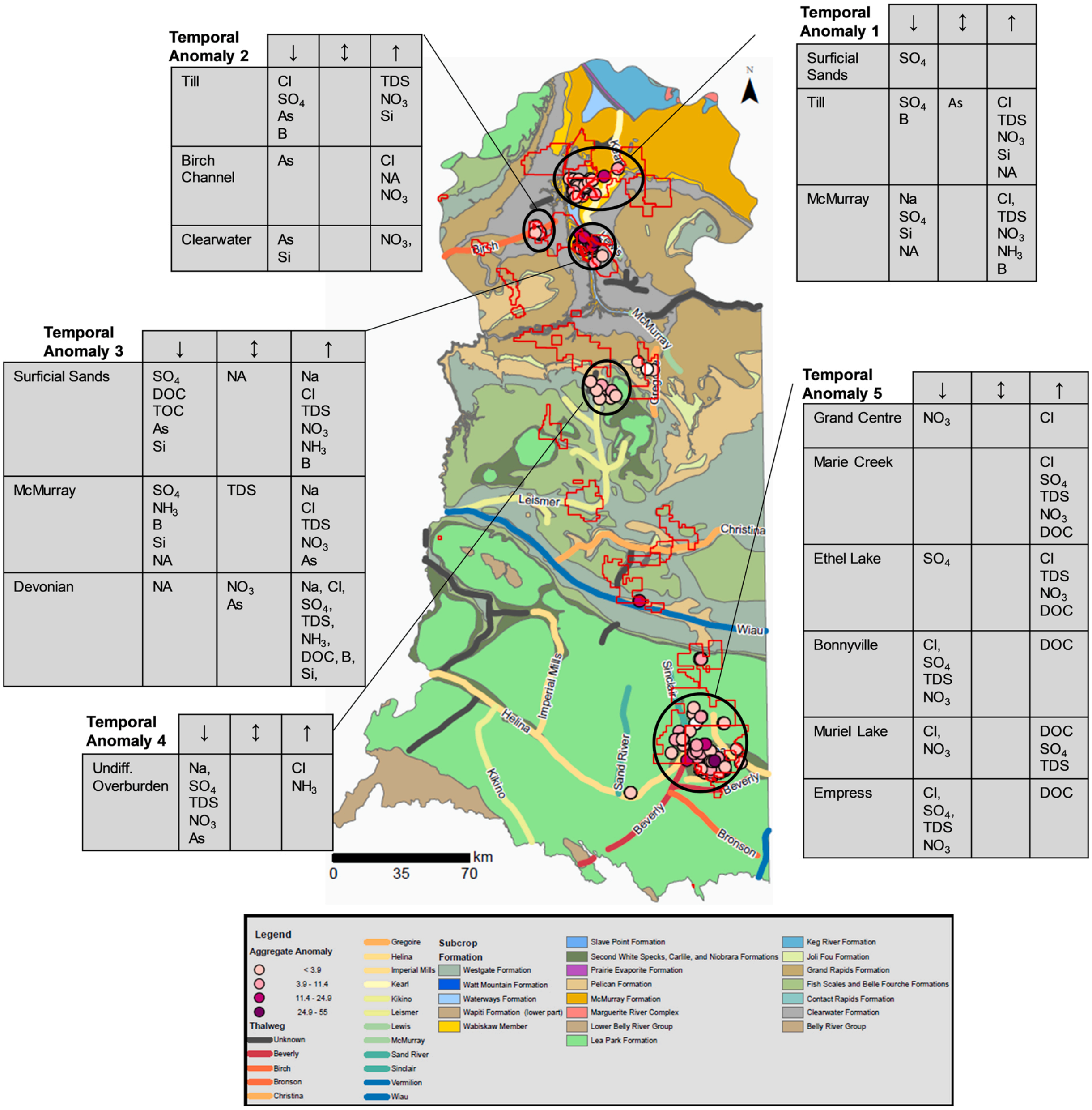

Fig. 9. Location temporal anomalies detected before and after 2003 for the oil sands MW's and Baseline datasets with tables showing parameters that decreased, varied, or increased. Anomalies are shaded using an aggregate value of all parameters (see Supplemental information). Red outlines show the lease boundaries of oil sands operations active as of 2016.

water type that could indicate greater mixing with the adjacent, more saline formations in groundwater the Gregoire, Beverly, Bronson and Kikino Channels.

In the Grand Rapids Formation, the -HCO_3 type water (Fig. 6) and low TDS concentrations near the northern edges of the formation where the Colorado Group is thin or absent (Fig. 7) suggest mixing with shallower flow. The east-west divide in TDS concentrations and water type for the McMurray Formation aligns with the location of the Devonian scarp, and are consistent with greater connectivity with saline Devonian aquifers near this feature (Cowie et al., 2015; Birks et al., 2019).

4.5. Temporal anomalies

Temporal anomalies for a subset of parameters (Na, Cl, SO_4, TDS, NO_3, NH_3, DOC, TOC, As, B, Si, naphthelene, pyrene, naphthenic acids, and temperature) were evaluated in the combined MW and Baseline dataset for each hydrostratigraphic unit and over each of the data-rich time periods (Fig. 8). Sampling scores and temporal anomalies are shown for the periods before and after 1990, 2003 and 2008 in Fig. 8. The sampling score is a measure of the uniformity of MW and Baseline samples for a given indicator relative to the global distribution of the associated indicator and formation. Sampling scores with values > 0.3 indicate a sampling bias, either that the parameters is under or over represented for that hydrostratigraphic unit. Parameters with data from 1 well, or with no data are also flagged. The direction and significance of temporal anomalies are indicated by the color and thickness outline of each of the boxes in Fig. 8. The anomaly plots does not indicate any consistent trends in groundwater quality that are present in the entire region over the three time periods, which is not surprising based on the discontinuous nature of the hydrostratigraphic units across the region. Comparison of water quality parameters before and after 1990 indicated primarily decreasing trends, but before and after the 2003 and 2008 periods include more increasing or mixed trends. Comparison of data before and after 2008 indicated the fewest temporal anomalies, with about half of them indicating decreases in concentration. Across the entire dataset, sampling scores for naphthalene, pyrene, and naphthenic acid tended to have the greatest sampling bias, likely because these organics are not part of routine water quality analyses and would only have been analyzed for selected wells. Note that temporal changes in routine field parameters such as pH, temperature, and redox were not given as much weight in the assessment since methodology used to acquire these data has the potential to influence the results, and recognizing that there was little information available on whether consistent historical field and analytical practices were used. For some parameters analytical detection limits may have improved over the time period covered by the dataset, leading to detectable concentrations for parameters in more recent data that were previously below detection limits. However, most of the parameters with increasing trends (Fig. 8) were for routine parameters (e.g. TDS, Cl, Na, SO_4, NO_3) where significant changes in detection limits are not expected, but this will be more thoroughly reviewed in follow-up investigations.

The location of the temporal anomalies relative to hydrogeological features and potential groundwater stressors are also of interest and they were found to occur in distinct clusters in the NAOS, SAOS and CLBR areas (Fig. 9). Closer inspection of these clusters shows that all are located in areas where enhanced vertical connectivity due to the presence of buried channels, incised rivers, or where there is limited to no Colorado Group cover occur (Fig. 9). The parameter scores within each of the clusters were used to identify the direction of changes in groundwater quality for indicator parameters in each hydrostratigraphic units (summary Tables in Fig. 9) (parameter score plots for each anomaly are included in S9 Supplementary material).

Temporal anomaly 1 occurs in the NAOS in a group of wells screened in the Surficial Sands, Till, and McMurray Formations in an area adjacent and east of the Athabasca River where surface mining occurs. This is an area where the McMurray and Devonian formations have high concentrations of solutes, and these formations are directly overlain by Quaternary sediments. This area is also notable because it coincides with locations where there is evidence of natural saline groundwater seepage discharging to the Athabasca River (Birks et al., 2018; Gibson et al., 2013; Gue et al., 2015). The temporal anomalies included increasing trends in TDS, Cl, and NO_3 in the Till and McMurray Formations, as well as decreasing concentrations in SO_4 in the Surficial Sands, Till and McMurray Formations.

Temporal Anomaly 2 is in the NAOS and includes a small group of wells screened in the Birch Channel, Clearwater, and McMurray Formations located over a buried Quaternary channel. At this location increases in NO_3 were observed in all three formations whereas dissolved As concentrations decreased.

Temporal Anomaly 3 includes a group of wells in the NAOS screened in the Surficial Sands, McMurray and Devonian formations adjacent to the Athabasca River and near the Lewis and Clark buried channel and characterized by trends of increasing concentrations of TDS, Na, Cl, and decreasing concentrations of naphthenic acids and SO_4. This area has previously been identified as a potential Investigation Area (Fig. 1c) for oil sands monitoring (WorleyParsons, 2009b), but there are currently no MW located in this area. Temporal anomalies in the McMurray Formation include increases in Cl, TDS, B, and naphthenic acids, and decreases in SO_4. Temporal anomalies for As in the McMurray Formation are time-dependant, with increasing trends noted for 1990 and 2003, and decreasing trends after 2008.

Temporal Anomaly 4 is located in the SAOS over the northern portion of the Leismer Channel in wells screened in undifferentiated overburden deposits and is the only temporal anomaly not located over an active oil sands lease. This portion of the SAOS is located near the edge of Colorado Group cover, at the margin where the Grand Rapids Formation directly underlies Quaternary deposits. The changes in groundwater quality at this location include decreases in TDS, Na, SO_4, NO_3, and As and increases in Cl and NH_3.

Temporal anomaly 5 is located in the CLBR area, and includes a group of wells screened in the Grand Centre, Marie Creek, Bonnyville, and Empress Formations centered over the confluence of the Helina, Sinclair and Beverly Channels, in an area of in-situ oil sands development (Fig. 9). Temporal anomalies were detected in the Ethel Lake Formation, a formation that has naturally elevated concentrations of As due to the presence of As-bearing minerals (Moncur et al., 2015a). The changes in groundwater quality in these locations included increased concentrations of dissolved organic carbon (DOC) in all of the formations except the shallowest, the Grand

Centre Formation.

5. Discussion

Analysis of the new compiled AOSR dataset has provided better understanding of the range and spatial distribution of water quality parameters in the different hydrostratigraphic units across the region. This information can be used to help refine conceptual models of groundwater flow (Birks et al., 2019), to identify areas of aquifer connectivity and vulnerability, and to provide insight into the establishment and applicability of water quality limits and triggers. Detection of spatial geochemical anomalies, and areas with temporal changes in groundwater geochemistry, may be helpful for identifying areas of greater cross-aquifer connectivity to focus future sampling campaigns. Geochemical indicators of shallow groundwater flow in deep aquifers, or the opposite pattern of geochemical indicators of deep groundwater in shallow aquifers, may be a useful proxy for hydraulic connectivity between surface and underlying aquifers, and can be a key indicator of potential vulnerability. Conversely, where aquifers are poorly-connected to surface or adjacent aquifers, there may be a reduced likelihood that groundwaters are impacted by surface activities or contamination, or that aquifer drawdown will affect groundwater-reliant ecosystems.

5.1. *Distribution of water quality parameters relative to hydrogeological controls*

The maps of stable water quality values (e.g., Fig. 7) that have been developed from the new MW and Baseline datasets provides an archive that can be checked against future values and to help identify potential areas for subsequent monitoring based on identifying areas with high uncertainty in the existing data. The distribution of geochemical parameters in the Surficial Sands aquifer support the hypothesis that shallow aquifers are dominated by topographically-driven groundwater flow from uplands to lowlands. Geochemical anomalies in this formation are interpreted as being the result of differing degrees of flow path interaction between shallow aquifers

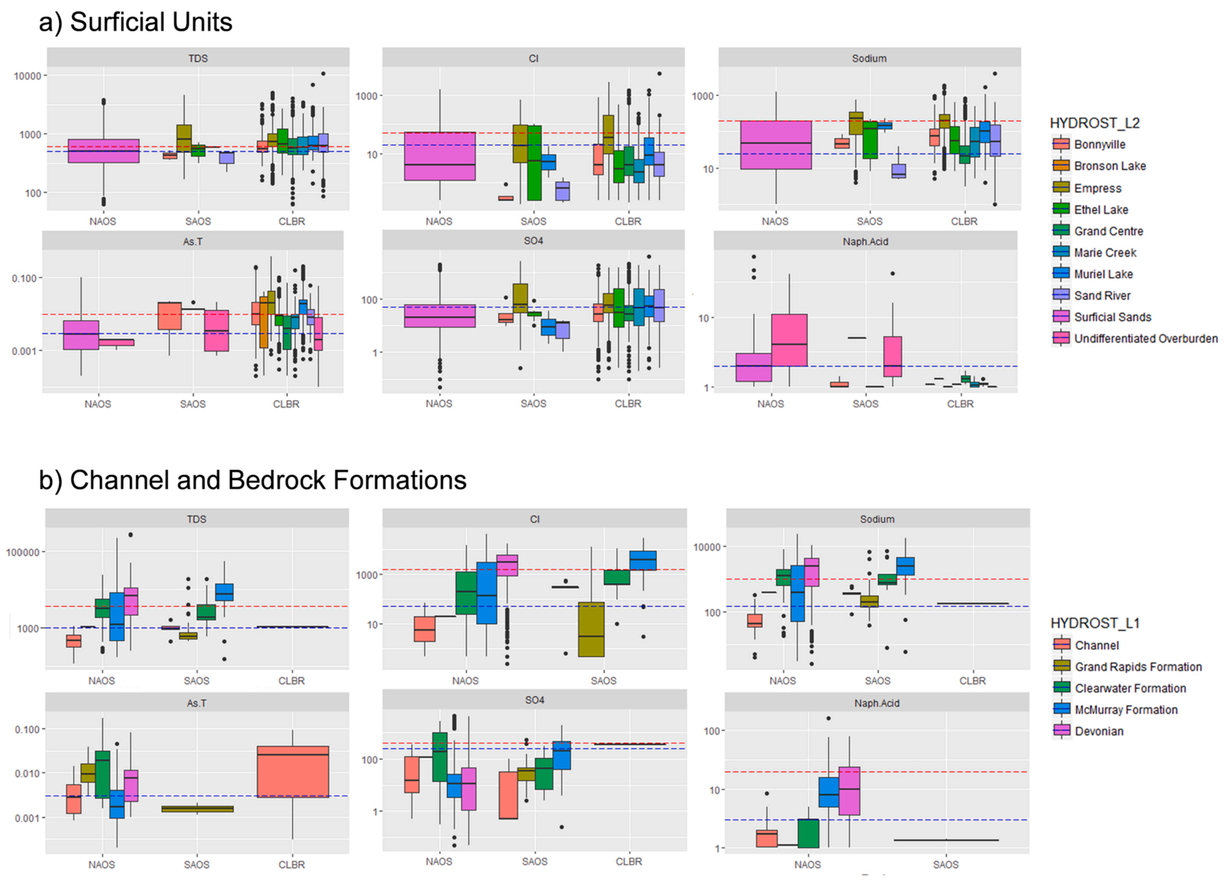

Fig. 10. Box and whisker plots showing the range of concentrations of in TDS, Cl, Na, SO_4, As (Total) and Naphthenic acids in MW and Baseline wells installed in a) surficial units and b) channel and bedrock formation in the three main oil sands areas. The GMWFs include interim triggers for specific hydrostratigraphic unit, and by region (Matrix Solutions Inc (Matrix), 2015a, 2015b), but only the upper and lower values for all of the hydrostratigraphic units on each plot are shown for comparison (blue = lower, red = upper). If all of the hydrostratigraphic units had the same trigger than only a single value was shown. The median, 10th and 90th percentile are indicated by the box boundaries and outliers are shown as filled circles.

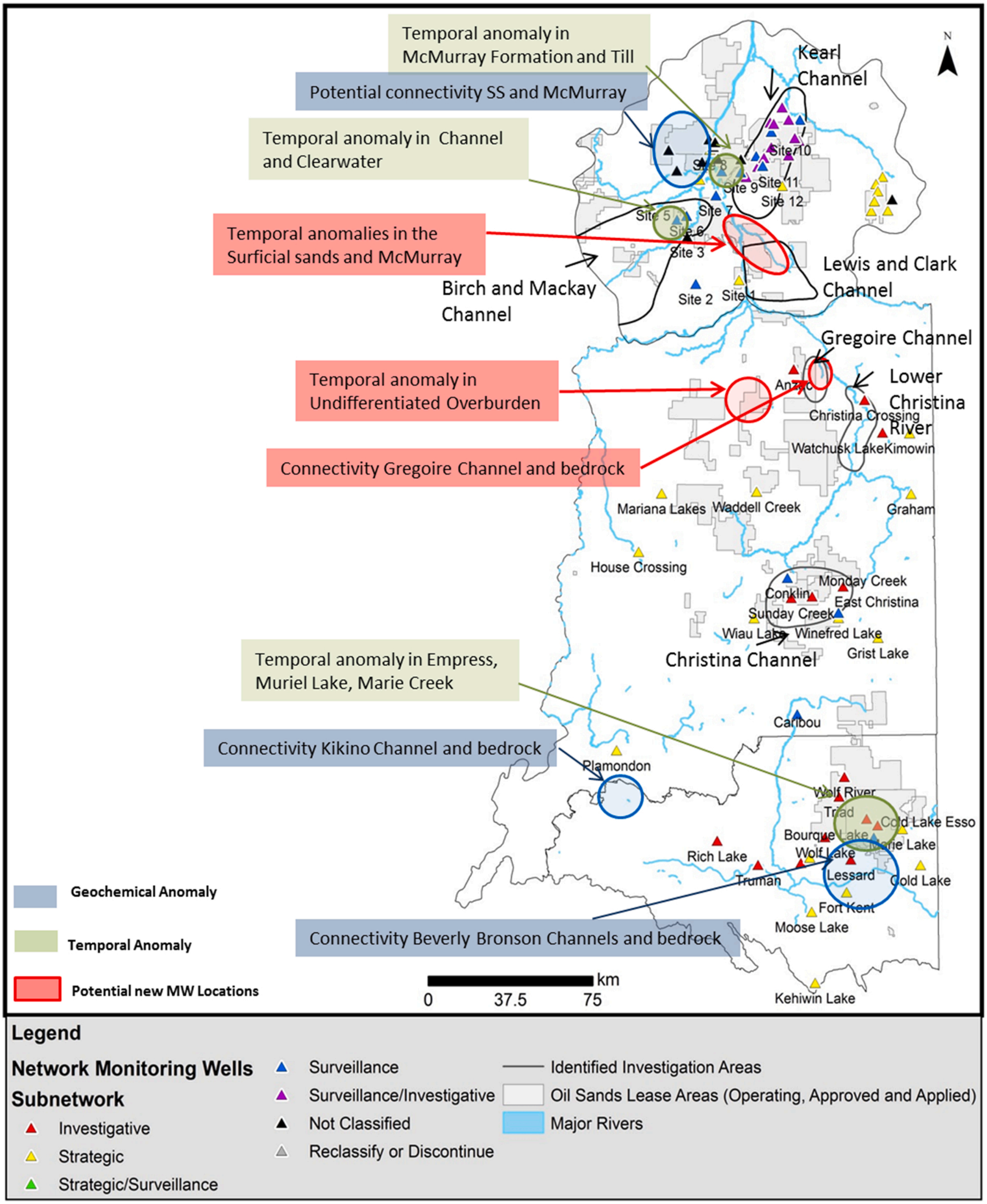

Fig. 11. Map showing the locations of current MW and investigation areas (black outlines) with temporal and spatial geochemical anomalies highlighted. Locations with anomalies not currently within an investigation area and without MW are highlighted red as potential locations for future MWs.

and the more saline underlying Cretaceous formations.

Topographically-driven flow is also evident the distribution of TDS and water type in the Neogene and Quaternary aquifers from the CLBR area, with lower values associated with recharge areas beneath the Moostoos Uplands and higher values observed progressively along the flow systems (e.g. Fig. 5b increasing TDS along Helina Channel). The general trend of increasing dissolved solids along the flowpath appears to occur consistently, as revealed by the Baseline data. Higher TDS and Cl concentrations were also observed in aquifers in the Southwest Beaver River flow system in the Whitefish Uplands. In some locations within the channel aquifers, the composition of the groundwater is more consistent with deeper formation waters consistent with mixing with adjacent units. Some of the geochemical anomalies were detected in the Baseline dataset, that hasn't been as rigorously vetted as the groundwater MW data, and so other factors (e.g. well integrity, sampling error) influencing water quality cannot be excluded. However, these areas coincide with elevated values of mean stable TDS (Fig. 7) and Cl; we expect that this conclusion is not due to spurious data. Also, several of the observed anomalies in major ion type (Fig. 5) and TDS (Fig. 7) are present in approximately the same location within multiple aquifers (Bonnyville, Muriel Lake and Empress Formations), which strongly suggests that they are related, not outliers.

The compiled oil sands MW and Baseline data for some of the deeper Cretaceous formations are considerably sparse, although available results are consistent with recent geochemical and isotopic data that have recently been made available for the SAOS (Birks et al., 2019). Groundwater in the Grand Rapids Formation increases in TDS and shifts towards more Na-Cl waters in the southwest portion of the aquifer, where the formation is present at greater depths and overlain by a thicker Colorado Group cover (Birks et al., 2019). This trend is evident in the compiled MW and Baseline data, and the new data compiled for this study has shown that this trend extends to the NAOS, where even more dilute, Ca-HCO_3-rich groundwaters are present, consistent with their shallower depth and greater potential for mixing with overlying aquifers. Lower TDS, and more HCO_3-dominant groundwaters are found in the Grand Rapids Formation near the Christina River, which was an area identified as having greater vertical connectivity based on the presence of glaciogenic isotopic signatures originating from the underlying Devonian aquifers (Birks et al., 2019). The importance of geochemical anomalies adjacent to buried channels is also evident (e.g. HCO_3-dominant groundwaters present within deeper formations, and Cl-dominant groundwaters in shallow formations). The distribution of geochemical facies (Fig. 6d) and TDS (Fig. 7d) in the McMurray Formation show the importance of vertical features, especially the Prairie Evaporite dissolution scarp (Broughton, 2013; Cowie et al., 2015; Birks et al., 2018). The stable TDS values modeled for this formation highlights the challenge in establishing baseline values in areas with very heterogeneous water quality and sparse data. Vertical preferential flow features such as faults and dissolution scarps can create highly variable water quality distributions that are hard to detect with sparse networks, and not suited for many interpolation methods.

5.2. Comparison with interim triggers

The data in the compiled AOSR database was used to look at the range of concentrations for the main indicator parameters defined under LARP GWMF in each of the hydrostratigraphic units relative to the interim triggers currently in place for each region (Fig. 10, Supplemental material S3). There is a fairly narrow range in water quality parameters in most of the Quaternary formations in the NAOS and SAOS (Fig. 10a), but greater ranges observed in the bedrock units (Fig. 10b). The CLBR region had a very large Quaternary water quality dataset due to the large number of wells located in this region, and there were many outliers. One prevalent trend is that of increasing Na and Cl concentrations with depth in the stratigraphic sequence from shallower Grand Centre to deeper Empress Formations. The median values found for some parameters are higher than the interim triggers (e.g. Empress Formation- As, TDS, Na and SO_4; Muriel Lake- As; McMurray Formation: naphthenic acids; Devonian: naphthenic acids). In the CLBR, naturally occurring As has been measured in groundwater from a number of the surficial deposits (e.g. 180 μg/L in buried channels; Moncur et al., 2015a), Median naphthenic acid concentrations for McMurray and Devonian formations in the NAOS are higher than the interim trigger, consistent with other measurements of groundwater from bitumen saturated portions of this formation (Kilgour et al., 2019). The analysis of the new AOSR dataset has highlighted the variability in individual aquifers and shown that in some aquifers even the median values are well above the interim triggers (Fig. 10).

The presence of highly variable and saline aquifers (Birks et al., 2019; Cowie et al., 2015; Gibson et al., 2013) and glacial sediments with the potential to release metals during weathering parameters (Moncur et al., 2015a) are potential causes for the naturally high concentrations of some parameters and exceedances detected across the region.

5.3. Implications for oil sands groundwater monitoring network design

There are many approaches for optimizing groundwater monitoring network design including: simple random sampling, stratified random sampling, systematic grid sampling, and random sampling within blocks (Gilbert, 1987; Alley, 1993). However, given the large size of the AOSR (> 50,000 km^2) and remoteness of some locations, it is not economically or logistically feasible to implement high data-density collection programs across all aquifers over the entire region, so an approach for prioritizing areas based on vulnerability to potential impacts from oil sands activities is needed to help guide monitoring network design. The original oil sands monitoring design for the NAOS and the SAOS used risk-based modeling (WorleyParsons, 2009b; Matrix Solutions Inc (Matrix), 2013) to identify vulnerable areas based on proximity to oil sands activities, and potential hydrogeological pathways connecting the surface to aquifers used for water sources. This approach may not capture all of the potential risks from oil sands activities where some of the potential stressors occur at depth (e.g. groundwater withdrawals and disposal) and in complex hydrogeological settings where all of the potential hydrogeological pathways have not been well defined.

The interpretation of the new combined groundwater quality dataset show how temporal and spatial geochemical anomalies can be used as an additional source of information about potential groundwater vulnerability and connectivity. Spatial and temporal geochemical anomalies can indicate areas where groundwater conditions are changing, or have been subject to interactions with overlying or underlying formations (recently or in the past) both of which are potential indicators of vulnerability. The location of spatial geochemical anomalies (Section 4.4) and temporal geochemical anomalies (Section 4.5) were compiled and summarized on Fig. 11 to identify potential areas requiring additional monitoring. Areas of potential vulnerability can be identified based on indicators of cross formation mixing and using temporal trends in water quality. Temporal geochemical anomalies signify a change in the state of groundwater quality that can be from a variety of natural or anthropogenic stressors and can be used to identify areas for further investigation. For example, the temporal anomalies detected in the MW and Baseline dataset could be due to a natural shifts in groundwater flow systems due to changes in recharge, or changes in flow systems due to groundwater withdrawals by domestic or industrial users, or due to contamination. The spatial geochemical anomalies do not necessarily indicate influence of oil sands activities but indicators of vertical connectivity between shallow and deep formations suggest a more dynamic hydrogeological settings that may be more vulnerable to oil sands stressors.

The current distribution of oil sands monitoring network (MWs on Fig. 3) are summarized by hydrostratigraphic unit (Table 3), with reference to whether spatial or temporal anomalies have been identified to identify potential improvements to the network. Although the required number of observation wells needed to examine a system will ultimately depend on the objectives of the monitoring program and available budget, approaches used in other regional programs include prescribing a minimum number of monitoring sites by aquifer, or prescribing a sampling density by aquifer (National Groundwater Water Monitoring Network; NGWMN, Subcommittee on Ground Water of the Advisory Committee on Water Information, 2013). The well density for the oil sands MW ranges from 1 well/311 km^2 to 1 well/8694 km^2, which can be compared to the US National Groundwater Monitoring program for principal aquifers where the well density ranges from 1 well/3 km^2 to 1 well /82,288 km^2 (average density across entire program 1 well/ 5755 km^2) (Subcommittee on Ground Water of the Advisory Committee on Water Information, 2013).

The Grand Rapids Formation is the most heavily used aquifer for in-situ water sourcing, and this aquifer has fairly limited monitoring in the AOSR with a density of 1 well/6868 km^2.

The limited number of regional MW that are operating in the SAOS (Fig. 11) do not include the thousands of on-lease monitoring wells that industry are required as part of regulatory compliance monitoring. These industry owned wells are another source of monitoring data that could be further utilized for characterizing baseline groundwater quality conditions, changes over time.

The results from numerical groundwater modeling done in EIA's to predict the cumulative impacts of oil sands operators withdrawals and injections are another source of information that could be used to identify groundwater vulnerability that have not yet

Table 3
Summary of main hydrostratigraphic units in the AOSR with number of oil sands monitoring wells, presence of temporal or spatial anomalies and comments on coverage.

	# Current wells	Well/km^2	Aquifer/Aquitard	Temporal anomalies	Spatial anomalies	Comments
Surficial Sands	24	1/311	Aquifer	Yes	Yes	Density of wells appears good, small cluster of temporal and spatial anomaly indicating potential connectivity with underlying saline groundwater.
Grand Centre	0	–	Aquitard	Yes	Yes	Several temporal and spatial anomalies in CLBR, consider monitoring in overlying aquifers at these locations.
Marie Creek	0	–	Aquitard	Yes	No	Cluster of temporal anomalies in CLBR, consider monitoring adjacent aquifers at these locations.
Sand River	5	1/2456	Aquifer	No	No	Monitored in SAOS, wells could be added in CLBR.
Ethel Lake	5	1/3929	Aquifer	Yes	No	Cluster of temporal anomalies in CLBR, already monitored.
Bonnyville	11	1/1727	Aquifer	Yes	Yes	Cluster of temporal spatial anomalies, already monitored. Some of the proposed wells in CLBR GWMF are well-placed.
Muriel Lake	13	1/369	Aquifer	Yes	Yes	Cluster of temporal anomalies and spatial anomalies, already monitored.
Bronson Lake	0	–	Aquitard	Yes	No	Anomalies in CLBR, but aquitard with limited extent. Possible monitoring of adjacent aquifers depending on nearby activity.
Empress	11	1/937	Aquifer	Yes	Yes	Coverage appears good for the main anomaly areas, spatial anomalies where Kikino Channel meets Helina Channel might be considered, but no apparent nearby activity.
Channel	11	1/826	Aquifer	No	Yes	Most of the channel areas have good coverage.
Grand Rapids	8	1/6868	Aquifer	No	No	Very little data available in baseline, and only limited coverage of MW in the SAOS. Consider additional monitoring given importance of this aquifer for water supply.
Clearwater	7	1/8694	Aquitard	Yes	No	Some temporal anomalies in the north, already monitored.
McMurray	32	1/2000	Aquifer	Yes	Yes	Coverage appears good except for small cluster of anomalies in the NAOS.
Devonian	14	1/4644	Aquifer	Yes	–	Coverage appears appropriate for NAOS where anomaly was observed.

been fully utilized for monitoring design. EIAs require predictions of the potential changes to the groundwater flow systems under full development conditions which are compared to base case scenarios with no development to identify potential environmental impacts to groundwater. These predictions of the impacts from groundwater withdrawals (e.g. changes to hydraulic head distributions around groundwater withdrawal and injection wells) have not been compared to monitoring data and could be used to help guide monitoring network design.

Examples of other monitoring programs around oil and gas activities (e.g. Colorado Oil and Gas Association Voluntary Baseline Groundwater Quality Sampling Program; Colorado Oil and Gas Association, 2011; Wheaton and Donato, 2004; ENTRIX Inc., 2009; Australia Pacific LNG, 2012; Australia Pacific LNG Upstream Project, 2016) give insights into network design approaches that have worked in other resource development areas, but they also highlight some of the specific challenges in groundwater monitoring in the AOSR, such as the large spatial extent, remote access, the discontinuous distribution of oil sands deposits, the variety of resource development approaches (surface mining vs in-situ) conducted by multiple different operators, and the natural variability of groundwater quality due to discontinuous features like the Prairie evaporite dissolution scarp and buried channels.

Four of the five clusters of temporal anomalies occur in areas where oil sands activities coincide with areas of enhanced vertical connectivity due to buried channels or incised rivers, and where adjacent formations have contrasting geochemical compositions (Fig. 11). In most cases, the areas with spatial and temporal geochemical anomalies had previously been identified as potential "Investigation Areas" and already have oil sands MWs. There are some interesting groupings in the geochemical parameters with increasing trends across the NAOS and CLBR that are consistent with conceptual models of potential groundwater stressors in these regions. Decreasing trends in As concentrations were observed in a few of the temporal anomalies (2, 3 and 4) and this could indicate a shift in redox conditions at these locations. In the NAOS, muskeg drainage and dewatering are needed prior to surface mine development. Nitrate in groundwater is typically associated with fertilizer use, or septic system effluent, but can also be released from drainage from peatlands (Wind-Mulder et al., 1996; Munir et al., 2017). The increasing trend in NO_3 across all aquifers in the NAOS could be consistent with this potential effect of large-scale peat drainage. In the CLBR area increasing trends in DOC were identified in multiple wells in this area. Heating of Quaternary sediments from the CLBR has been found to result in increased TDS and DOC concentrations (Moncur et al., 2015b). However, the increases in NO_3 and DOC identified in the combined MW and Baseline dataset could also be due to other natural or anthropogenic sources, and more detailed causal investigations, including review of the MW data and expanded set of water quality parameters in these areas would be required.

6. Conclusions

Given the large size of the AOSR and remoteness of some locations, it is not feasible to collect groundwater data at high spatial resolutions, so methods including spatial and temporal data analyses can improve our ability to assess groundwater quality in these data sparse areas. Approaches are needed to identify and prioritize groundwater aquifers most vulnerable to impacts from oil sands developments. Overlaying spatial and temporal anomalies can assist to characterize aquifer connectivity, and other approaches such as vulnerability mapping, ideally using the results of groundwater modeling can be used to identify potential new oil sands groundwater monitoring locations.

The interpretation of the combined AOSR groundwater geochemistry dataset provides support that conceptual models of vulnerability guiding the initial selection of MW locations appear valid. The focus on areas where the Colorado Group aquitard is absent due to incised rivers or buried channels is considered appropriate. The results of comparisons between the new AOSR database and the interim triggers in the NAOS, SAOS, and CLBR provides strong support for the idea that aquifer-based triggers and limits may not be suitable for groundwater monitoring in the AOSR, especially given the limited amount of available data in some aquifers. Single number triggers or limits for large and heterogeneous aquifers may not be representative of the entire aquifer, and it is recommended that approaches that account for wide range in aquifer quality, such as well-specific limits of change, or limits more closely linked to geological mapping should be explored.

The newly compiled AOSR baseline database has highlighted the value of groundwater quality data originally collected for other purposes to define baseline conditions at a regional scale. Provided that the associated metadata contain reliable information about completions and hydrostratigraphic units, and that data are required to pass the appropriate QA/QC screening, large volumes of groundwater quality data collected for other regulatory and monitoring purposes (e.g., EPEA compliance monitoring, applications for water use permits, domestic water well data) are likely to be an extremely valuable data source of baseline and timeseries information, one that is complementary to operation of a dedicated set of groundwater monitoring reference wells that are sampled and maintained by the appropriate monitoring agency. Additional recommendations for enhancing understanding of regional groundwater quality in the AOSR include continued groundwater monitoring (with expansion coverage in the central area and in regions with high potential for surface water-groundwater interaction), collection of a consistent set of water quality parameters, and recurring database maintenance, updates, and analysis. Appropriate statistical techniques such as bootstrapping (Manchuk et al., 2021) can remove anomalous data points and can be extremely valuable for incorporating these large regional datasets into distilled baseline data products. This assessment of a regional groundwater dataset from the AOSR highlights the challenges of groundwater monitoring in an area with diverse resource development activities associated with establishing baseline water quality distributions in a region with a high degree of spatial variability due to discontinuous geological features.

As a foundational step of adaptive monitoring, this study improved understanding of baseline groundwater quality in the AOSR conditions by statistically defining and spatially mapping baseline water quality conditions in the NAOS, SAOS, and CLBR sub-regions, for a subset of the primary and secondary water quality indicators in the LARP GWMF, such as TDS. Due to data limitations, there are still some areas where baseline groundwater quality has yet to be defined (e.g., for some parameters in some aquifers, as well as in the

Peace River region). Changes in groundwater quality over time were observed in 5 areas, 3 in the NAOS, one in the SAOS, and one in the CLBR. Confirmation of groundwater quality changes, and investigation of cause are recommended as next steps. To ensure that current and future development of oil sands resources do not pose a significant risk to groundwater and the connected groundwater dependent ecosystems, further characterization of regional baseline and natural variability of groundwater quantity, and groundwater discharge to rivers, lakes, and wetlands is also needed to serve as a basis for evaluating and attributing change and cumulative effects on the environment in view of a changing climate and other anthropogenic pressures within the region.

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.

Acknowledgements

This work was funded under the Oil Sands Monitoring (OSM) Program, of the Government of Alberta (Alberta Environment and Parks) and Environment and Climate Change Canada (20AEM841). It is independent of any position of the OSM program. Database and GIS support was provided by Don Jones.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101079.

References

Alberta Environment and Parks (AEP), 2012. Lower Athabasca Region– Groundwater Management Framework, ⟨https://open.alberta.ca/publications/9781460105344⟩.

Alberta Environment and Parks (AEP), 2013a. Lower Athabasca Region – Groundwater Management Framework Supporting Document for the North Athabasca Oil Sands (NAOS) Area. ISBN 978-1-4601-1118-5.

Alberta Environment and Parks (AEP), 2013b. Lower Athabasca Region – Groundwater Management Framework Supporting Document for the South Athabasca Oil Sands (SAOS) Area. ISBN: 978-1-4601-1119-2.

Alberta Environment and Parks (AEP), 2013c. Lower Athabasca region groundwater management framework: supporting document for the Cold Lake – Beaver River (CLBR) area. ISBN: 978-1-4601-1117-8.

Alberta Environment and Parks (AEP), 2018. Alberta merged wetland inventory (online). Available from ⟨https://maps.alberta.ca/genesis/rest/services/Alberta_Merged_Wetland_Inventory/Latest/MapServer/⟩.

Alley, W.M. (Ed.), 1993. Regional Groundwater-water Quality. Van Nostrand Reinhold, New York, p. 634.

Andriashek, L.D., 2003. Quaternary Geological Setting of the Athabasca Oil Sands (In Situ) Area, Northeast Alberta. Alberta Geological Survey Earth Sciences Report 2002-03.

Australia Pacific LNG, 2012, Australia Pacific LNG Upstream Phase 1 Groundwater Monitoring Plan, Q-LNG01-10-MP-005.

Australia Pacific LNG Upstream Project, 2016. 2015–2016 Groundwater Assessment Report, Australia Pacific LNG Upstream Project QLD-1000-E75-RPT, 437pp.

Andriashek, L.D., Atkinson, N., 2007. Buried Channels and Glacial-drift Aquifers in the Fort McMurray Region, Northeast Alberta (EUB/AGS Earth Sciences Report 2007-01). Alberta Energy and Utilities Board, p. 169.

Bachu, S., 1996. Regional Subsurface Hydrogeology in Northeast Alberta, Alberta Geological Survey Open File Report, 1996-14, 149pp.

Bachu, S., Underschltz, J.R., Hitchon, B., Cotterill, D., 1993. Regional-Scale Subsurvey Hydrogeology in Northeast Alberta, Bulletin, No. 61. Alberta Geological Survey, Alberta Research Council, 44pp.

Birks, S.J., Moncur, M.C., Gibson, J.J., Yi, Y., Fennell, W.J., Taylor, E.B., 2018. Origin and hydrogeological setting of saline groundwater discharges to the Athabasca River: geochemical and isotopic characterization of the hyporheic zone. Appl. Geochem. 98, 172–190. https://doi.org/10.1016/j.apgeochem.2018.09.005.

Birks, S.J., Fennell, J.W., Gibson, J.J., Yi, Y., Moncur, M.C., Brewster, M., 2019. Using regional datasets of groundwater isotope geochemistry to evaluate conceptual models of groundwater flow in the Athabasca Region. Appl. Geochem. 101, 140–159. https://doi.org/10.1016/j.apgeochem.2018.12.013.

Broughton, P.L., 2013. Devonian salt dissolution-collapse breccias flooring the Cretaceous Athabasca oil sands deposit and development of lower McMurray Formation sinkholes, northern Alberta Basin, Western Canada. Sediment. Geol. 283, 57–82.

Broughton, P.L., 2015. Collapse-induced fluidization structures in the Lower Cretaceous Athabasca Oil Sands Deposit, Western Canada. Basin Res. 28, 507–535. https://doi.org/10.1111/bre.12120.

Canadian Association of Petroleum Producers (CAPP), 2018. Crude Oil: Forecasts, Markets and Pipelines. CAPP report prepared.

Colorado Oil and Gas Association, 2011. Voluntary Baseline Groundwater Quality Sampling Program: Example Sampling and Analysis Plan Developed in Cooperation with the Colorado Oil and Gas Conservation Commission, 29 pp. Accessed February 2019 from ⟨http://region8water.colostate.edu/PDFs/Factsheet/COGA-sample-analysis-Plan.pdf⟩.

Cowie, B.R., James Bruce, Mayer, B., 2015. Distribution of total dissolved solids in McMurray formation water in the Athabasca Oil sands region, Alberta, Canada: implications for regional hydrogeology and resource development. AAPG Bull. 19 (1), 77–90.

Ellis, J., Jasechko, S.J., 2018. Formation waters discharge to rivers near the oil sands projects. Hydrol. Process. 32 (4), 533–549.

ENTRIX Inc., 2009. PXP Groundwater Monitoring Program and Work Plan: Inglewood Oil field, Baldwin Hills CSD Condition 19. Plains Exploration and Production Co., p 23

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall Inc, Toronto, Canada.

Gibson, J.J., Fennell, J., Birks, S.J., Yi, Y., Moncur, M., Hansen, B., Jasechko, S., 2013. Evidence of discharging saline formation water to the Athabasca River in the northern Athabasca oil sands region. Can. J. Earth Sci. 50 (1244–1257), 2013. https://doi.org/10.1139/cjes-2013-0027.

Gibson, J.J., Yi, Y., Birks, S.J., 2016. Isotope-based partitioning of streamflow in the oil sands region, northern Alberta: towards a monitoring strategy for assessing flow sources and water quality controls. J. Hydrol. 5, 131–148.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. Wiley, New York, p. 320.

Government of Alberta, 2014. Domestic Well Water Quality in Regions of Alberta: Physical and Chemical Testing. Alberta Domestic Well Water Quality Monitoring and Assessment Program. https://open.alberta.ca/publications/9781460119068.

Government of Alberta, 2017. Memorandum of Understanding Respecting Environmental Monitoring of Oil Sands Development. ⟨http://environmentalmonitoring.alberta.ca/wp-content/uploads/2018/03/OSM-MOU-December-1-2017.pdf⟩, 7pp.
Grasby, S.E., Chen, Z., 2005. Subglacial recharge into the Western Canada Sedimentary Basin – impact of Pleistocene glaciation on basin hydrodynamics. GSA Bull. 117, 500–514.
Gue, A.E., Mayer, B., Grasby, S.E., 2015. Origin and geochemistry of saline spring waters in the Athabasca oil sands region, Alberta, Canada. Appl. Geochem. 61, 132–145.
GW Solutions, 2015. Scientific Panel Review of the Groundwater Monitoring Plans in the Athabasca Oil Sands Region. Report Prepared for the Alberta Environmental Monitoring, Evaluation and Reporting Agency (AEMERA) and Environment Canada (EC).
Hackbarth, D.A., Nastasa, N., 1979. The hydrogeology of the Athabasca oil sands area, Alberta. Alta. Res. Counc. Bull. 38, 39.
Hrudy, S.E., Gosselin, P., Naeth, M.A., Plourde, A., Therrien, R., Van der Kraak, Xu, Z., 2010. Environmental and Health Impacts of Canada's Oil Sands Industry. The Royal Society of Canada Expert Panel: The Royal Society of Canada, Ottawa, p. 414. ⟨http://www.rsc.ca/expertpanels_reports.php⟩.
Integrated Sustainability, 2013a. Northern Athabasca Oil Sands Regional Groundwater Monitoring, Summary of 2012 Program. Report Prepared for Alberta Environment.
Kilgour, B., Mahaffey, S., Brown, C., Hughes, S., Hatry, C., Hamilton, L., 2019. Variation in toxicity and ecological risks associated with some oil sands groundwaters. Sci. Total Environ. 659, 1224–1233.
Lemay, T., Parks, K., Andriashek, L.D., Michael, K., Jean, G., Kempin, E., Stewart, S., 2005. Regional Groundwater Quality Appraisal, Cold Lake – Beaver River Drainage Basin, Alberta. EUB/AGS Special Report. ⟨https://ags.aer.ca/publication/spe-073⟩.
Manchuk, J., Birks, S.J., McClain, C., Bayegnak, G., Gibson, J.J., Deutsch, C., 2021. Estimating stable measured values and detecting anomalies in groundwater geochemistry time series data across the Athabasca Oil Sands Area, Canada. Nat. Resour. Res. 30, 1755–1779. https://doi.org/10.1007/s11053-020-09801-5.
Matrix, 2012. Guidelines for Groundwater Monitoring Best Practices Regional Municipality of Wood Buffalo. Prepared for Cumulative Environmental Management Association, p. 79.
Matrix Solutions Inc (Matrix), 2014a. 2013 Program Report South Athabasca Oil Sands Area Regional Groundwater Monitoring Network. Report prepared for Alberta Environment.
Matrix Solutions Inc (Matrix), 2014b. 2013 Groundwater Monitoring and Well Rehabilitation North Athabasca Oil Sands Area. Regional Groundwater Monitoring Network. Report Prepared for Alberta Environment.
Matrix Solutions Inc (Matrix), 2015a. 2014 Regional Groundwater Monitoring and Wells Rehabilitation Program North Athabasca Oil Sands Area Regional Groundwater Monitoring Network. Report Prepared for Alberta Environment.
Matrix Solutions Inc (Matrix), 2013. Framework for Development of a Regional Groundwater Monitoring Network – Interim Report, Southern Athabasca Oil Sands Area. Report prepared for Alberta Environment.
Matrix Solutions Inc (Matrix), 2015b. 2014 Program Report South Athabasca Oil Sands Area Regional Groundwater Monitoring Network. Report Prepared for Alberta Environment and Sustainable Resource Development.
Moncur, M.C., Paktunc, D., Birks, S.J., Ptacek, C.J., Welsh, B., Thibault, Y., 2015a. Source and distribution of naturally occurring arsenic in groundwater from Alberta's Southern Oil Sands Region. Appl. Geochem. 62, 171–185.
Moncur, M.C., Birks, S.J., Gibson, J.J., Yi, Y., Paktunc, D., 2015b. Predicting the mobilization of dissolved metals, organics and gas generation from aquifer sediments prior to in-situ operations. In: GeoConvention 2015. Canadian Society of Petroleum Geologists, Calgary, AB, pp. 4.
Munir, T.M., Khadka, B., Xu, B., Strack, M., 2017. Mineral nitrogen and phosphorus pools affected by water table lowering and warming in a boreal forested peatland. Ecohydrology 10, e1893. https://doi.org/10.1002/eco.1893.
Nie, M.A., Shultz, C.A., 2012. Decision-making triggers in adaptive management. Conserv. Biol. 26, 1137–1144. ⟨https://www.jstor.org/stable/23360129⟩.
Ozoray, G.F., 1974. Hydrogeology of the Waterways-Winefred Lake Area, Alberta (Report 74-2). Alberta Research Council, p. 18.
Parks, K., Andriashek, L.D., Michael, K., Lemay, T., Stewart, S., Jean, G., Kempin, E., 2005. Regional Groundwater Resource Appraisal, Cold Lake – Beaver River Drainage Basin, Alberta. EUB/AGS Special Report 74.
Schmidt, A., Gibson, J.J., Santos, I.R., Schubert, M., Tattrie, K., Weiss, H., 2010. Hydrol. Earth Syst. Sci. 14, 79–89.
Schneider, C.L., Cotterill, D., 2017. Introduction: the Devonian beneath the oil sands. Bull. Can. Pet. Geol. 65, 5–63. https://doi.org/10.2113/gscbull.65.1.64.
Teck, 2011. Environmental Assessment- Teck Resources Limited Frontier Oil Sands Mine Project Integrated Application, Volume 5: Water, 515 pp. ⟨https://open.alberta.ca/dataset/5da3a4f0-f982-4f8e-af9b-cb00c39fb165/resource/c0e63194-188e-4843-a078-41ab779786fc/download/fpvol5water.pdf⟩.
Volik, O., Elmes, M., Petrone, R., Kessel, E., Green, A., Cobbaert, D., Price, J., 2020. Wetlands in the Athabasca Oil Sands Region: the nexus between wetland hydrological function and resource extraction. Environ. Rev. 28 (3), 246–261.
Walker, J., Almasi, I., Stoakes, F., Potma, K., O'Keefe, J., 2017. Hypogenic karst beneath the Athabasca Oil Sands: implications for oil sands mining operations. Bull. Can. Pet. Geol. 65 (1), 115–146.
Wheaton, J.R., Donato, T.A., 2004. Ground-water Monitoring Program in Prospective Coalbed-Methane Areas of Southeastern Montana, Year One. Montana Bureau of Mines and Geology Open-file MBMG 508, p. 94.
Wind-Mulder, H.L., Rochefort, L., Vitt, D.H., 1996. Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. Ecol. Eng. 7, 161–181.
WorleyParsons, 2009a. Interim Groundwater Management Framework – Southern Athabasca Oil Sands (SAOS) Region. Report prepared for Alberta Environment.
WorleyParsons, 2009b. Vulnerability and Risk Mapping of the Lower Athabasca Region Plan. Report prepared for Alberta Environment.
WorleyParsons, 2010a. Regional Groundwater Quality Study and Monitoring Network Design in the Athabasca Oil Sands: Phase 1. Unpublished report prepared for Cumulative Environmental Management Association.
WorleyParsons, 2010c. Regional Groundwater Monitoring Network Implementation in the Northern Athabasca Oil Sands (NAOS): Phase 2 Program Summary. Report prepared for Alberta Environment.
WorleyParsons Canada Ltd, 2011. Northern Alberta Oil sands Regional Groundwater Monitoring Network Implementation 2010–2011 Program. Report prepared for Alberta Environment.