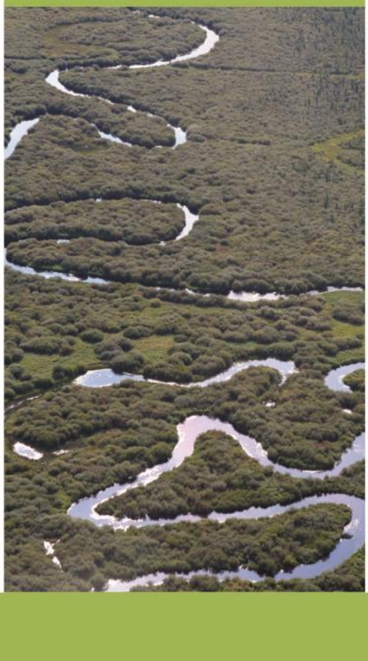
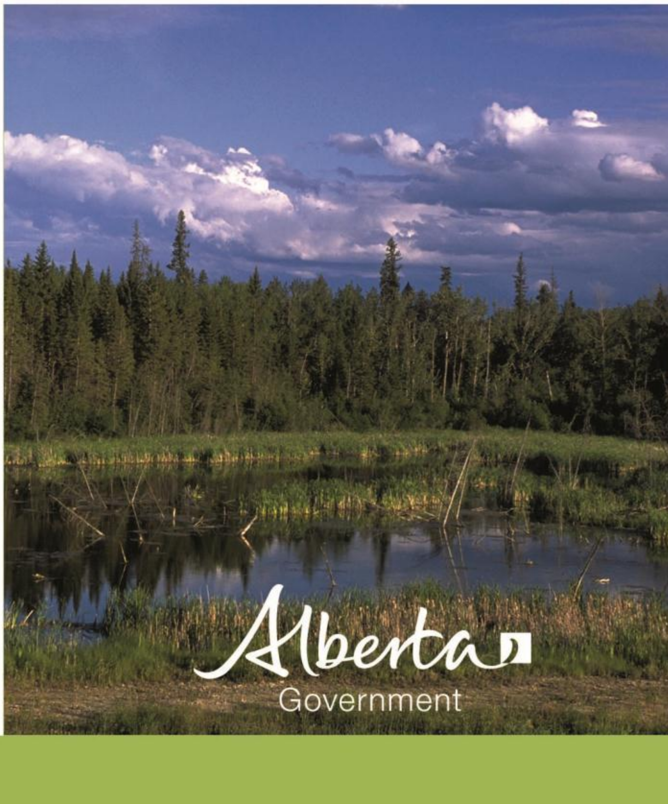
Lower Athabasca Region
Groundwater
Management Framework

Supporting Document for the
North Athabasca Oil Sands (NAOS) Area





LOWER ATHABASCA REGION
GROUNDWATER MANAGEMENT FRAMEWORK

SUPPORTING DOCUMENT FOR THE
NORTH ATHABASCA OIL SANDS (NAOS) AREA

Alberta Environment and Sustainable Resource Development

June 2013

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1 Introduction

In summer of 2012 the Government of Alberta approved the *Lower Athabasca Regional Plan* and with it, three environmental management frameworks that aim to manage the cumulative effects of different activities in the region. These are the *Lower Athabasca Region Air Quality*, *Surface Water Quality* and *Groundwater Management Frameworks*. The *Groundwater Management Framework* outlines a strategy for monitoring, evaluation and reporting, sets early warning triggers to indicate changes in groundwater conditions, and identifies management actions that may be taken when such changes are observed.

Because of the diverse hydrogeological conditions and development pressures across the Lower Athabasca Region, Alberta Environment and Sustainable Resource Development (AESRD) developed three supporting documents for the *Lower Athabasca Region Groundwater Management Framework (The Framework*). Regional-scale groundwater management is described in more detail in these *Supporting Documents for the*:

1. *North Athabasca Oil Sands (NAOS) Area*
2. *South Athabasca Oil Sands (SAOS) Area*
3. *Cold Lake Beaver River (CLBR) Area.*

In addition to the regional groundwater management approach described in these *Supporting Documents*, *The Framework* requires site-specific groundwater management strategies and the development of groundwater management plans for facilities and development activities approved under the *Environmental Protection and Enhancement Act (EPEA)*. These will be addressed in:

- *The Groundwater Monitoring Directive*[1], which will assist operators of industrial facilities across Alberta in developing and implementing site-specific Groundwater Management Plans; and
- *The Guidance Document for Groundwater Management Plans for In Situ Operations*[2], which will assist operators of in situ oil sands facilities in developing and implementing Groundwater Management Plans specifically for the management of thermally-mobilized elements.

1.1 Regional-scale Management of Cumulative Effects

The current process whereby the cumulative effects of known and planned projects in a given area are estimated in project-specific environmental impact assessments is suitable when a small number of projects are in development. With the large scale of development underway and projected for the future, a more systematic regional approach to cumulative effects management is necessary.

The Framework defines regional objectives for groundwater quantity and quality in the Lower Athabasca Region as follows.

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[1] *The Groundwater Monitoring Directive* is currently under development by AESRD and will be available through AESRD once completed.

[2] *The Guidance Document for Groundwater Management Plans for In Situ Operations*, as referenced in the *Groundwater Management Framework*, is currently under development by AESRD and will be available through AESRD once completed.

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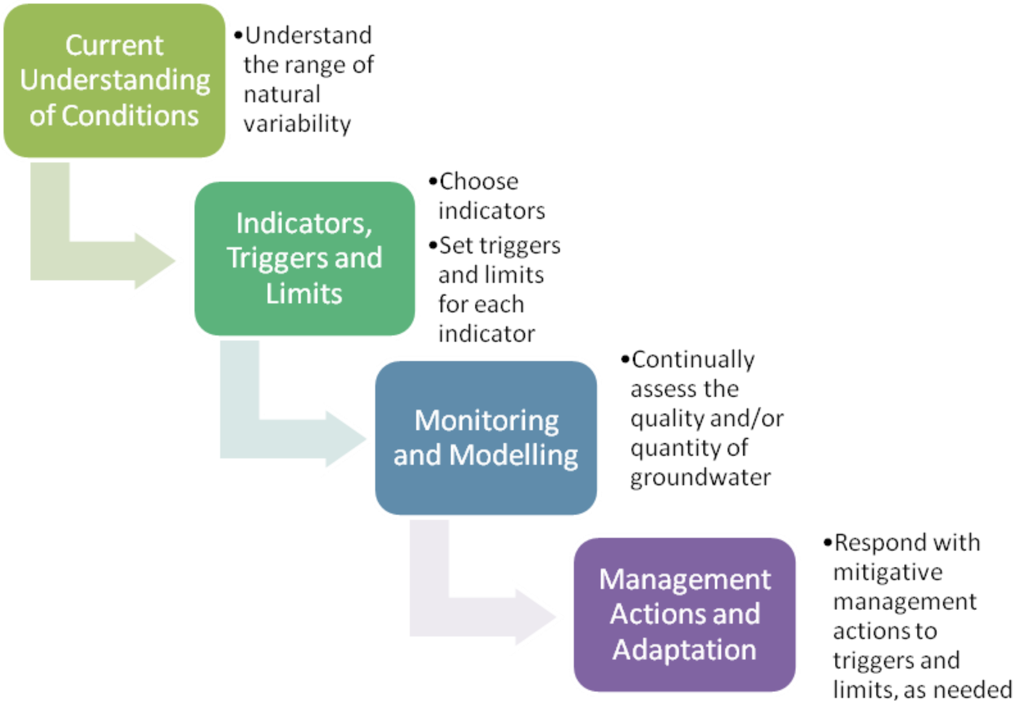
Regional Groundwater Quality Objective:

Groundwater quality is protected from contamination by maintaining conditions within the range of natural variability and not exceeding established limits.

Regional Groundwater Quantity Objective:

Groundwater resources continue to support human and ecosystem needs and the integrity of the regional flow system is maintained.

The management approach shown in the graphic below builds on that highlighted in *The Framework* and is part of evolving environmental management in the province aimed in this case at achieving the regional objectives for groundwater.



This Supporting Document is organized such that each component of the management approach shown above is elaborated upon in its own section.

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Section 2: Current Understanding of Groundwater Conditions

This *Supporting Document* provides summary information about the geology and hydrogeology of the NAOS area, providing a basis for understanding groundwater conditions. Data that is thought to represent un-impacted aquifer conditions is considered as baseline. Current understanding of baseline conditions for groundwater quality and quantity is predicated on historical data obtained from government and industry monitoring wells.

Using the current understanding of groundwater conditions, risk analysis and vulnerability assessments were conducted across the region to facilitate the identification of key aquifers and Aquifer Management Units (AMUs). AMUs are spatially-continuous and relatively chemically homogeneous groundwater systems.

For the purposes of this document, the terms aquifers, formations and AMUs are known as "intervals."

Under the mandate of Alberta Environment and Sustainable Resource Development, *The Framework* and this *Supporting Document* apply to non-saline groundwater resources: water that has a mineralization of 4,000 mg/L TDS or less (as measured by standard, accepted methods). Water possessing a mineralization in excess of 4,000 mg/L TDS (referred to as saline water) falls outside Alberta Environment and Sustainable Resource Development's mandate. However, if the initial mineralization is in excess of 4,000 mg/L TDS, and over time mineralization changes to below 4,000 mg/L, or evaluation identifies that saline groundwater would move into a non-saline aquifer or surface-water body, then this framework and provisions under the *Water Act* apply.

Section 3: Indicators, Triggers and Limits

The Framework identifies indicators related to oil sands mining operations, in situ operations and other activities in the Lower Athabasca Region areas under study. Once groundwater conditions of an area are known, the cumulative effects approach described in *The Framework* can be applied, and triggers can be established for each indicator. At this point in time, interim triggers have been set because there is insufficient data and information to allow for the establishment of final triggers or limits. That is the subject of continuing work.

Section 4: Monitoring and Modelling

Monitoring and modelling initiatives are being used to further understand groundwater conditions in the oil sands regions and to facilitate the evaluation of the cumulative effects of development. Existing information and historical monitoring data in the NAOS area was analyzed and used to develop conceptual and numerical models. These efforts helped establish the foundation of current knowledge of groundwater conditions in the area and informed the selection of interim regional groundwater indicators and triggers. Ongoing modelling work for the NAOS area will be used to further expand and refine monitoring initiatives, while monitoring data will further enhance groundwater models through the calibration process.

Section 5: Management Actions and Adaptation

Adaptation of *The Framework* will take place as additional experience is gained, new data is compiled, and understanding of groundwater management grows. Adjustments will focus on defining baseline conditions for wells in the NAOS groundwater monitoring network, confirming regional indicators, and finalizing triggers. A management response, as laid out in *The Framework*, will be required when the finalized triggers or limits are exceeded, with management actions commensurate with the risk level.

In preparing *The Framework* and *Supporting Documents*, the government consulted with stakeholders who live and work within the Lower Athabasca Region. Existing literature, monitoring data and regional studies were used to establish the foundation for knowledge of baseline conditions. This *Supporting Document* provides

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individuals and agencies operating in the NAOS area with information about groundwater conditions, and together with *The Framework*, build a shared understanding of the effects of past, current, and future development. Advancing the cumulative effects management approach, these documents complement existing policies, legislation, regulations, and management tools guiding sustainable development in our province.

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1.2 Purpose

The purpose of this *Supporting Document* is to provide technical detail and background related to *The Framework*, its regional objectives and stated goals. Sections 2, 3 and 4 support the specific goals of *The Framework*, as noted below in the outline.

Section 2	**Current Understanding of Conditions** **Goal 1: Establish the baseline groundwater conditions and range of natural variability in the Lower Athabasca Region to facilitate enhanced knowledge and detection of change.** • Section 2 provides background information about the geology and hydrogeology of the NAOS area and identifies priority intervals. Existing data is used to describe the current understanding of conditions for groundwater quality and quantity. **Goal 4: Support and supplement the current pollution prevention and risk management principles as part of groundwater quality and quantity management.** • Vulnerability and aquifer risk-mapping has been conducted based on current data, the results of which are used to define priority aquifers and aquifer management units (AMU).
Section 3	**Indicators, Triggers and Limits** **Goal 2: Provide a consistent approach to understanding potential effects from all development activities on the surrounding environment.** • Section 3 describes proposed methodologies for establishing a baseline, indicators, and setting regional triggers and limits. Outstanding considerations and future work are also described.
Section 4	**Monitoring and Modelling** **Goal 3: Facilitate projections of change based on future scenarios, such as expanding development, or climate variability and change.** • Section 4 describes current and planned initiatives with respect to monitoring and modelling. Criteria for developing the NAOS groundwater monitoring network and proposed oversight of the network are discussed.
Section 5	**Management Actions and Adaptation** • Section 5 highlights next steps in the adaptive implementation of *The Framework* and *Supporting Document for NAOS Area*.
Appendices	A – Figures B – Tables C – Vulnerability Assessment and Risk Mapping

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2 Current Understanding of Groundwater Conditions

GOAL 1: Establish the baseline groundwater conditions and range of natural variability in the Lower Athabasca Region to facilitate enhanced knowledge and detection of change.

GOAL 4: Support and supplement the current pollution prevention and risk management principles as part of groundwater quality and quantity management.

The geology and hydrogeology of the NAOS area are summarized in the following sections. Groundwater conditions for quality and quantity are described based on historical monitoring data. Risk assessment and vulnerability mapping tools are then applied to define priority areas, which may require further attention with respect to model development, monitoring activities, and management of groundwater resources.

2.1 The North Athabasca Oil Sands Area

At an estimated 169 billion barrels, Canada's crude oil reserves represent the third largest petroleum reserve in the world, next to Saudi Arabia and Venezuela, respectively (CAPP, 2012). The bulk of this crude oil is located in Alberta's oil sands deposits, which represents more than 82 per cent of the provinces oil reserves. The majority of Alberta's oil sands deposits are located in the Lower Athabasca Region (LAR), which covers approximately 93,212 km^2 in the northeast corner of Alberta.

The NAOS area, as shown in Figure 2-1, encompasses approximately 18,000 km^2 in the north part of the Lower Athabasca Region. Within this area approximately 950 km^2 (or 6 per cent) is underlain by oil sands deposits accessible from the surface using traditional mining techniques. To access the remaining oil sands requires drilling and completing of wells, and using steam or other mechanisms to reduce the viscosity of the bitumen so that it can be pumped to the surface. To date, the majority of activity is open pit mining; however, the number of in situ operations is increasing.

Figure 2-2 shows the coverage of oil sands leases in the NAOS area, while Figure 2-3 indicates the location of existing developments, as of 2010.

2.2 Summary of Geological Conditions

The principal geologic intervals beneath the NAOS area, in ascending order, are:

- Precambrian (basement)
- Devonian
- Cretaceous
- Quaternary.

Bedrock geology in the NAOS area is shown in Figure 2-4, and cross-sections are provided in Figure 2-5. These transects illustrate the major geologic units and their relative positions.

The stratigraphy of the bedrock units in the NAOS area (and other outlying areas) has been defined by Bachu and Underschultz (1993) of the Alberta Research Council (ARC). This is shown in Figure 2-6. The regional classification was derived by identifying sequences of aquifers (geologic layers that have the ability to transmit significant amounts of water), aquitards (geologic layers that transmit water at much lower rates and volumes and therefore impede water movement to some degree), or aquicludes (geologic layers that generally do not transmit much water) from which overall common characteristics could be recognized. A summary of the hydrostratigraphic column is presented in Table 2-1 (Appendix B).

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2.2.1 Precambrian

Solid rock of the Precambrian Shield forms the surface upon which the entire succession of younger stratigraphic units has been deposited (Bachu and Underschultz, 1993). Given that the rocks comprising the Precambrian Shield are very old (approximately 1.7 to 2.5 billion years old), significant modification by major structural and/or deformational activity has occurred.

Out-cropping of the Precambrian Shield occurs outside the north-east portion of the NAOS area where meta-sedimentary and granitic-type rocks dominate the sequence. The Precambrian surface dips uniformly to the southwest at four to five metres per kilometre (Bachu et al., 1991), and has local relief up to 50 metres. The Precambrian surface is very important from a hydrogeological perspective, as it is generally expected that water is neither stored nor transmitted by these rocks. The Precambrian surface is generally interpreted to represent the regional base of any substantial groundwater circulation.

2.2.2 Devonian

There is a major stratigraphic gap (unconformity) between the underlying Precambrian rocks and the overlying Devonian deposits due to a significant period of exposure and weathering. The Devonian formations sub crop along the Athabasca River Valley and at the north-central edge of the NAOS area.

The first known formation, the La Loche (or Granite Wash as it is locally referred to), comprises a fine- to coarse-grained arkosic sandstone that rests in contact with the Precambrian surface. The thickness of this permeable interval varies up to 40 metres (Sproule, 1974). This stratigraphic unit forms the oldest Devonian rocks in the area, and represents the deepest potential water-bearing strata.

Formations of the Elk Point Group, within the Middle Devonian, consist of shale, dolomite/dolostone, limestone and marl, and salt deposits consisting of sodium chloride (halite) and calcium sulphate (anhydrite). The shale, siltstone, and dolostone beds of the McLean River Formation (20 to 50 metres thick) conformably overlie the La Loche Formation.

The oldest rocks of the Upper Elk Point Subgroup belong to the Keg River Formation, also referred to as the Winnipegosis Formation or Methy Formation. These deposits consist of reefal dolostone, conformably overlying the McLean River Formation. Sproule (1974) indicates a formation thickness up to 80 metres with structural elevations of about 50 to 100 metres above sea level. The reefs are often porous at their crests, becoming more fine-grained and much less porous toward their bases. Greiner (1956) found that porosity of the main reef systems was high; whereas, the porosity of the off-reef (layered) limestones and dolomites was low. The porous sections of the reefal dolostone therefore exist as potential aquifers. Groundwater in this interval is typically a saline to very saline sodium-chloride type with a mineralization reaching in excess of 337,000 mg/L total dissolved solids (TDS) in some areas (WorleyParsons, 2010a). Concentrations as low as 450 mg/L TDS have been reported in some areas further to the east of the Athabasca River valley (Encana, 2007)

The Prairie Evaporite Formation, capped by the Muskeg Formation, overlies the Keg River Formation. The Prairie Evaporite Formation is a succession of evaporites (predominantly anhydrite with some halite accumulation), carbonates, and shale. The Muskeg Formation also consists of evaporites and carbonate deposits. Extensive removal of soluble salt layers by subsurface dissolution has resulted in localized collapse breccias in some areas (Grobe, 2000). In areas unaffected by salt dissolution, the Prairie Evaporite Formation dips gently to the southwest. This interval is expected to form a significant barrier to cross-formation groundwater flow between the Keg River Formation and the Upper Devonian Beaverhill Lake Group (Bachu and Underschultz, 1993), and is only present over the western portion of the area (i.e., the west side of the Athabasca River).

The youngest unit of the Upper Elk Point Subgroup is the Watt Mountain Formation, which disconformably overlies the Prairie Evaporite Formation. This aquitard interval is primarily comprised of dolomitic shale reaching up to about 15 metres thick (Sproule, 1974).

The Beaverhill Lake Group of sediments resides in the Upper Devonian strata within the NAOS area, and sub crops along the sub-Cretaceous unconformity. The thickness of the Beaverhill Lake Group varies between 50 and 100

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metres (Bachu et al., 1991). Within this group are the Slave Point Formation and the Waterways Formation. The Slave Point Formation is a thin rock unit (generally less than 15 metres) consisting of limestone, silty limestone and siltstone. The Waterways Formation overlies the Slave Point Formation and is the main Upper Devonian rock unit beneath the NAOS area. Crickmay (1957) subdivided the Waterways Formation into five members. In ascending order, the members are:

- Firebag
- Calumet
- Christina
- Moberly
- Mildred Lake.

The different members of the Waterways Formation form an alternating series of calcareous shales and carbonate intervals (Bachu et al., 1991). Hackbarth and Nastasa (1979) refer to the Waterways Formation as part of the "D2" hydrostratigraphic unit, which is expected to act as an effective barrier to vertical flow except in areas where prominent fracturing has occurred.

2.2.3 Cretaceous

Another significant time gap resides between the Devonian rocks and the overlying Cretaceous deposits. The two Cretaceous Groups present in the NAOS area are the Mannville Group and the Colorado Group.

Deposits of the Lower Cretaceous Mannville Group rest unconformably on the Devonian erosional surface. These deposits consist of a suite of heterogeneous clastic sedimentary units and are relatively uniform in thickness. In the NAOS area, the Mannville Group generally comprises three major formations. In ascending order, they are:

- McMurray Formation
- Clearwater Formation
- Grand Rapids Formation.

Deposition of McMurray Formation was largely controlled by topography of the erosional surface of the Devonian deposits (Wightman et al., 1995). Together with the overlying Wabiskaw Member of the Clearwater Formation, the McMurray Formation forms a mould of the pre-Cretaceous erosional surface, infilling the valleys and depressions with granular deposits (Wightman et al., 1995).

The McMurray Formation contains the oil sands being extracted in the area, and has been divided into four stratigraphic units (Carrigy, 1959):

- the coarse-grained, cemented quartzose sandstone of the pre-McMurray (not commonly found in the NAOS area)
- the Lower Member of the McMurray Formation whose lowest beds consist of residual clays formed from weathering of Devonian limestones, overlain by continental mudstones and medium- to coarse-grained sands
- the Middle and Upper Members of the McMurray Formation mainly comprised of oil-saturated quartz sand, interbedded with lenticular beds of micaceous silts, shales and, in places, clay.

Where it is oil-saturated, the McMurray Formation is considered an aquitard, thus impeding cross-formational flow of water from the deeper intervals to the shallower deposits. Where it is water-saturated, it is referred to as the "Basal Aquifer," and is shown in Figure 2-7. The thickness and distribution of the Basal Aquifer is largely controlled by the erosional surface of the underlying Devonian deposits and low bitumen content (e.g., less than 6 per cent residual). The Basal Aquifer is absent in some parts of the NAOS area and is generally thickest and most continuous east of the Athabasca River. Groundwater movement in the Basal Aquifer, in a regional context, is towards the Athabasca River. According to the groundwater surface elevations, the Basal Aquifer has the potential to discharge to the Athabasca River in areas where they interact (i.e., base flow contribution to the river). Groundwater quality in this interval varies significantly from non-saline to a saline sodium-chloride-bicarbonate

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type. Mineralization has been found to range from 182 mg/L to 278,000 mg/L TDS across the NAOS area (WorleyParsons, 2010a).

The Clearwater Formation conformably overlies the McMurray Formation, and consists of black to greenish-grey shales and greenish, glauconitic sands and silts. The most recent drilling information in the area suggests that the Clearwater Formation is present along the west, south and east portions of the NAOS area, and is largely absent from the lowlands surrounding the Athabasca River valley. The top of the Clearwater Formation slopes gently toward the Athabasca River from uplands in the Birch Mountains and Muskeg Mountain. This formation is classified as an aquitard.

Hamilton et al. (1999) indicate that the Grand Rapids Formation is absent over much of the NAOS area; however, it does sub crop beneath Muskeg Mountain and on the flanks of the Birch Mountains. Where it occurs, it is described as deltaic to marine in origin and an uncemented “salt and pepper” sand consisting of fragments of quartz, feldspar, glauconite, chert, muscovite, and biotite with interbeds of dark grey to black shale. The Grand Rapids Formation is informally divided into upper and lower units, with the upper unit containing more inter-bedded silt and shale compared to the relatively uniform lower sand unit. Bachu et al. (1991) state that the total thickness of the Grand Rapids Formation can reach up to 100 metres. Groundwater movement is expected to be largely controlled by its upland position; therefore, it is expected that groundwater would flow radially northward, westward and southward from, for example, Muskeg Mountain, and eastward to south eastward from the Thickwood Hills and Birch Mountain.

Hydraulic connectivity with the Grand Rapids Formation is anticipated between permeable glacial drift deposits such as outwash sands and buried valleys and channels (Birch, Clarke, Clarke T1, Clarke T2 and Lewis channels; and, Pemmican, South Pemmican, Pine, Thickwood and Spruce valleys) where they directly overlie, or are incised into, this bedrock unit. The Grand Rapids Formation is considered an aquifer in the NAOS area where it is sufficiently porous and permeable.

Deposits of the Colorado and Smoky Groups constitute the youngest Cretaceous rocks in the NAOS area, and are only encountered beneath Birch Mountain. The Colorado Group, which consists of the Joli Fou, Pelican, and LaBiche formations, generally consists of thick successions of shale aquitard intervals (Joli Fou and LaBiche Formations) interspersed with sand/sandstone intervals (Pelican). The Smoky Group, which was undifferentiated by Hamilton et al. (1999), consists of shale and silty shale sequences; however, data control beneath Birch Mountain area is poor.

2.2.4 Surficial Geology

The bedrock formations of Cretaceous and Devonian age are generally blanketed with Quaternary-aged deposits consisting of till, sands, clays, and silts. These surficial deposits, also known as “drift,” refer to all non-consolidated sediments that rest upon the bedrock surface, irrespective of age or genesis (Andriashek and Atkinson, 2007).

In general, the Quaternary sediments have been deposited by continental glaciers (till, ice contact moraine), by water associated with the melting and wasting of glacial ice (lacustrine deposits, fluvial outwash deposits), or by wind modification of water-laid sediments (aeolian deposits). Till and lake deposits dominate in the central, southern, western and north-western regions of the NAOS area. Localized areas of aeolian deposits are also present in those areas. Outwash sand and gravel deposits dominate in the eastern and northern regions of the NAOS area. Bayrock (2006), Bayrock and Reimchen (2005) and Turchenek and Lindsay (1982) indicate the distribution of the various surficial deposits over the NAOS area, as shown in Figure 2-8.

At least 27 buried bedrock channels or valleys have been mapped to date in the NAOS area (Andriashek and Atkinson, 2007). The locations of these features are illustrated on Figure 2-9. In general, the buried channels tend to be well-defined, linear to sinuous, and deeply incised. Within these channels are accumulations of drift (up to 100 metres), with coarse-grained sediments sometimes resting on the channel floors. The orientation of the buried channels and valleys tends to be parallel to sub-parallel to the Athabasca River, or run perpendicular to that main drainage feature. To date, no information has been put forward to indicate the presence of pre-glacial sand and gravel deposits in the area (Andriashek and Anderson, 2007).

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The more extensive areas of sand and gravel (glacial outwash deposits) can represent localized to sub-regional scale aquifers. Groundwater in these shallow intervals is typically a non-saline, calcium magnesium bicarbonate type with a mineralization of less than 1,000 mg/L TDS (WorleyParsons, 2010a).

This section has highlighted the regional geology; it does not focus on local-scale features, such as karst topography, the Devonian drop-down block, or glacial thrusting in the Fort Hills. All of the aforementioned local scale features have significant implications to groundwater movement, recharge and ultimately the management of groundwater. These local features significantly complicate the groundwater regime in the area, and operators may have to deal with very different challenges at a project scale. This also lends weight to the argument for having very good baseline data for each project site, as conditions can vary significantly over short distances.

2.3 Key Aquifers

The above geological formations consist of three main types of aquifers: near-surface sands, buried channels and valleys, and bedrock aquifers with primary and/or secondary porosity. From these formations, key aquifers have been identified based on size, yield potential, and groundwater quality (WorleyParsons, 2010a). These are the:

- Surficial deposits (including buried channels and outwash sands)
- Grand Rapids Formation
- Basal McMurray Aquifer sand unit (Basal Aquifer)
- Devonian Formations.

2.4 Overview of Groundwater in the NAOS Area

Following the summary of geological information provided in Sections 2.2 and 2.3, and using the comprehensive studies and data compilation conducted in 2010 (WorleyParsons, 2010a, 2010b), this section provides an overview of groundwater flow conditions and interactions with the surface water environment.

Groundwater in the NAOS area is contained within unconsolidated surficial deposits made up of sand and gravel of glacial and recent origin, buried channel deposits of glacial origin and permeable sediments of deeper, much older bedrock formations. The most important intervals pertaining to non-saline groundwater in the region include the near surface sand and gravel deposits and buried channel aquifers. In some cases, intervals within the Grand Rapids and Clearwater formations and Basal McMurray Aquifer contain non-saline water, which are also are managed through *The Framework.*

2.4.1 Groundwater Flow Conditions

A conceptual view of the regional groundwater flow patterns in the area is provided in Figure 2-10. Groundwater flow patterns are controlled, in a regional sense, by topography. Recharge (downward flow potential) generally occurs in uplands areas, while discharge (upward flow potential) occurs in adjacent low-lying areas and river valleys. Radial and semi-radial flow outward from regional upland areas is anticipated. The Athabasca and Clearwater river valleys exist as the dominant regional drains to groundwater, and receive portions of their flow from groundwater discharge (i.e., base flow).

2.4.2 Groundwater Flow Velocity

Calculated lateral groundwater flow velocities for the unconsolidated sediments (surficial sands and buried channels) have been estimated at less than one metre per year up to 140 metres per year or more. In contrast, flow velocities of less than one to 35 metres per year have been noted for the deeper and more consolidated bedrock formations (WorleyParsons, 2010a).

With respect to vertical flow, low permeability Clearwater Formation shales, McMurray Formation oil sands deposits, Upper Devonian Waterways Formation limestone and marlstone deposits, and intact evaporite deposits of the Middle Devonian act as regional aquitards. Although this is true on a regional scale, there are occurrences where the shale, McMurray and Devonian are not aquitards on a local or project scale.

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In the absence of defined pathways, these confining intervals effectively restrict cross-formational flow between the surficial deposits, the non-saline bedrock formations (Clearwater, Grand Rapids and Basal McMurray - in some locations) and the deeper saline intervals (i.e., Keg River and La Loche formations). Anticipated vertical flow velocities are on the order of 0.01 metres per year or much less.

2.4.3 Groundwater – Surface Water Interaction

In the NAOS area, groundwater – surface water interaction is known to occur between a number of features. These interactions primarily take the form of direct or indirect pathways allowing movement of natural oil sands-related constituents and natural formation waters towards, and in some cases into, receiving water bodies. Receiving bodies may include wetlands, fen and bog complexes, tributary streams to major rivers, or the Athabasca and Clearwater rivers themselves. Natural pathways may also contribute to the effects of drawdown from mine dewatering, water use in support of in situ development, or water disposal activities.

2.4.3.1 Surficial Deposits and Buried Channels

In the NAOS area, surficial outwash sands and buried channel deposits with a high potential for connectivity to surface water features have been designated as direct pathways. Several known points of potential interaction between the groundwater formation and surface water receiving bodies are shown in Table 2-2. McClelland Lake, Isadore’s Lake and Kearl Lake have been shown to contribute to groundwater recharge with values ranging from less than 0.15 to 0.3 million m^3/year (WorleyParsons, 2012).

In turn, buried channels and outwash deposits with a low potential for interaction with surface water bodies have been designated as indirect pathways by virtue of low permeability geological materials residing between them and downgradient water features. Indirect pathways exist for the following buried features:

- Willow Channel
- Thickwood Valley
- Spruce Valley
- Ruth, Inglis and Stony valleys
- Pemmican and South Pemmican valleys.

2.4.3.2 Devonian Formations and Basal McMurray Aquifer

Natural discharge of saline or low quality water into the Athabasca and Clearwater rivers, and seepage of water from the Devonian formations or the Basal McMurray Aquifer represent some existing pathways for groundwater movement in the NAOS area. There are multiple locations where visible springs discharge from out-crops along the valley walls. There is also potential for groundwater contamination at a local and regional scale through vertical pathways such as disposal wells and connected fracture systems transiting across aquitard intervals. The total discharge from groundwater aquifers to the Athabasca River and its tributaries within the NAOS area is estimated to be 236 million m^3/year to 590 million m^3/year (WorleyParsons, 2012).

2.5 Potential Influences on Groundwater Conditions in the NAOS Area

A number of activities within the NAOS area could potentially influence groundwater quality and quantity conditions in the non-saline water-bearing intervals. These activities include mining and in situ development, as well as other human-related and natural influences. All of these influences and additive effects must be taken into account when assessing groundwater quality and water level fluctuations across the area.

2.5.1 Mining

Mining of the oil sands results in significant land disturbance. Large amounts of earth are removed and stockpiled to facilitate access to the mineable ore deposits. Active mine areas must be de-watered for safe development; therefore, large areas of drawdown (tens of square kilometres) may develop. Changes to groundwater quantity may affect water sources close to the surface.

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With respect to groundwater quality, impacts tend to be localized due to the slow movement of groundwater (i.e., less than one to tens of metres per year) and attenuating processes that occur in the subsurface. Current knowledge of groundwater quality conditions around existing operations indicates the presence of some localized changes, which are being dealt with under existing *EPEA* approvals.

The main challenges associated with mine development include:

- physical disturbance of the landscape and alteration to natural drainage and recharge patterns
- drawdown effects from de-watering of overburden aquifers and bedrock formations to facilitate safe mine development
- potential seepage of constituents from established waste containment structures
- leaching of constituents from overburden waste dumps and material stockpiles
- pressure effects and constituent mobility following downhole injection of depressurization water and process wastewater
- operational upsets (spills and leaks of chemicals and hydrocarbons at processing facilities and active mine areas).

Potential inputs to the environment from mine development include: soluble salts, dissolved organics (including naphthenic acids), metals, trace elements, phenols, and low molecular weight (LMW) hydrocarbons (e.g. polycyclic aromatic hydrocarbons).

2.5.2 In Situ

In situ activities affect water levels in various aquifer intervals primarily through the extraction and use of groundwater for steam generation to assist bitumen recovery.

There is also potential to influence quality conditions as a result of:

- physical and chemical effects from localized heating of subsurface formations
- pressure effects and constituent migration from waste disposal activities
- the unlikely release of production fluids from casing failures or annular leakage
- other operational upsets such as spills, leaks and uncontrolled releases of chemicals and hydrocarbons.

Potential inputs to the environment from in situ development include soluble salts and dissolved organic matter (including naphthenic acids), metals, trace elements, phenols, and low molecular weight hydrocarbons (e.g., polycyclic aromatic hydrocarbons). Impacts to groundwater quality may occur due to the disruption of natural barriers, creation of pathways for groundwater movement, and changes to the connection between otherwise discrete aquifer intervals.

In situ operations affect a relatively small footprint, as seen in Figure 2-11; however, overall development planned for the future results in a diffuse, but notable, surface disturbance through linear corridor development and well pad construction.

It is recognized that in situ development will have local-scale effects, but collectively these developments need scrutiny from a cumulative perspective.

2.5.3 Other Influences

Other potential sources of groundwater impacts related to human and natural influences include:

- municipal development (including landfills, waste storage areas, modified infiltration and run-off patterns)
- aggregate (gravel) mining operations
- forestry cut blocks and wood processing mills

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- upstream oil/gas activity (effects of gas production on the Cretaceous bedrock aquifer water levels)
- leaching of pesticide and fertilizer residues into shallow aquifers from municipal applications
- effects of natural disturbances such as forest fires, climate variability and climate change on regional groundwater levels and quality.

Potential inputs to the environment from these human and natural sources include municipal wastes, fertilizers, pesticides, halogenated compounds, soluble salts, hydrocarbons and polycyclic aromatic hydrocarbons, metals, trace elements and dissolved organics.

The various geological formations also have natural influences on groundwater and surface water quality, such as the following:

- leaching of soluble hydrocarbons, salts, and trace elements from exposed bedrock formations and muskeg deposits into local water bodies; for example, the Athabasca River cuts through oil sands deposit and into the underlying Devonian formations, exposing bitumen deposits
- some buried channels have eroded into the underlying oil sands deposit and are in direct contact with saline and bitumen-laden material resulting in measurable concentrations of soluble salts and hydrocarbons in the natural groundwater of the area
- natural discharge of low-quality, saline waters from the bedrock formations into local water bodies or aquifers; for example Saline Lake is a natural water body that receives saline water from the Devonian formations
- leaching of soluble hydrocarbons, salts, and trace elements to the local groundwater from segments of oil sands present within the overburden deposits.

2.6 Historical Groundwater Monitoring Systems

A large majority of monitoring wells in the NAOS area belong to oil sands operators. Since 1993, the *Environmental Protection and Enhancement Act* (*EPEA)* has had provisions to require companies to manage on-site monitoring wells. When a company receives an approval there may be a requirement from the Director for the implementation of groundwater monitoring programs. This compliance monitoring is designed to be protective of the environmental resources surrounding all operating facilities. Approval requirements are the primary regulatory tools for enforcing goals of the *EPEA*. Groundwater monitoring and reporting is also a requirement of licences issued under the *Water Act.*

Groundwater monitoring has also taken place on a province-wide basis through the Groundwater Observation Well Network (GOWN). This network was initiated by the Alberta Research Council (ARC) in 1957, and was taken over by AENV in 1982. Within the NAOS area, there are approximately 77 GOWN wells at 27 sites, with wells completed at depth intervals ranging from 20 to over 400 metres below ground surface. AENV actively monitored 16 of these wells at five sites. The data generally covers the early 1970s to mid-1990s and includes both water level measurements and occasional water quality sampling. Given the scale of development at the time and the location of the wells, the information obtained from this monitoring may, in many cases, be considered to represent pre-development information.

While site-specific monitoring conducted by operators has been continuous, regional monitoring conducted by AENV decreased significantly from the mid-1990s until 2008. The department began work in 2008 to develop a NAOS Groundwater Monitoring Network to fill knowledge gaps left from historical monitoring systems and improve understanding of the complex groundwater conditions in the NAOS area. This current and developing monitoring network is described in Section 4.1.

2.7 Current Understanding of Groundwater Quality and Quantity

The historical chemistry and water level data used in this *Supporting Document* was compiled from groundwater monitoring wells in the NAOS area, the majority of which are owned and managed by oil sands operators (WorleyParsons, 2010a). The data was reviewed for quality assurance and quality control (QA/QC) purposes, and

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erroneous values were removed to create a reliable database. This historical record was used to establish preliminary baseline conditions and formed the basis for determining interim trigger values in *The Framework.*

2.7.1 Groundwater Quality in the NAOS Area

Chemistry records from 419 wells were used to determine preliminary baseline conditions conditions representing main aquifers, including buried channels and valleys. Data collection spanned 1970 to 2008. Figure 2-12 shows the distribution of these wells within the NAOS area. Observed parameters include major ions, nutrients, metals and trace elements, and select hydrocarbons.

Due to the variability in both reliability and completeness of historic well records, a data quality rating system was developed, based on temporal, spatial, and physical data for each interval. Table 2-3 describes the three categories for data: good, fair and poor.

Groundwater quality data is considered fair for the surficial sands, Birch channel, and Basal McMurray aquifer, while data for the Kearl and Thickwater channels, and the Grand Rapids,Wabiskaw and mid Devonian/Keg River bedrock aquifers is considered poor. More groundwater quality monitoring data are needed from the buried valleys, Grand Rapids Formation and several buried channels (i.e., Clark, Fort Hills, North Spruce, South Spruce, Willow, Upper Kearl, and Lewis channels) to sufficiently frame baseline conditions and there is limited temporal data for most aquifers. Table 2-4 gives an overview of the available data for each interval, as well as the data quality rating.

The data described in Table 2-4 were used to develop preliminary baseline conditions and interim triggers. A summary of preliminary baseline conditions is presented in Table 2-5, while complete data sets are shown in Tables 2-6 to 2-9. Triggers that were set are interim due in part to the poor quality of this data.

A considerable range in concentration exists for the various indicators assessed. This illustrates the high degree of variability throughout the area resulting from the natural hydrogeologic complexity (i.e., the presence of mixing zones and interaction with near-surface, and active, flow systems) or potentially, well-screen placement in relation to certain formations.

With respect to salinity, groundwater mineralization for the surficial deposits, including surficial sands and buried channels, is generally less than 1,000 mg/L TDS, as shown in Figure 2-13. For the shallower bedrock aquifers, TDS values range from non-saline up to saline (1,000 to 4,000 mg/L), with the deeper formations (Basal McMurray and Keg River aquifers) generally indicating saline to brine conditions (4,000 to greater than 300,000 mg/L TDS). Spatially, chemistry results vary substantially for the Basal McMurray Aquifer, with all classes of salinity found in the aquifer, as shown in Figure 2-14. The aquifer management units (AMU) for the Basal McMurray Aquifer were designated based, in part, on this chemical variability, as described in Section 2.9.

As there is limited temporal data available in the NAOS area, no significant trends in key indicators have been recorded since initial sampling back in 1975. General patterns of groundwater quality indicated by a review of the data are listed below.

- Mineralization in the bedrock aquifers east of the Athabasca River tends to be much lower compared to formations on the west side of the river. This suggests a more active groundwater system in the east portion of the area when compared to the west portion.
- The presence of deep-seated structures resulting from bedrock movement following dissolution of the Prairie Evaporite salt deposits and resulting collapse of the overlying formations (down-drop blocks) results in significantly different quality conditions in localized areas within certain formations.
- Differences in quality conditions between the surficial sand aquifers and underlying buried channels are minor compared to the differences between the bedrock aquifers and overlying surficial deposits.
- Effects of mixing between bedrock waters and surficial aquifers are recognized based on the occurrence of elevated TDS and certain parameters (e.g., sodium and chloride ions) within discrete intervals. The variability of these effects is likely due to the placement of the well screen in relation to underlying bedrock or rafted sections of bedrock.

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- The presence of naturally-occurring hydrocarbons is evident based on visual observations of asphalt pads and hydrocarbon sheen along the shores of the Athabasca River, and results from monitoring wells established outside existing development areas.

2.7.2 Groundwater Quantity in the NAOS Area

To gain an understanding of the approximate quantity of groundwater in the study area, information and data for the major water-bearing intervals, including the near surface sand and gravel deposits and buried channel aquifers, is required. This data includes:

- groundwater surface elevations
- maps of aquifer distribution and thickness (i.e., volume)
- estimates of effective porosity
- estimates of recharge, or groundwater replenishment
- maps describing areas where surficial aquifers are potentially hydraulically-connected to surface water features
- estimates of the groundwater fluxes discharging to surface water.

Information on historical groundwater surface elevations, estimated recharge volumes, and known water use can provide a preliminary indication of changes in groundwater quantity and its sustainable use. In-depth analysis of all the above parameters will be conducted through modelling efforts to more accurately estimate total groundwater volumes and sustainable yield.

To date, only preliminary estimates of non-saline groundwater volumes have been obtained for the various aquifer systems in Alberta (AI-EES 2011), and nothing particular to the oil sands has been completed. However, policies such as the *Water Conservation and Allocation Guideline for Oilfield Injection* (AENV, 2006) and the *Alberta Environment Guide to Groundwater Authorization* (AENV, 2011) provide guidelines and processes to limit groundwater use and protect the volumes of groundwater needed to sustain environmental needs.

2.7.2.1 Groundwater Surface Elevation

Baseline conditions for groundwater quantity can be represented by groundwater surface elevations prior to, or in the absence of, any impact from human-related activities. A total of 5,480 groundwater surface elevation records were accessed from 684 monitoring wells in the NAOS area, dating between 1972 and 2008. The number of groundwater surface elevation readings for a given monitoring well ranges from a single measurement up to 82 readings. Table 2-10 summarizes the number of wells and number of records for the surficial and bedrock formations identified. From this data set, temporal fluctuations and the potential occurrence of drawdown effects across the area were assessed.

Initial results from the surface elevation assessment indicate isolated areas of drawdown in the Basal McMurray Aquifer located in the Muskeg River watershed where active dewatering for mine development is occurring. This effect has been projected based on model results from cumulative impact assessments conducted by the various operators in that part of the area. Drawdown of 15 to 25 metres has been observed (WorleyParsons, 2010b) near active mining areas. In more remote locations, natural water level fluctuations in the area’s aquifers have been recorded in the range of one to four metres. Wells completed in the surficial deposits and channels have shown fluctuations consistent with natural seasonal, intra-decadal and inter-decadal variability, but have not shown significant impacts due to deep aquifer pumping. This suggests limited interconnectivity between the shallow and deep aquifers, and limited spatial effects of drawdown related to water use.

2.7.2.2 Groundwater Use

Groundwater withdrawal is known from water licensing data. Table 2-11 shows the number and volume of licences in 2009 assigned to each major aquifer interval, as well as the volume of water actually withdrawn. The total licenced volume is approximately 52 million m^3 per year, while the average annual volume of water withdrawn is 30 million m^3, or 57 per cent. While over half of the licences are in the surficial deposits, 87 per cent of water used

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is from the Kearl Channel. Figures 2-15 and 2-16 show the spatial distribution of licenced groundwater use in surficial sands and the Basal McMurray Aquifer, respectively.

As of October 2011, groundwater allocation had risen by approximately 40 per cent from 2009 values, to 72.8 million m^3/year (WorleyParsons, 2012). Assuming the constant withdrawal rate of 57 per cent, it is estimated that corresponding groundwater withdrawal volume was 41.5 million m^3/year.

2.7.2.3 Groundwater Recharge

Groundwater recharge data from the infiltration of precipitation in the NAOS area have been estimated based on published studies for till-covered settings in the Plains Region of North America (Fortin et al., 1991; Rehm et al., 1982; Meyboom, 1967; Smerdon, 2007), as well as the mapped surficial geology units across the NAOS area. See Table 2-12 for a summary of findings from these studies. Overall, the reported recharge rates range from 0.5 – 17 per cent of annual precipitation.

The overall estimate of recharge to the surficial deposits in the region ranges from 200 million m^3 per year, for the low recharge rates of 1.5 per cent of annual precipitation in till areas and 5 per cent in sandy areas, to 750 million m^3 per year for the higher recharge rates of 9 per cent of annual precipitation in till areas and 17 per cent of precipitation in sandy areas. Using average recharge rates, the overall estimated annual recharge to the shallow deposits in the NAOS area is calculated to be on the order of 470 million m^3 per year. See Table 2-13 for recharge estimates regarding the surficial deposits.

2.8 Aquifer Risk Mapping

Risk mapping was completed across the Lower Athabasca Region to identify aquifers that may be naturally vulnerable to the potential effects of existing or planned development activities (WorleyParsons, 2009). These aquifers are a priority for future groundwater monitoring and management.

Risk exists only if there is a source of contamination, a receptor, and a pathway between the source and the receptor. The severity of risk will be determined by the nature of each of these attributes. Figure 2-17 provides a conceptual view of environmental risk based on source, receptor and pathway. In groundwater risk mapping, source is represented by the type and intensity of development; pathways are determined by the intrinsic properties and features of the subsurface; and receptors are either human or ecological and have varying degrees of sensitivity to effects. Aquifers may be considered both a receptor as well as a pathway to other receptors.

The method of risk assessment is described briefly below. A more complete description of methods used for risk mapping is provided in Appendix C and WorleyParsons (2009).

2.8.1 Intrinsic Vulnerability

An enhanced version of the USGS model DRASTIC (Aller et al., 1987) was used to map potential groundwater vulnerability for surficial deposits and the Basal McMurray Aquifer, using the hydrogeological and risk-based attributes listed in Table 2-14. The model was adjusted to account for buried channels in the surficial deposits, and for dewatering and injection activities in the Basal McMurray Aquifer; however, only the portion of the Basal McMurray Aquifer within the NAOS area was considered.

A weighting system was developed to reflect the relative significance of each attribute at a given location, where a high value represents vulnerable conditions and a low number represents more robust conditions. Figures 2-18 and 2-19 show results for these individual attributes, indicating areas of high and low vulnerability, for surficial deposits and the Basal McMurray Aquifer, respectively.

2.8.2 Risk Mapping

The modified DRASTIC model that was used to map aquifer vulnerability was further adapted to include two additional layers, allowing for a more complete assessment of source, pathways and receptors. These layers identify existing and potential development activities, buried channels and faults and potential surface water body receptors.

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Together, this information creates a picture of the potential for cumulative effects of development in the Lower Athabasca Region.

Areas with the highest development rating are concentrated around the older mine areas such as Suncor and Syncrude due to their age and existing infrastructure (i.e., tailings ponds). Smaller areas of high development rating are present at the newer mines in the north central portion of the NAOS area (Albian and Aurora) and SAGD activities in more peripheral areas with a lower density of potential contaminant sources.

2.8.3 Risk Mapping Results

Risk was assessed by superimposing the additional layers representing source, pathways and receptors onto the vulnerability maps. Areas identified with high vulnerability, high receptor sensitivity, and high potential development pressures have higher potential risk to groundwater resources. The approach to assign potential risk across the Lower Athabasca Region is provided in Figure 2-20.

2.8.3.1 Results of Aquifer Risk Mapping for Surficial Deposits

Figure 2-21 shows the aggregate vulnerability ratings (background colours) and development ratings (overlain grey areas) for surficial deposits (WorleyParsons, 2009). Several areas exist where vulnerability is rated as moderate or high, which when coupled with the development rating and receptor sensitivity, results in various risk scenarios for impacts to groundwater. Channels are ranked independently, based on their connection to rivers. Risk ratings for key areas are summarized below.

- Much of the Kearl Channel has a high vulnerability rating, due to aquifer media and hydraulic conductivity. Further, the channel is identified as being potentially connected to the Firebag River. Development pressures are rated as high as development intensity is poised to increase with the commissioning of the new mines in the area (i.e., Imperial Oil Kearl and Shell Jackpine), and expansion of others. This area therefore represents a high risk to the groundwater environment.

- The Clearwater and Athabasca river valleys and surrounding low-lying areas were identified as having moderate vulnerability due to less protective cover, moderate soil media and shallow depth to water. There are areas where development is occurring, or is planned to occur, along the Athabasca River and its tributaries. Such areas have an overall risk to groundwater that is considered high.

- A high vulnerability rating was also determined for the southern portion of the NAOS area east of the Athabasca River near the Lewis and Clark channels, due primarily to aquifer media and hydraulic conductivity. The Lewis and Clark channels are identified as being potentially connected to the Athabasca River and associated tributaries (North Steepbank and Steepbank rivers). Development pressures are presently low in this area, except for in situ operations planned near the northern part of the Lewis Channel. Overall risk is therefore moderate, except in areas of in situ development, where risk is considered high.

- High vulnerability due to aquifer media and hydraulic conductivity was associated with small areas on the west side of the Athabasca River along the Birch and Willow channels. The Birch Channel is also identified as being potentially connected to a tributary of the Athabasca River (i.e., MacKay River). Due to the existing in situ development over the Birch Channel, the risk rating for this area is considered high.

- The Fort Hills Channel in the northern portion of the NAOS area is identified as being potentially connected to the Athabasca River and nearby surface water bodies (i.e., McClelland Lake and associated fen and wetland complex). The area is represented by moderate intrinsic vulnerability due to infiltration potential and depth to water and the sensitivity of the nearby surface water bodies is considered high. It has a low to moderate level of development. Overall risk to groundwater is therefore moderate.

- The areas flanking the Muskeg Mountain to the north and east were identified as having moderate to high vulnerability, primarily driven by the thickness of surficial deposits and mapped soil media (i.e., outwash

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sands). This is also a significant upland feature for recharge. Due to existing and planned development in this area, the overall risk is considered moderate.

2.8.3.2 Results of Aquifer Risk Mapping for Basal McMurray

Figure 2-22 shows the aggregate vulnerability rating for the Basal McMurray Aquifer, representing the sum of vulnerability ratings for the different attributes. Overlain are water quality assessment wells in the formation, representing development activities. The highest overall risk is where the wells exist in areas of high vulnerability.

One of the highest areas of vulnerability of the Basal McMurray Aquifer is along the Athabasca River in the central portion of the NAOS area. This is primarily based on the low thickness of protective surficial deposits, the presence of known and suspected fault features, and the potential for interaction with the Athabasca River. Development pressures include anticipated drawdown from mine dewatering and potential interaction between non-saline portions of the Basal McMurray Aquifer and lower quality porewater residing in the backfill of abandoned mine pits.

In the central portion of the NAOS area, and east of the Athabasca River, high vulnerability is due to the proximity of large wetland areas and the presence of aquifers with potable or useable water supplies. Development risks are associated with the presence and anticipated development of tailings structures and anticipated drawdown intensity. Both of these areas overlay the Basal McMurray Aquifer and risk for potential impacts to groundwater is considered high.

2.9 Aquifer Classification

The above risk assessment contributed to the identification of priority areas for groundwater management. By defining these areas and the respective aquifers of concern, the management of the groundwater can be adapted to the area’s diverse conditions and specific intervals can be more effectively managed according to their intrinsic qualities.

The aquifer classification system used to identify priority intervals is based on the following attributes:

- aquifer size
- yield capacity
- existing potability conditions or potential
- potential for groundwater/surface water interaction
- type of use (supply or disposal)
- current and future water use demand
- presence of quality and quantity concerns
- existence of knowledge and data gaps
- overall risk rating.

For a given interval, a score was determined for each attribute and then all of the attribute scores were summed for a total score. The highest score represents the higher priority aquifers. Table 2-15 shows the scoring for each interval.

The following intervals yielded the highest scores and are considered a priority for assessment and/or protection.

- Surficial sands (in active areas)
- Buried channels (Birch and Kearl channels)
- Basal McMurray Aquifer (in the Albian, Jackpine, Aurora, and Kearl mine development areas)

The Basal McMurray Aquifer has highly variable chemical composition (fresh to saline) and diverse actual and potential uses (e.g. water supply and waste disposal). Given these rather unique properties, it was necessary to sub-divide the interval into Aquifer Management Units (AMUs). These management units are defined as spatially continuous and chemically homogeneous groundwater systems that have different characteristics, influences and risks. At present, four separate AMUs for the Basal McMurray Aquifer have been identified, of which two relate to

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non-saline conditions (AMU 1 and AMU 2). These two AMUs are described in Table 2-16 and illustrated in Figure 2-23, and will be the focus of monitoring and management efforts for the Basal McMurray Aquifer.

Similar conditions may exist for the Keg River Formation near sub cropping areas; however, not enough information is available at present to warrant the development of AMUs for this water-bearing interval.

To date, no AMUs have been defined for the surficial sands and buried channels; however, as additional information becomes available this may change.

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3 Indicators, Triggers and Limits

GOAL 2: Provide a consistent approach to understanding potential effects from all development activities on the surrounding environment.

Once hydrogeological conditions of an area are known, the cumulative effects approach described in *The Framework* can be applied. The intention is to establish regional indicators and associated triggers and limits. Data from individual monitoring wells will be assessed and then compiled for each key aquifer. It will be used to create and refine baseline values for indicators in each interval, and to define associated triggers and limits. Triggers and limits are designed to meet the regional objectives for groundwater quality and quantity, shown in Section 1.

This section describes the key components of the regional cumulative effects approach: indicators, baseline, triggers and limits.

The Framework also describes the need for site-specific groundwater management. This will be achieved through the preparation and submission of groundwater management plans by regulated operators. Site-specific management will be undertaken to control potential impacts to groundwater at approved facilities and developments to minimize the potential for regional cumulative effects. Site-specific requirements are described in *The Groundwater Monitoring Directive*, *The Guidance Document for Groundwater Management Plans for In Situ Operations* and through regulatory authorizations.

3.1 Regional Indicators

Indicators are used to measure the cause-and-effect relationship between human activities and natural influences on the landscape, and the environmental response to those influences. They can provide information about whether or not a regional objective is being met. Appropriate indicators include those that are:

- commonly present in the environment
- relatively easy and inexpensive to measure
- sensitive to environmental change
- specific to disturbance effects
- affected by project design and management.

3.1.1 Methodology for Establishing Indicators

Indicators for groundwater quality and quantity have been divided into primary, secondary and tertiary indicators. Primary indicators are the initial screening tool. Secondary indicators are intended to support any follow-up investigation required under the management framework. Tertiary levels are implemented only when required; these tend to be more sophisticated, but can assess conditions at a high level of refinement. Primary, secondary and tertiary indicator levels for mining, in situ and other influences were identified in *The Framework* and are shown in Tables 3-1 to 3-3.

3.1.1.1 Groundwater Quality Indicators

Indicator selection for groundwater quality in the NAOS area considered mining, in situ and other anthropogenic and natural influences on groundwater as described in Section 2.5. Mining indicators were selected by reviewing descriptive statistics for chemical constituents associated with process-affected mine waters, consolidated tailings samples, and mature fine tailings samples (Imperial Oil, 2006).

Indicators for in situ developments were identified as those constituents with potential for mobilization from sediments due to localized heating from steam injection operations, as well as substances with the potential to be introduced into the surrounding environment through casing failures or annular seepage through connected pathways.

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Indicators must be differentiated according to whether or not they are present naturally in groundwater, as the determination of baseline and triggers will differ accordingly. Indicators that are not present naturally in groundwater include substances which may be introduced into the subsurface through human activity (e.g. hydrocarbons, process chemicals), as well as natural constituents which are present at concentrations below the Action Level (AL) defined in the *Groundwater Monitoring Directive* (e.g. certain metals and trace elements).

The AL is the minimum analytical value at which a laboratory can reliably report the concentration of a given substance. The substance may be detected at a lower concentration, but due to the uncertainty of results at or near the method detection level, only results above the AL are considered reliable. The AL will be used to differentiate between indicators that are naturally occurring and those that are not, each with its own method for determining baseline and triggers, as described in Section 3.3.

Monitoring activities will include indicators that are present naturally in groundwater and those that are not.

3.1.1.2 Groundwater Quantity Indicators

Groundwater surface elevation is identified in *The Framework* as the primary indicator for groundwater quantity and availability. Secondary indicators include the impact to sensitive water bodies or wetlands as demonstrated by water level changes, as well as the accuracy of modelling results versus measured values for surface water and water table levels.

3.1.2 Considerations and Future Work on Indicators

3.1.2.1 Refinement of Indicators

The selection of primary indicators for quality and quantity will be assessed, and either revised or confirmed, as more monitoring data becomes available and understanding of hydrogeological conditions evolves. Experience gained through the application of the framework will also allow for refinement and adaptation. For groundwater quantity, confirmation of indicators will have to consider natural fluctuations in water level elevations in monitoring wells that occur over the short-term and long-term, in response to barometric pressure changes or variability in climatic conditions. The use of secondary and tertiary indicators will be further explored in the future, as required.

3.1.2.2 Development Indicators

Currently the framework uses “condition” indicators, which relate to the physical, chemical and biological aspects of the ecosystem. Future work may involve identifying “development” indicators which relate to anthropogenic activities that may affect the surrounding area, such as the density of certain activities. Examples of development indicators are shown in Table 3-4.

3.2 Baseline Groundwater Conditions

To assess potential cumulative effects in the NAOS area, an understanding of baseline groundwater conditions and sufficient knowledge of the range of natural variability is required. Baseline data represents areas where development may or may not be occurring, but where there are believed to be no observed impacts The cumulative effects approach is based on maintaining environmental conditions as close to baseline or the natural state as possible, consistent with the principles of pollution prevention.

3.2.1 Methodology for Establishing Baseline

The current state of baseline conditions in the main aquifers beneath the NAOS region has been summarized in detail in WorleyParsons (2010a), and is provided in Section 2.7 of this document. Spatial and temporal groundwater chemistry data has been evaluated for key intervals (including surficial sand aquifers, buried channels and valleys, and certain bedrock formations). This data forms the basis for the current understanding of baseline quality conditions and has identified knowledge and data gaps for certain areas and certain intervals. In some cases, description of baseline conditions for groundwater is impossible because of a lack of

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data. The data quality rating scheme described in Table 2-4 provides some context on how well baseline conditions were defined for particular intervals.

As our current understanding of groundwater conditions is based on data with poor spatial and temporal representation, the baseline will be refined for each key interval using more robust data sets from monitoring wells strategically located across the area. A NAOS groundwater monitoring network has been established to collect this data, as described in Section 4. Wells that are considered to provide baseline data are located hydraulically upgradient or outside of the zone of operational effects for existing activities in the area (WorleyParsons, 2010b). These differ from compliance wells, which assess quality conditions in close proximity to operating facilities, as required under *EPEA* approvals. Wells that are deemed to have been previously impacted (i.e. as identified in the EIA process) are not included in the establishment of baseline values.

The Upper Control Limit (UCL) and Lower Control Limit (LCL) will be calculated for each naturally-occurring indicator at wells where a sufficient number of data points exist, defining the upper and lower bounds on the temporal data set (Gibbons, 1994). The Shewhart-CUSUM statistical method will be used for this intra-well analysis (USEPA, 2009). This method combines the Shewhart control chart process with the cumulative sum control chart to detect immediate and gradual changes in groundwater quality, respectively. A minimum of eight data points is required for each monitoring well. The range of natural variability will be established for each key aquifer for naturally-occurring indicators by compiling data from all wells in a given interval, thereby defining baseline conditions and associated control limits. For indicators that do not naturally occur in groundwater, the baseline groundwater concentration is considered to be zero, or more precisely the AL.

3.2.2 Considerations and Future Work on Baseline

Ongoing and future work will focus on refinement of the NAOS groundwater monitoring network and regular sampling events. When sufficient data is available, baseline conditions for each well will be determined. As the Shewhart-CUSUM method is applicable for a time series of data from an individual well, appropriate statistical methods for compiling baseline data from various wells across an aquifer will be determined. Aquifer-based upper and lower control limits will be defined once sufficient data with appropriate spatial representation is available from the monitoring network.

3.3 Regional Triggers and Limits

3.3.1 Methodology for Determining Final Triggers and Limits

The following methodology is proposed to establish final triggers for groundwater quality to replace the current interim values. The methodology is predicated on the use of more robust data sets from the NAOS groundwater monitoring network and appropriate statistical analysis. Triggers will be set to meet the regional objective for groundwater quality, (i.e. maintaining conditions within the range of natural variability), and quantity (i.e. supporting human and ecosystem needs and maintaining integrity of the regional flow systems).

3.3.1.1 Triggers for Groundwater Quality Indicators that are Present Naturally in Groundwater

The upper and lower control limits defined for each aquifer, as described in Section 3.2.1, will serve as triggers. Control charting will be used to compare monitoring data to these values to determine whether or not an observed value for a particular indicator is significantly different from baseline values (Gibbons, 1994). A data point that exceeds either control limit suggests that something unusual may be occurring within the groundwater regime, beyond the system's natural variability. A management response is required when either the UCL or LCL is exceeded.

As an added level of protection, temporal trend analysis will be used at individual wells as part of the approach to assess indicator conditions. The objective of this analysis is to detect changes in groundwater quality even though concentrations may be within the range of natural variability (i.e., between the LCL and UCL). A confirmed trend may no longer reflect baseline conditions, but may be an indication that groundwater quality

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has been compromised. The Shewhart-CUSUM control chart method includes an evaluation of gradual change over baseline conditions and will be used when there are 8 or more data points. The Mann-Kendall trend test will be used when there are fewer than 8 data points. Additional analysis may be used to quantify the rate of change.

3.3.1.2 Triggers for Groundwater Quality Indicators that are not Present Naturally in Groundwater

As baseline concentrations for indicators that are not naturally present in groundwater are less than the AL, unique criteria must be established to determine triggers. In this case, any reliable detection (i.e., above the AL) represents a change in the system and indicates the introduction of that substance into the groundwater. The AL value, as defined earlier, will therefore serve as the trigger, and any analytical result that is above the AL will require a management response.

The accepted ALs for various indicators are provided in *The Groundwater Monitoring Directive*.

3.3.2 Considerations and Future Work on Triggers and Limits

3.3.2.1 Finalizing Triggers and Limits for Groundwater Quality

The refinement of triggers for groundwater quality depends on data from the NAOS groundwater monitoring network and the determination of baseline conditions for each aquifer at each monitoring location. Confirmation of statistical methods and determination of final values for groundwater quality triggers will therefore only be possible after sufficient data is collected and aquifer baseline conditions are established. Until that point, the management approach will rely on interim triggers, as listed in *The Framework*, to elicit appropriate management response to any changes in groundwater conditions.

Due to limited understanding of groundwater conditions, it is too early in the process to establish numerical limits for groundwater quality indicators. A risk-based approach will be used in the absence of these values. The use of numerical limits will be considered as experience is gained in the use of triggers and implementation of the management response.

3.3.2.2 Triggers and Limits for Groundwater Quantity

There are currently no regional triggers or limits defined for groundwater quantity. Once the NAOS groundwater monitoring network is fully established, and associated modelling of the groundwater system and potential connections to the surface water environment is complete, indicators for groundwater quantity will be confirmed and associated methods and values for triggers and limits will be considered.

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4 Monitoring and Modelling

GOAL 3: Facilitate projections of change based on future scenarios, such as expanding development or climate variability and change.

As described in previous sections, the NAOS groundwater monitoring network supports the establishment of baseline conditions, the determination of final triggers and limits, the monitoring of indicators, and the identification of exceedances requiring a management response. In addition, the compilation of monitoring data will enhance the development of models that can be used to predict cumulative effects of future development.

A preliminary set of regional monitoring wells has been identified for the NAOS area. The following section discusses the process and criteria used in selecting wells for the NAOS groundwater monitoring network. A summary of modelling work is also provided.

4.1 NAOS Groundwater Monitoring Network

Regional and site-specific monitoring has taken place in the NAOS area as described in Section 2.6; however, there is no one coordinated program that assesses potential cumulative impacts from the various operations on regional water resources. Work began in 2008 to develop a regional-scale groundwater monitoring network for the NAOS area to fill knowledge gaps left from historical monitoring systems and improve understanding of the complex groundwater conditions in the area. Further refinement and/or expansion of the NAOS groundwater monitoring network will be based on results from modelling work, as described in Section 4.2.

The monitoring network is a key component of achieving the regional objectives for groundwater quantity and quality. Specific intents of the groundwater monitoring network include:

- understanding natural variability in the region
- providing baseline coverage in areas of no anthropogenic effects (e.g., establishment of baseline conditions for each monitoring location and interval)
- enhancing understanding of aquifer interaction and how groundwater is connected to surface environments
- assessing long-term geochemical and water level trends and potential cumulative effects
- refining values for regional triggers and limits for indicators at each monitoring well
- contributing to the development and refinement of regional-scale hydrogeologic models.

4.1.1 Criteria for Network Development

The following criteria are used to verify achievement of the regional objectives:

- level of risk considering vulnerability and future development
- priority of aquifer based on the aquifer classification scheme
- availability of data (priority given to areas with limited data)
- presence of existing monitoring infrastructure
- ease of site access
- spatial distribution of aquifers and associated monitoring locations
  - upgradient of development
  - downgradient of development
  - proximity to sensitive areas.

Figure 4-1 shows locations of NAOS groundwater monitoring network wells in relation to the mapped aquifer risk and associated development areas (at full build-out). In excess of 40 wells, established by the government

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of Alberta (GOWN and AGS) and various operators, have been accessed for information on the area's groundwater resources. The monitoring wells target major aquifers located within, and in close proximity to, areas of higher potential risk, as determined by the aquifer risk mapping and aquifer classification approaches described in Sections 2.8 and 2.9, respectively. Reconnaissance and sampling of select wells has taken place annually from 2009 through to 2012.

To date, intervals that have been sampled and instrumented for longer-term water level and groundwater quality monitoring include:

- Upper Kearl Channel
- Birch Channel (upgradient and down gradient)
- Thickwood Channel on the west side of the Athabasca (near AOSC MacKay lease)
- Basal McMurray Aquifer (east side of the Athabasca River, near Albian Sands Muskeg River Mine, Imperial Oil Kearl and Shell Jackpine leases)
- Basal McMurray Aquifer adjacent to the Athabasca River on both sides (and near existing natural seepages features including the Devonian down-drop block adjacent CNRL Horizon mine and Total's Joslyn lease)
- Surficial deposits near the MacKay and Athabasca rivers
- Areas remote from development to provide broader regional coverage (e.g., Cenovus Telephone Lake).

Monitoring will be conducted using scientific methods that cover all aspects of the sampling program including purging the well, collecting and storing samples, and delivering samples to the laboratory, using standard QA/QC and chain-of-custody procedures at all stages. Specific protocols are being developed to ensure the integrity of the sampling program. The frequency of monitoring will be determined by the Government of Alberta.

4.1.2 Management of the NAOS Groundwater Monitoring Network

A Regional Groundwater Monitoring Evaluation and Reporting (MER) Group has been established for the Athabasca Oil Sands. It is being led by AESRD, and includes representation from Alberta Energy Resources Conservation Board, industry, selected academics and consultants, and other stakeholders. The goal of the Regional Groundwater MER Group is to develop a scientifically rigorous system to monitor non-saline groundwater resources across the Lower Athabasca Region, evaluate the data in the context of *The Framework*, report on the state of groundwater resources in the region, and generate information and data to assist future planning decisions.

The Regional Groundwater MER Group has three technical sub-committees; one for each the NAOS, SAOS, and CLBR areas. The sub-committees oversee the establishment, expansion and refinement of the monitoring network in each area and its ongoing sampling. They will support the determination of baseline conditions, triggers and limits, and the identification of any changes in groundwater conditions.

There will be ongoing evaluation of monitoring activities in the oil sands to ensure their alignment with other policies and monitoring initiatives in the province.

4.2 Groundwater Modelling

The over-arching objective of ongoing modelling initiatives is to better understand the potential cumulative effects of current and future development on regional groundwater quality and quantity. Initial modelling work has helped determine where to focus monitoring activities, and the results from such activities will feed back into the models to further enhance understanding of the groundwater systems, including their potential connectivity to the surface water environment.

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4.2.1 Modelling of the Lower Athabasca Region

Work was undertaken in 2009 to develop a three-dimensional groundwater flow model for the entire Lower Athabasca Region (WorleyParsons, 2010c). The model was developed using MODFLOW and assessed available drawdown, maximum drawdown scenarios, and per cent drawdown exceedances over a time period of 100 years. A production rate of 4 million barrels of oil per day was assumed. The model was subject to certain data gaps for the north and northwestern parts of the LARP area, which were compensated for by using best professional judgment. This model represents a strategic-level assessment tool to evaluate potential impacts at the regional level. Results of this work are summarized below.

- The current available drawdown estimated in the various aquifers assessed is substantial.
- With time, a decreasing trend of drawdown is expected.
- Areas where over 50 per cent of available drawdown is exceeded are limited or non-existent in the buried channels, Grand Rapids and Clearwater intervals.
- Relatively large areas indicate an exceedance of 50 per cent of available drawdown in the Basal McMurray Aquifer, especially in the mineable area where de-watering of this interval occurs.
- Recovery of available head in the various aquifers following operational activities is relatively rapid. Within 20 years, major effects are projected to dissipate and it is expected that at year 80 water level recovery will be almost complete.

4.2.2 Modelling of the NAOS Area

Recent modelling initiatives aim to achieve a greater level of refinement for the NAOS area. A conceptual and numerical groundwater flow model has been developed using FEFLOW modelling software (WorleyParsons, 2012). The model describes the current understanding of the physiography, hydrology, geology, hydrogeology, recharge/discharge relationships and groundwater use in the NAOS area. Groundwater surface elevation maps have been developed for each major aquifer. A key output of this work is recommendations for the refinement and/or expansion of the existing groundwater monitoring network to ensure monitoring activities are able to detect any changes to regional groundwater conditions in a timely manner.

Continued refinement of groundwater models in the NAOS area will occur as new information from monitoring initiatives becomes available. Future efforts may include integrated modelling (groundwater, surface water, land cover and climate) to assess groundwater quantity, sustainable yields and groundwater-surface water interactions. Predictive modelling of cumulative effects, both from a quantity and quality perspective, may be used in the future to support regulatory decision-making.

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5 Management Actions and Adaptation

The final component of the management approach described by the graphic provided in Section 1.1 is Management Actions and Adaptation. The resolution of groundwater quality and quantity issues requires not only the substantive, collaborative work that has been completed to build *The Framework,* but the built-in flexibility and adaptability of its implementation. Over time, the regional management response and its specific management actions may be adjusted, as well as the various components of *The Framework* itself, to better ensure groundwater protection and align with expectations of stakeholders. These adaptations will be based on increasing experience in the application of *The Framework* and an evolving understanding of hydrogeological conditions in the oil sands region.

5.1 Regional Management Response

The management response initiated when a trigger or limit has been exceeded is outlined in *The Framework*. This includes elements of verification, investigation and mitigation. While interim values for regional triggers have been developed, a management response will not be a mandatory requirement of the regional plan until there is a better understanding of groundwater in the region and final regional triggers and limits have been established. A management response may be applied when interim triggers are exceeded; possible management actions will then be tested and adjusted accordingly.

Once regional trigger and limit values are finalized, the expectation is that the management actions will be more intensive for a trigger than for a limit.

5.2 Adaptive Management Process for *The Framework*

Adaptive management is defined as a structured, iterative process of optimal decision-making in the face of uncertainty with a focus on reducing uncertainty over time via system monitoring (Holling, 1978). Figure 5-1 outlines the components of an adaptive management approach (analyze, plan, do, evaluate and adjust), and describes the corresponding activities undertaken for the development of regional groundwater management in the Lower Athabasca Region.

- The ANALYZE phase of the adaptive management process has been completed through background technical studies including the compilation and assessment of monitoring data, risk mapping and numerical modeling, informing this, and other, *Supporting Documents*.
- The PLAN phase has consisted of the development of *The Framework* itself.
- The DO phase is currently being undertaken with the implementation of *The Framework,* and through the establishment of NAOS monitoring network and execution of monitoring programs.
- The ADJUST phase will focus on the refinement and finalization of threshold values, as additional experience is gained, new data is compiled and understanding of groundwater resources in the area increases.
- The EVALUATE phase will assess the effectiveness of the various components of *The Framework* and its overall implementation and develop strategies to incorporate outstanding groundwater issues into *The Framework*.

The Framework is considered to be a living document and will be updated as required, with a focus on the regional triggers and limits. AESRD will review and update the framework to ensure alignment with other policies that are developed or revised at a regional, provincial or national level, or at a minimum ten-year interval to align with regional planning.

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Acronyms

AENV	Alberta Environment (until 2011, then AEW)
AEW	Alberta Environment and Water (until 2012, then ESRD)
AGS	Alberta Geological Survey
AL	Action Level
AMU	Aquifer Management Unit
CLBR	Cold Lake Beaver River
CSS	Cyclic Steam Stimulation
CEMA	Cumulative Environmental Management Association
EIA	Environmental Impact Assessment
EPEA	*Environmental Protection and Enhancement Act*
ERCB	Alberta Energy Resources Conservation Board
ESRD	Alberta Environment and Sustainable Resource Development (since 2012; formerly AEW)
EUB	Alberta Energy and Utilities Board
LCL	Lower Control Limit
masl	Metres above sea level
mbsl	Metres below sea level
mg/L	Milligrams per Litre
m/s	Metres per second
NAOS	North Athabasca Oil Sands
SAGD	Steam Assisted Gravity Drainage
SAOS	South Athabasca Oil Sands
TDS	Total Dissolved Solids
The Framework	Lower Athabasca Region Groundwater Management Framework
UCL	Upper Control Limit
W4M	West of the Fourth Meridian

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Glossary

Alluvial	Applying to the environments, actions, and products of rivers or streams.
Aquifer	An underground water-bearing formation that is capable of yielding water (Water Act 2009)
Aquifer management unit	A hydraulically-connected groundwater system that is defined to facilitate management of the groundwater resources (quality and quantity) at an appropriate scale.
Aquitard	A water-saturated sediment or rock whose permeability is so low it cannot transmit any useful amount of water. An aquitard allows some measure of leakage between the aquifer intervals it separates.
Basal Aquifer	The interval of McMurray Formation that is lean of bitumen and predominantly water-saturated.
Baseline concentration	The baseline concentration of a substance in groundwater is the natural concentration of that substance in a particular groundwater zone in the absence of any input from anthropogenic activities and sources.
Bedrock	The solid rock that underlies unconsolidated surficial sediments.
Bedrock aquifer	A bedrock formation that has the ability to transmit significant volumes of water to a well completed within it. Typical examples include sandstone and siltstone or significantly fractured intervals.
Bitumen	A highly viscous, tarry, black hydrocarbon material having an API gravity of about nine (specific gravity about 1.0 g/cm3). It is a complex mixture of organic compounds. Carbon accounts for 80 to 85% of the elemental composition, hydrogen 10%, and sulphur 5% with nitrogen, oxygen and trace elements forming the remainder.
Buried valley	An eroded depression in the sol or bedrock within which sediments significant permeability (e.g. sand) or low permeability (e.g. till, clay) accumulate.
Channel	An eroded depression in the soil or bedrock surface within which alluvial deposits accumulate (i.e. gravel, sands, silt, clay).
Contaminant	A substance that is present in an environmental medium in excess of natural baseline concentration.
Cretaceous	A period of the Mesozoic era thought to have covered the span of time between 140 and 65 million years ago; also, the corresponding system of rocks.
Consolidated tailings (Ct)	A type of fine tailings that is produced by mixing dense extraction tailings with mature fine tailings and a coagulant aid (e.g. gypsum).
Cumulative Effects	The changes to the environment caused by all past, present, and reasonably foreseeable future human activities.
Dewatering	Removal of groundwater from geological formation using wells or drainage ditch system.

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Devonian	A period of the Palaeozoic era thought to have covered the span of time between 400 and 345 million years ago; also, the corresponding system of rocks.
Fen	Minerotropic peat-forming wetlands that receive surface moisture from precipitation and groundwater. Fens are less acidic than bogs, deriving most of their water from groundwater rich in calcium and magnesium.
Groundwater	All water under the surface of the ground whether in liquid or solid state.
Hydrogeology	The science that relates geology, fluid movement (i.e. water) and geochemistry to understand water residing under the earth's surface. Groundwater as used here includes all water in the zone of saturation beneath the earth's surface, except water chemically combined in minerals.
Infiltration	The flow or movement of precipitation or surface water through the ground surface into the subsurface. Infiltration is the main factor in recharge of groundwater reserves.
McMurray Aquifer	The interval of McMurray Formation that is lean of bitumen and predominantly water-saturated.
Mineralization of Groundwater	Synonymous with total dissolved solids (typically reported in mg/L).
Monitoring Well	A constructed controlled point of access to an aquifer which allows groundwater observations. Small diameter observation wells are often called piezometers.
Naphthenic acids	Naturally occurring hydrocarbons found in surface and groundwater in the Athabasca Oil Sands area. Primary group of compounds toxic to aquatic organisms in oil sands process-affected water.
Oil Sands	An agglomeration of sand and associated fines impregnated, and somewhat cemented, with an extremely viscous form of oil, commonly referred to as bitumen (see preceding definition for bitumen).
Overburden	Any loose material which overlies bedrock (often used as a synonym for Quaternary sediments and/or surficial deposits) or any barren material, consolidated or loose, that overlies an ore body.
Permeability	A physical property of the porous medium. Has dimensions Length2. When measured in cm2, the value of permeability is very small, therefore more practical units are commonly used - darcy (D) or millidarcy (mD). One darcy is equivalent to 9.86923×10−9 cm^{2}.
pH	The logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per litre; provides a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral and greater than 7 is more basic and less than 7 is more acidic).
Phenols	Oxygen–substituted benzenes commonly derived from the degradation of natural organic matter, the distillation of wood and coal, and the refining of oil. This particular class of organic compounds is ubiquitous in nature, and is common in groundwater.
Polycyclic Aromatic Hydrocarbons (PAH)	A group of over 100 different organic compounds composed of several benzene rings.

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Process-Affected Water	Any water that has come in contact with oil sands through an industrial process, and may contain hydrocarbons and other chemicals
Receptor	Components within an ecosystem that react to, or are influenced by stressors.
Recharge	The infiltration of water into the soil zone, unsaturated zone and ultimately the saturated zone. This term is commonly combined with other terms to indicate some specific mode of recharge such as recharge well, recharge area, or artificial recharge.
Stratigraphy	The geological science concerned with the study of sedimentary rocks in terms of time and space.
Stressor	Physical, chemical and biological factors that are either unnatural events or activities, or natural to the system but applied at an excessive or deficient level, which adversely affect the receiving ecosystem. Stressors cause significance changes in the ecological components, patterns and processes in natural systems.
Surficial Deposits	See Overburden.
Surficial sands	Located in the interval of unconsolidated soil above the first bedrock formation
Sustainable	A characteristic of an ecosystem that allows it to maintain its structure, functions and integrity over time and/or recover from disasters without human intervention
Total Dissolved Solids	Concentration of all substances dissolved in water (solids remaining after evaporation of a water sample)
Trend	The relationship between a series of data points (e.g. Mann Kendall test for trend)
Upland	Elevated land (e.g. hilly or mountainous)
Water-bearing	Containing water within the spaces between sediment grains or established fractures

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APPENDIX A - Figures

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Figure 2-1: Map Showing the NAOS Area

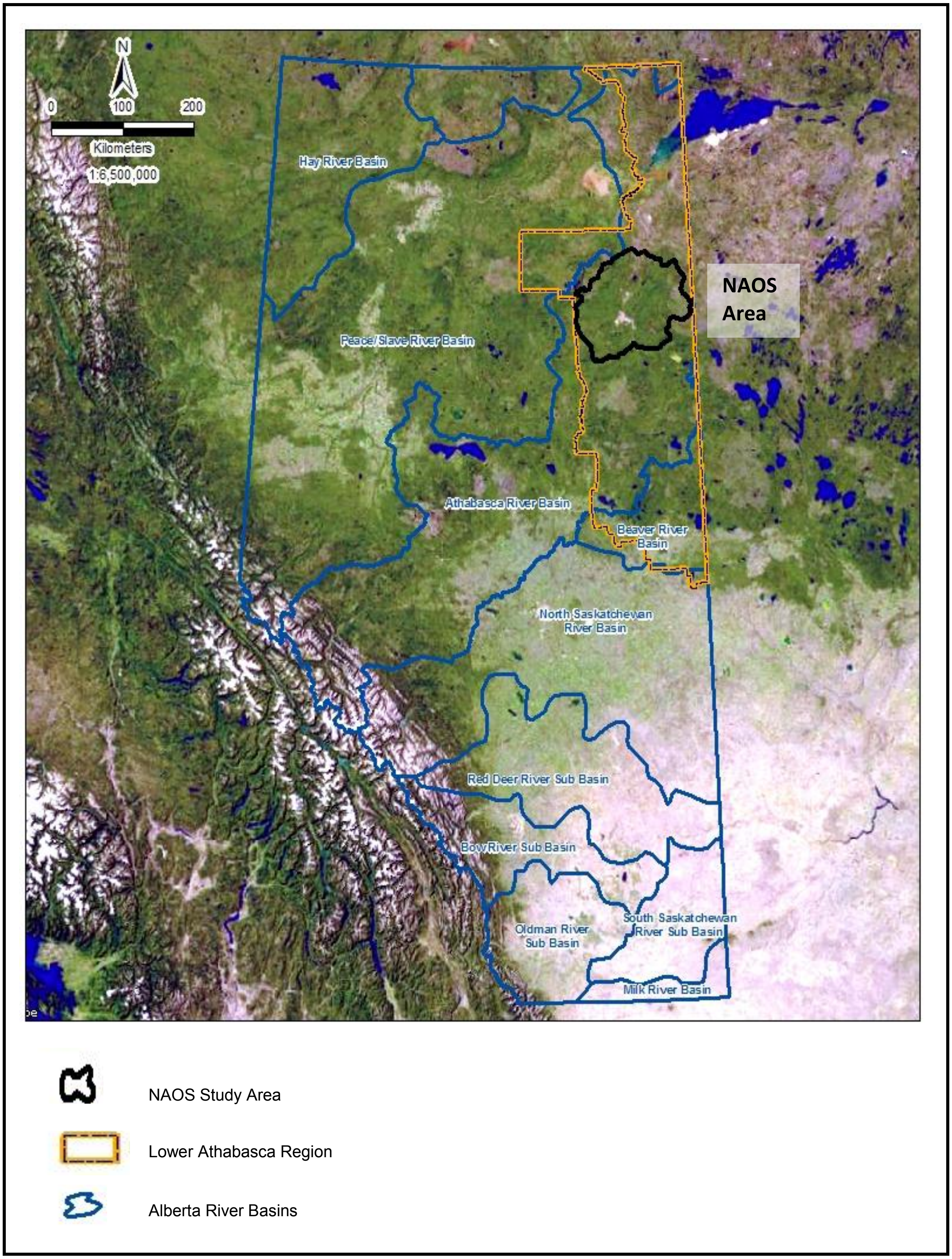

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Figure 2-2. Oil Sands Leases and Lease Holders

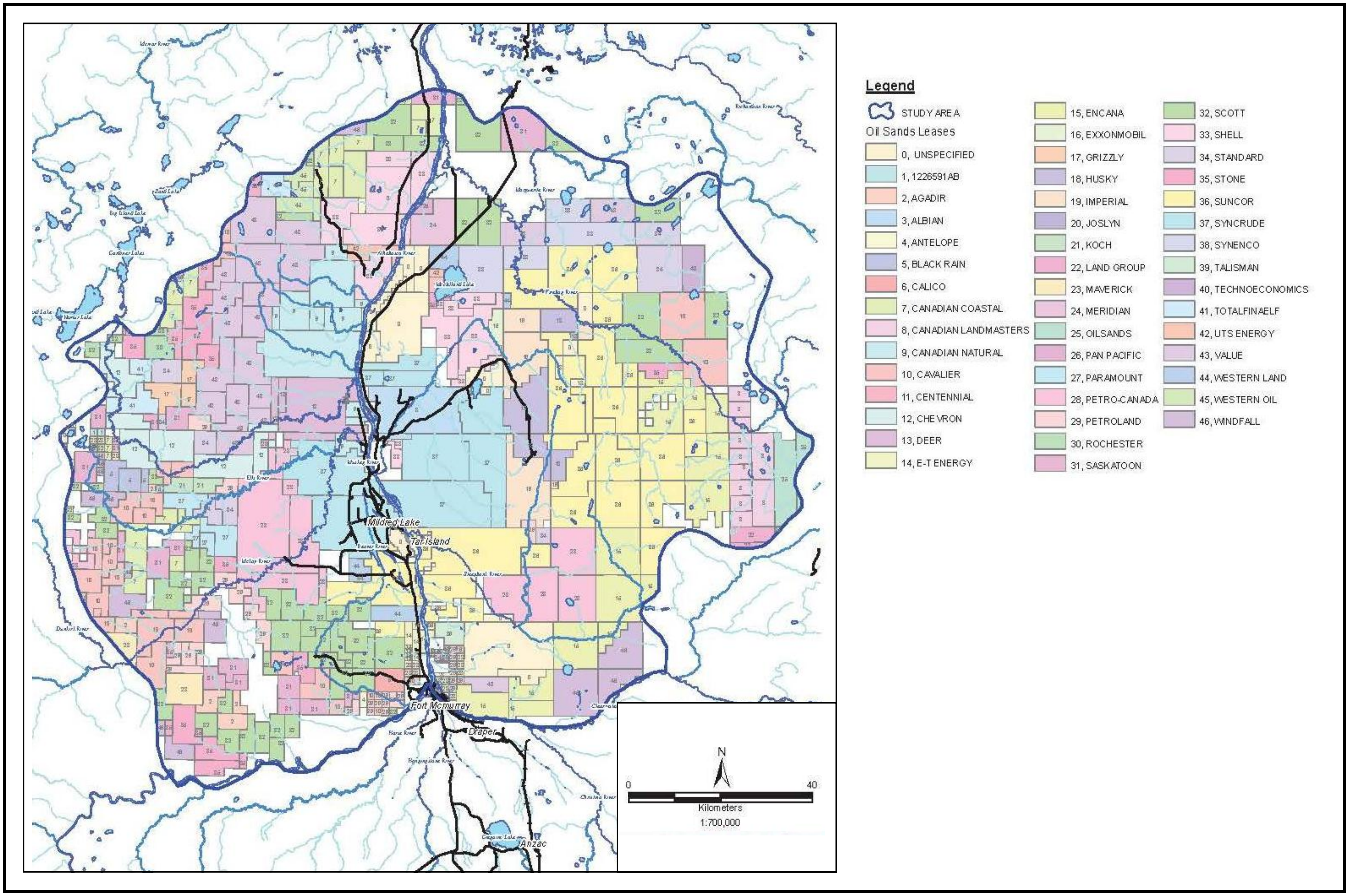

Figure 2-3. Oil Sands Projects in the NAOS Area (2010)

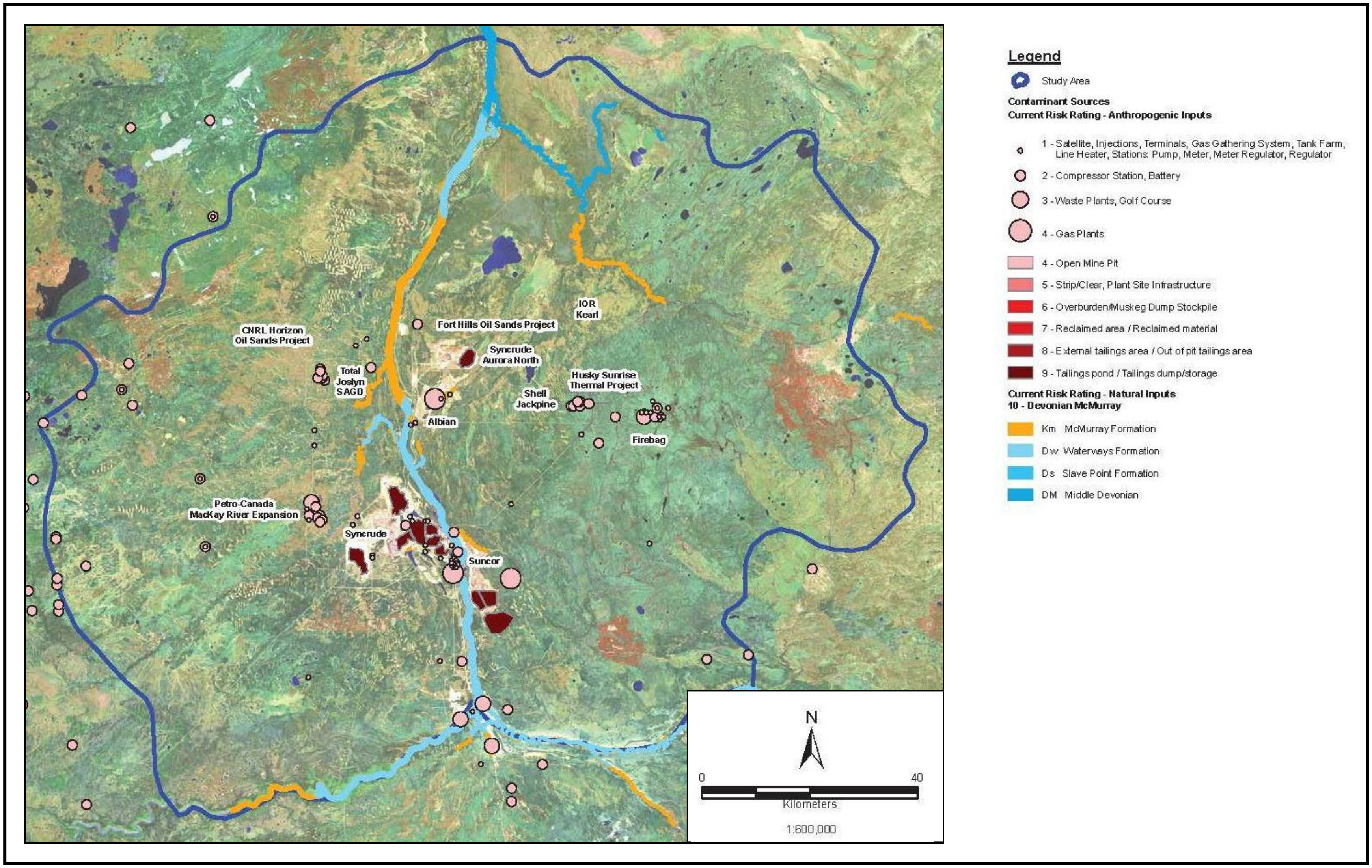

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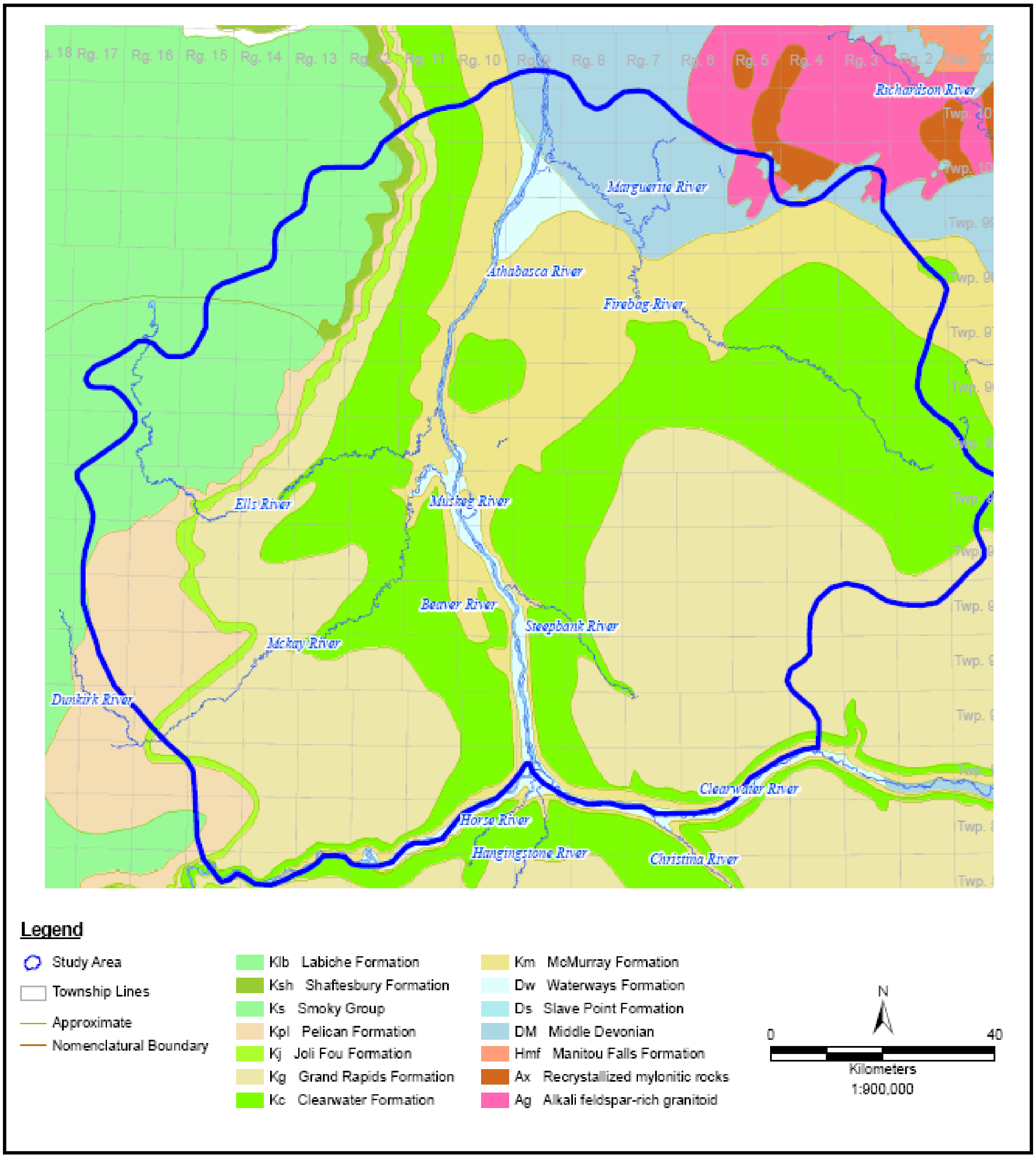
Figure 2-4. Bedrock Geology



Source: Hamilton et. al. 2004

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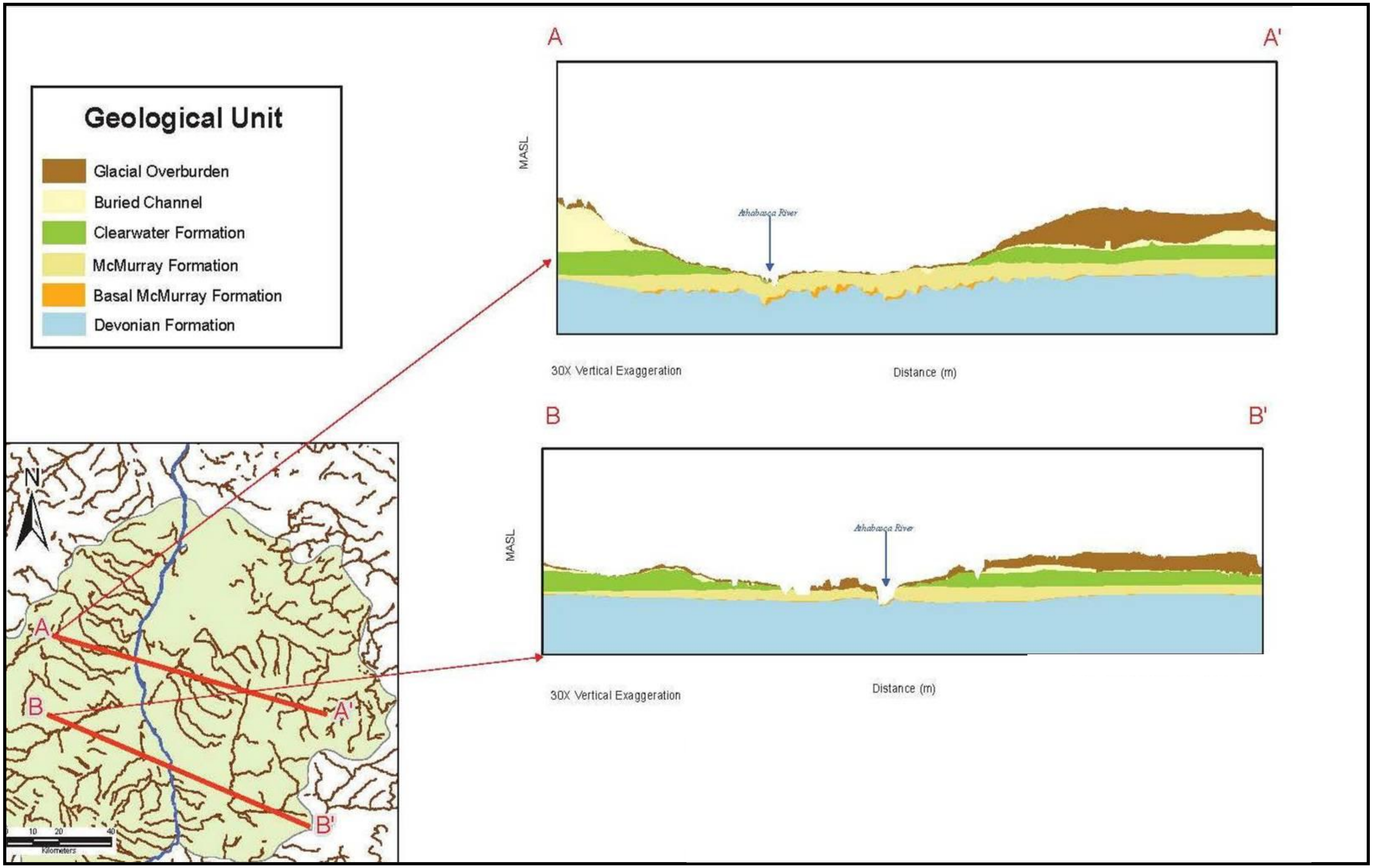
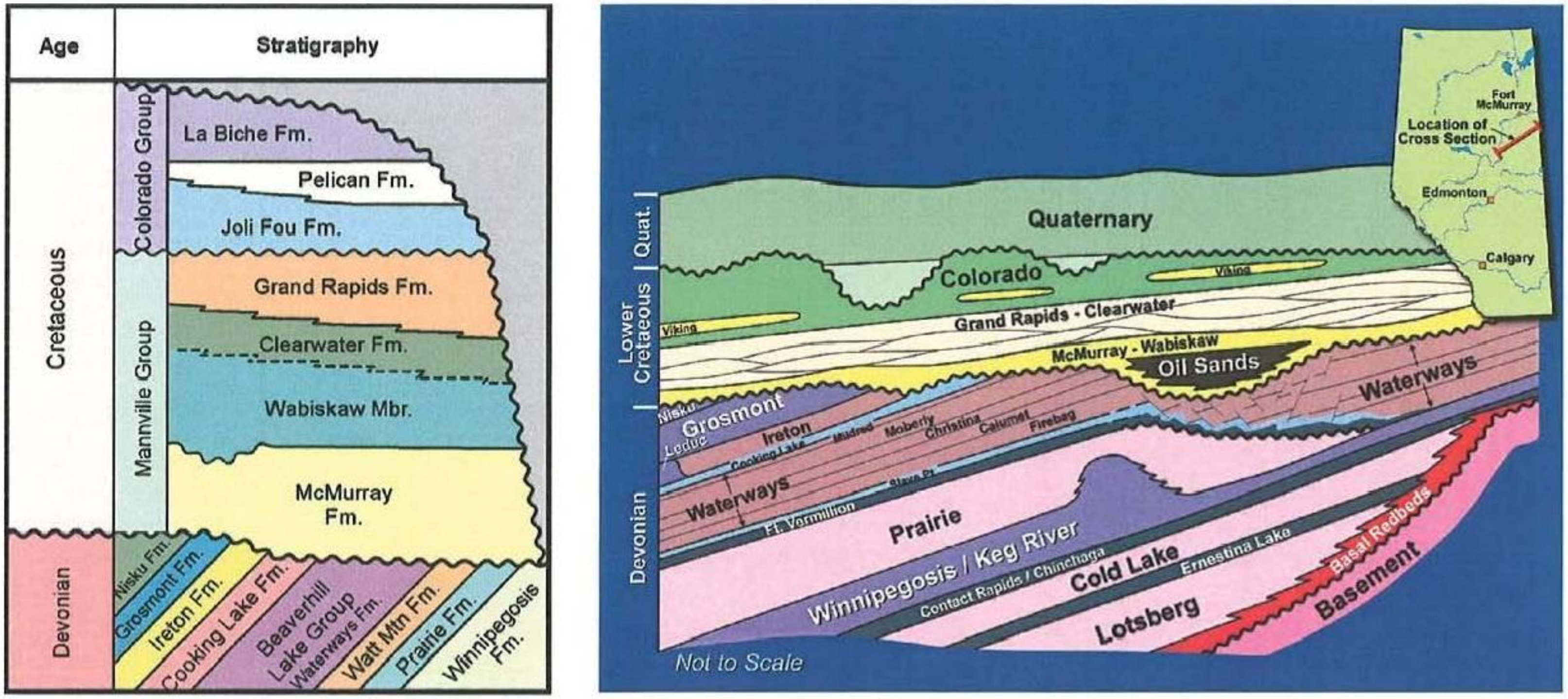
Figure 2-5. NAOS Area Cross-sections



Source: Modified from Andriashek & Atkinson 2007

Figure 2-6. Bedrock Stratigraphy in the NAOS Area



Source: Modified from Andriashek & Atkinson 2007

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Figure 2-7. Basal McMurray Sand Aquifer Isopach

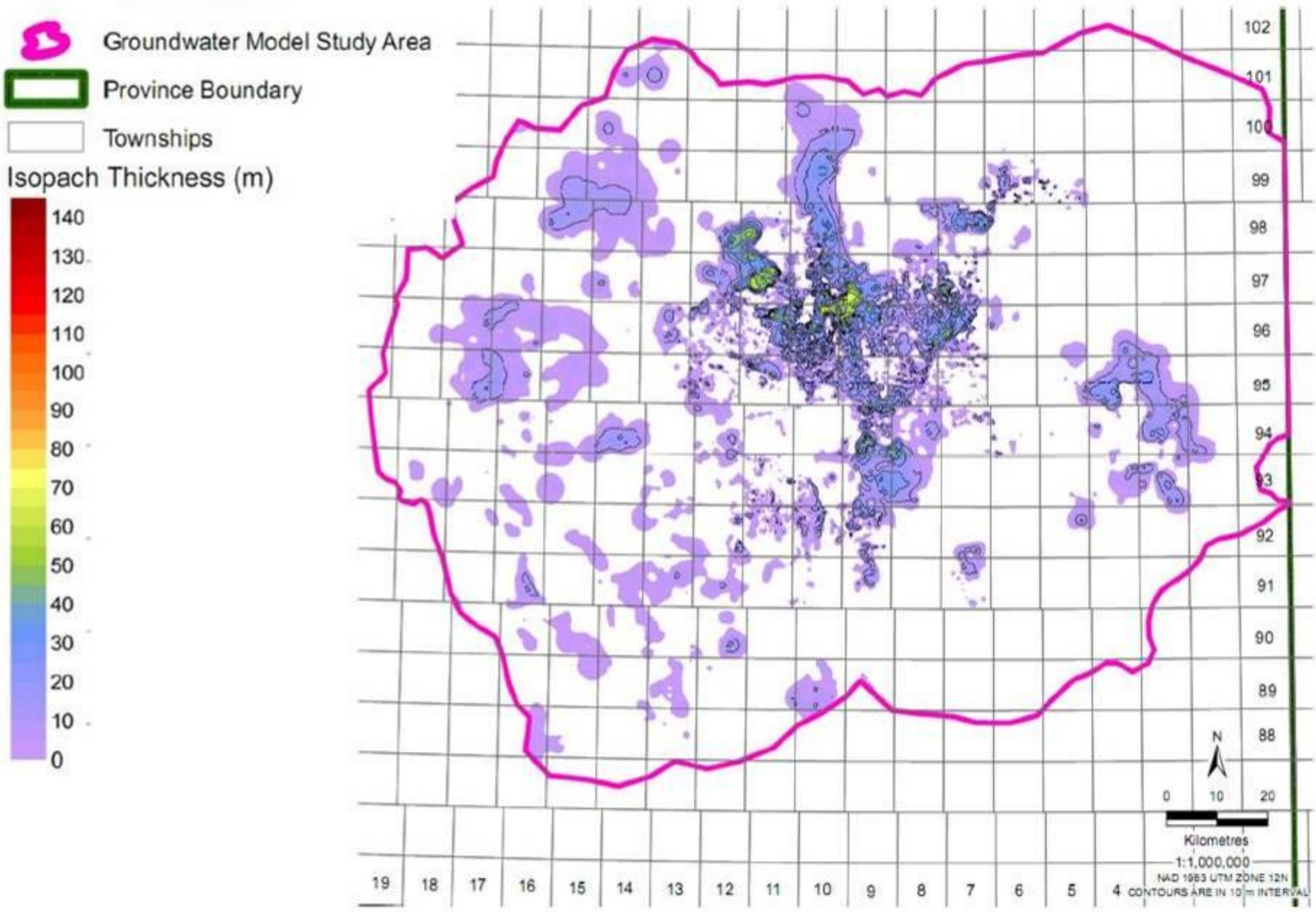

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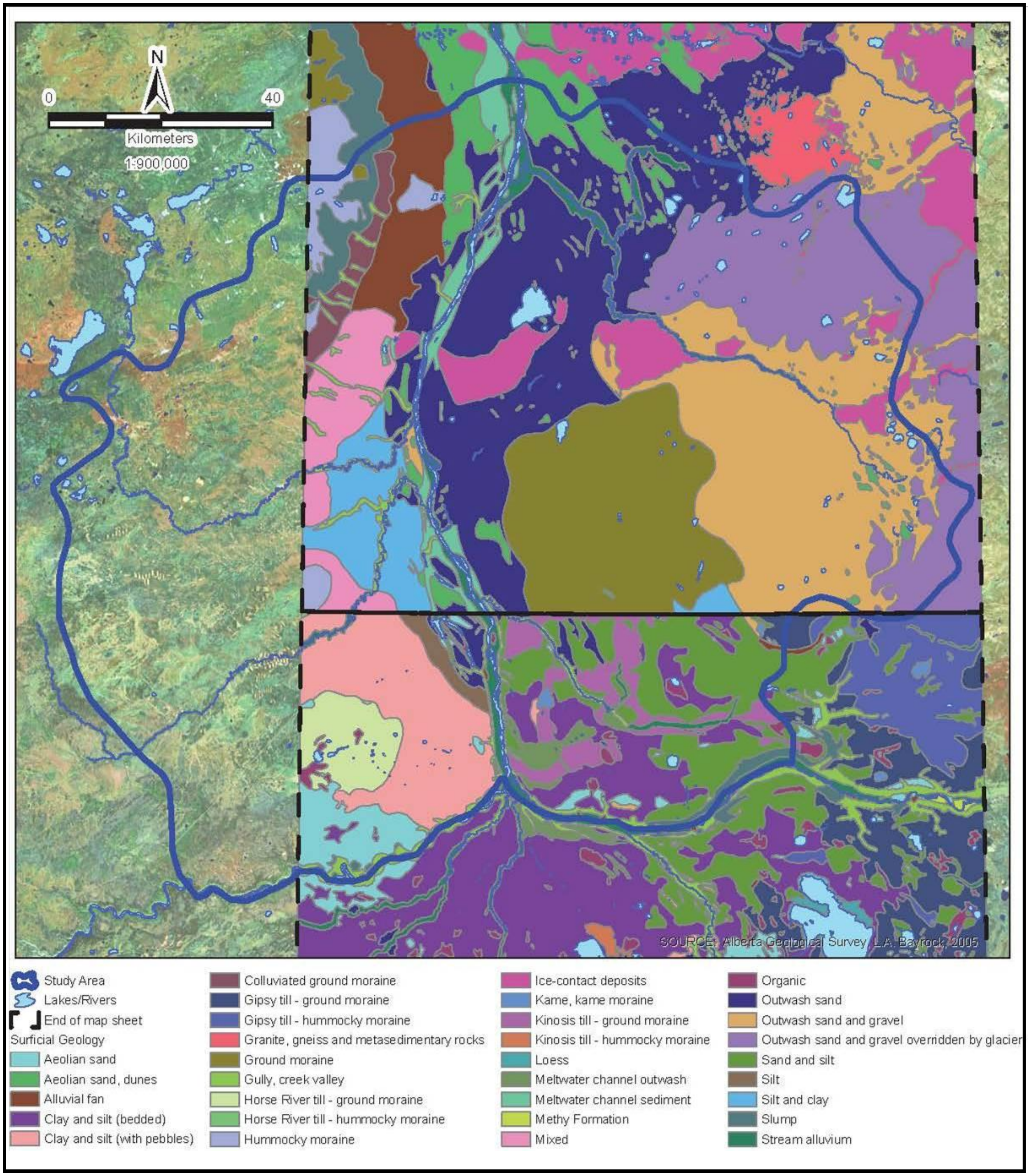
Figure 2-8. Surficial Geology



Source: Bayrock, 2006

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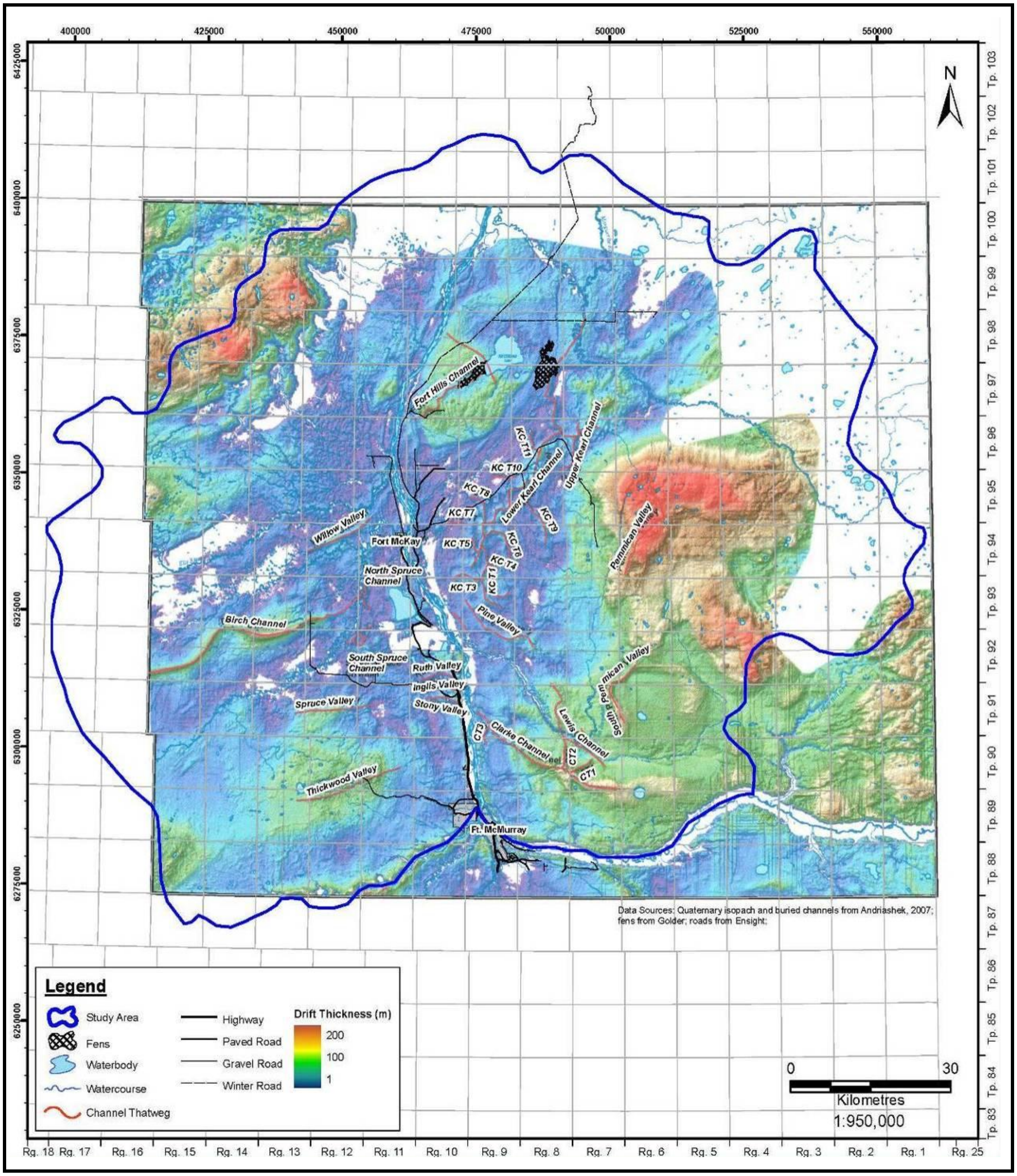
Figure 2-9. NAOS Area Isopach Map – Quaternary Deposits and Buried Channel Locations



Data Sources: Quaternary isopach and buried channels from Andriashek, 2007; fens from Golder; roads from Ensight;

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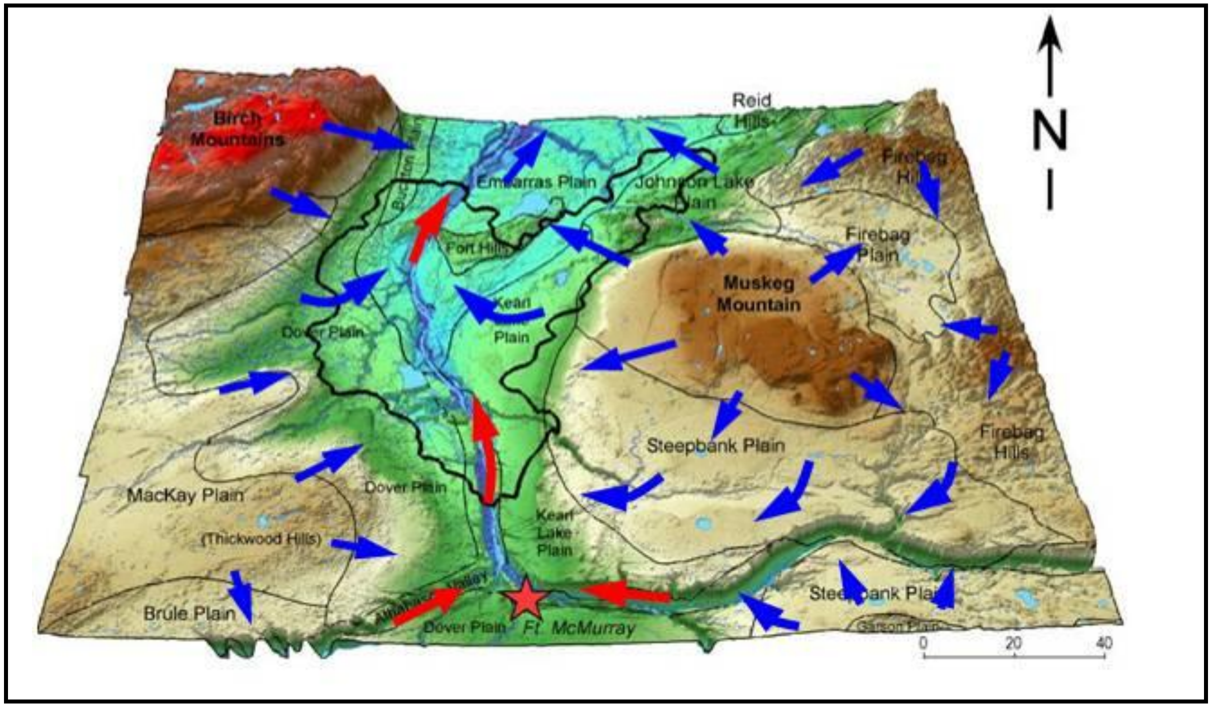
Figure 2-10. Conceptual Groundwater Flow Patterns in the NAOS Area



Source: Modified from Andriashek & Atkinson 2007

Blue arrows indicate general groundwater flow directions

Red arrows indicate river flow directions

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Figure 2-11: Surface Disturbance Associated with In Situ Development

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Figure 2-12. Location of Wells Used in Baseline Data Assessments

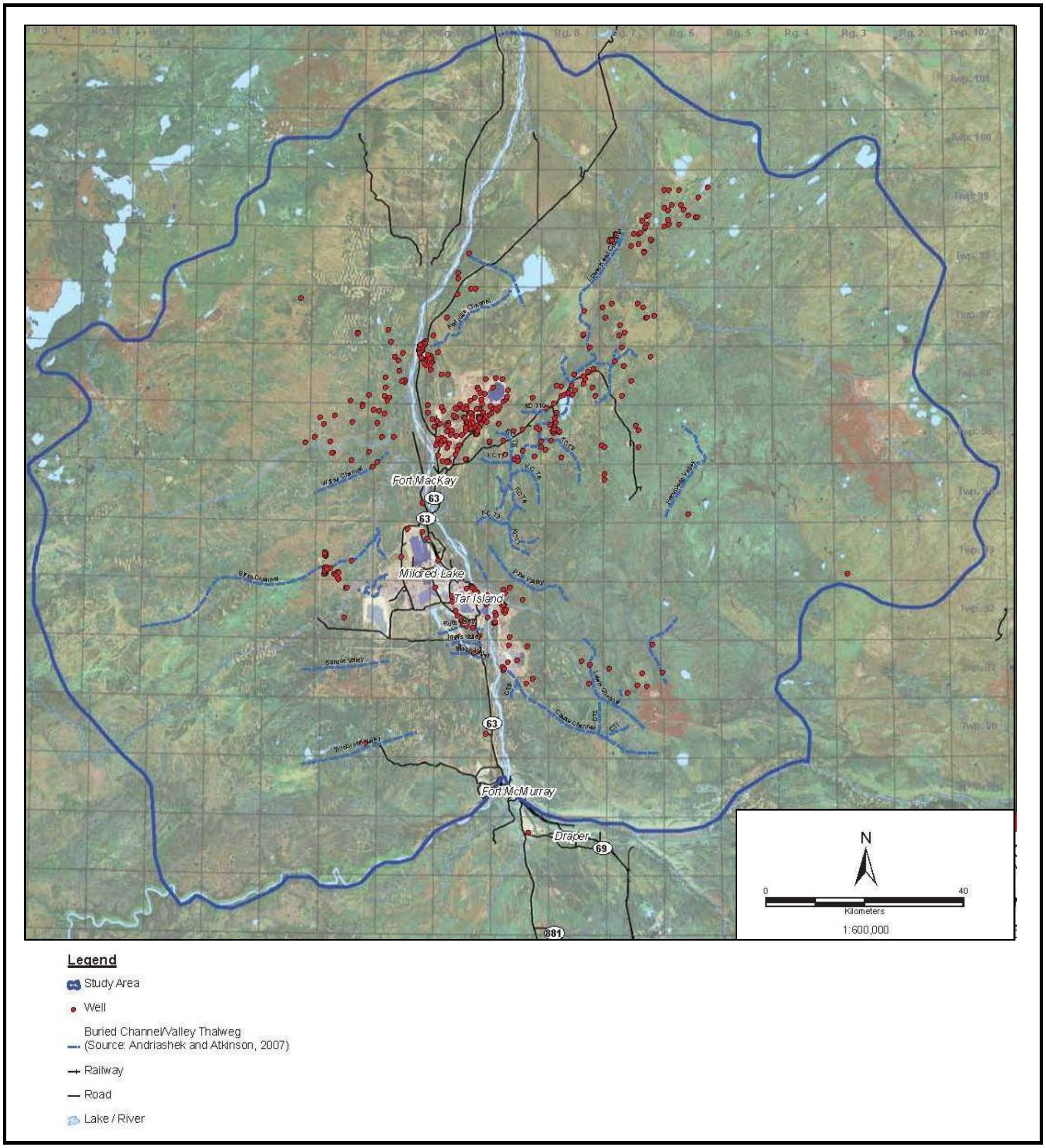

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Figure 2-13. Distribution of TDS in the Surficial Deposits

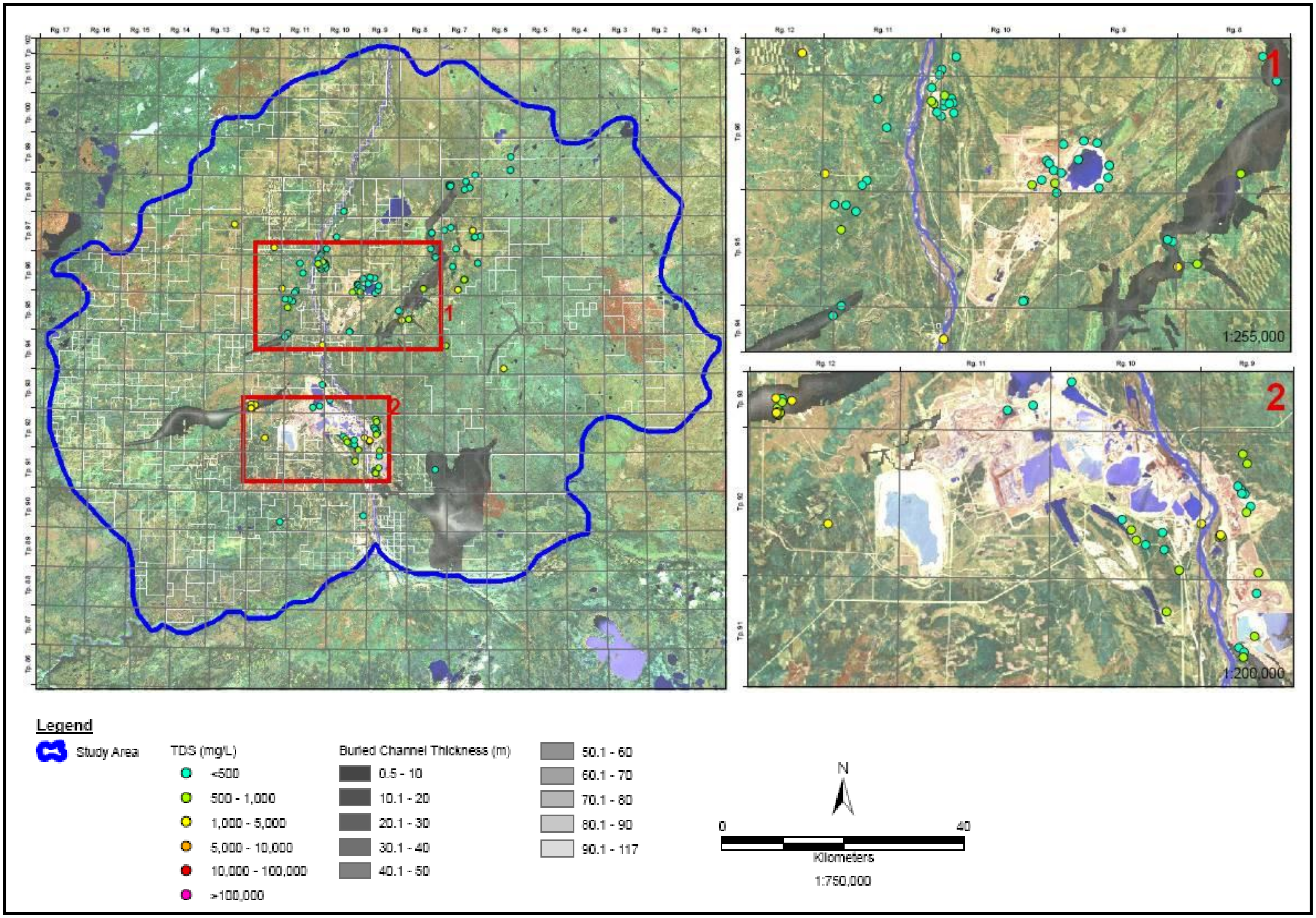

Figure 2-14. Distribution of TDS in the Basal McMurray

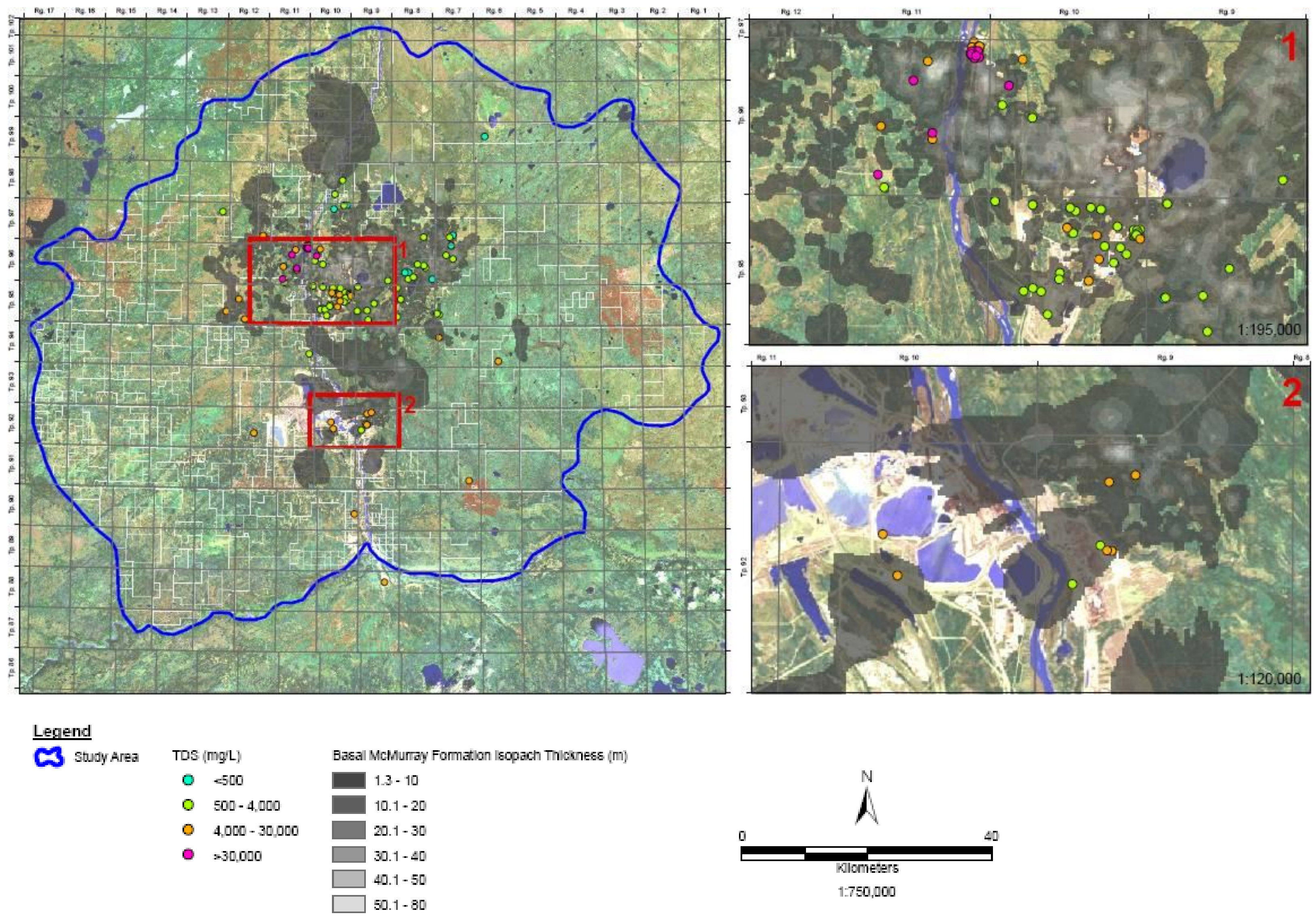

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Figure 2-15. Licenced Groundwater Use in the Surficial Sands

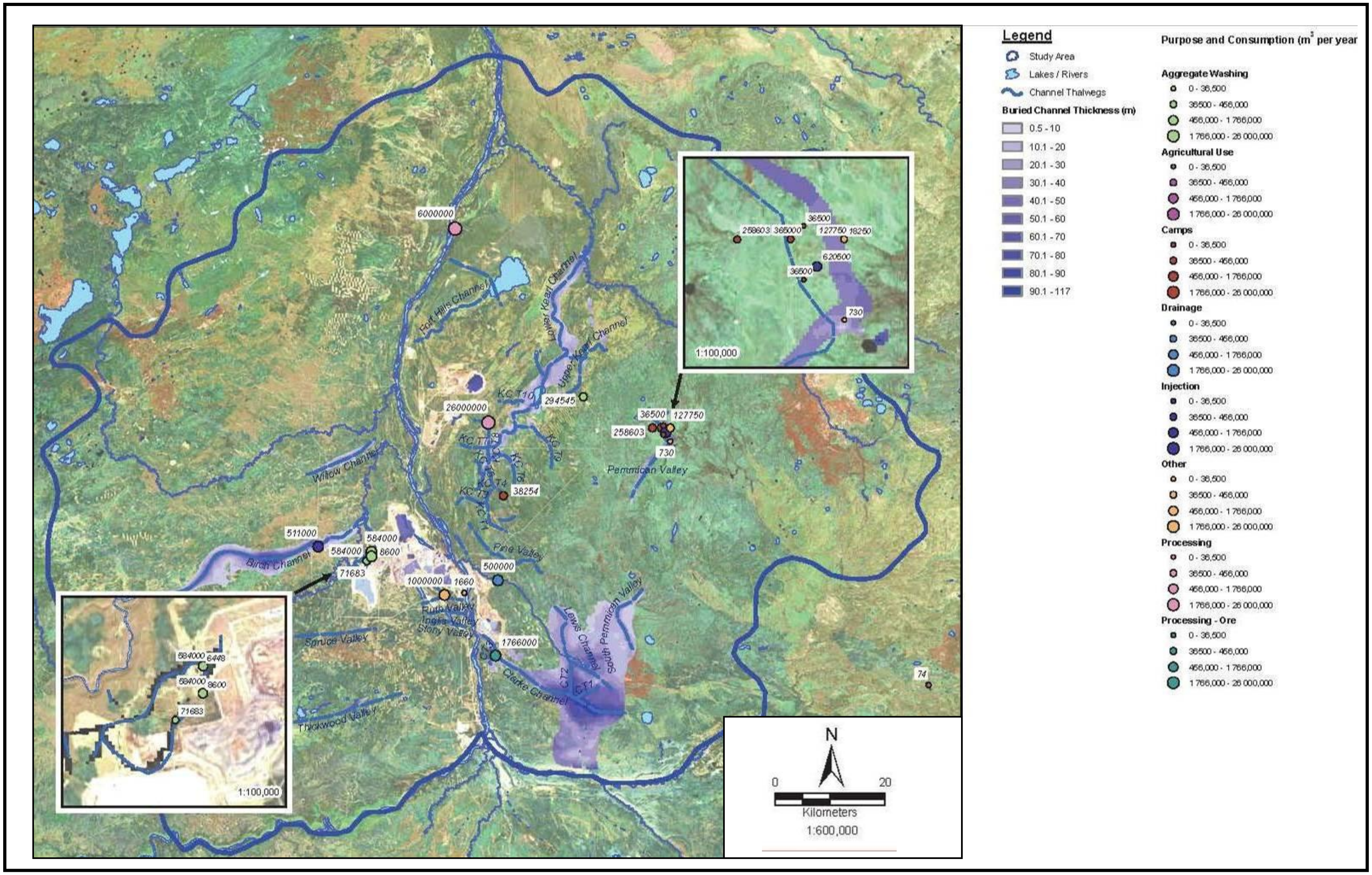

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Figure 2-16. Licenced Groundwater Use in the Basal McMurray Formation

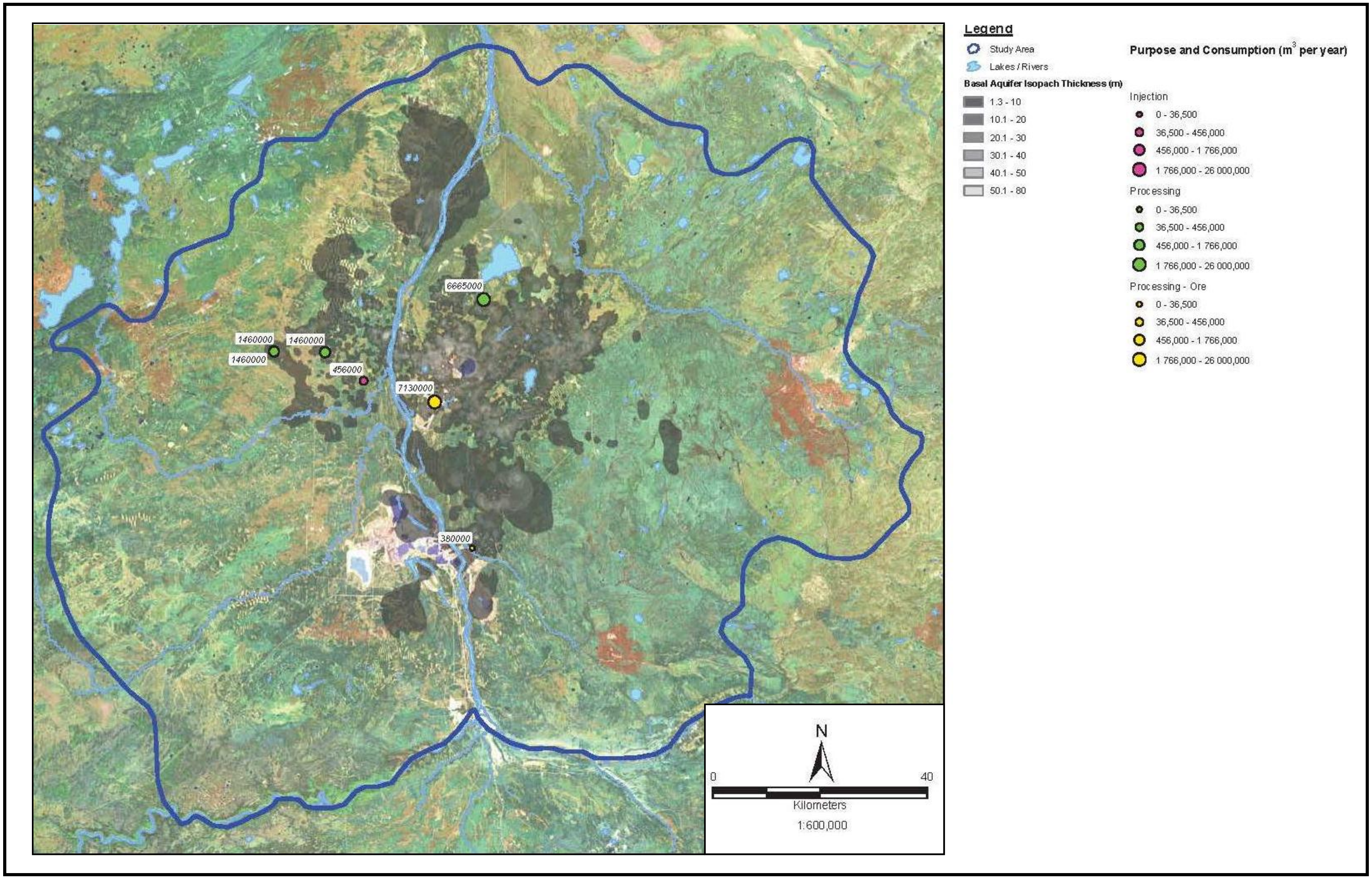

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Figure 2-17. Conceptual Description of Environmental Risk

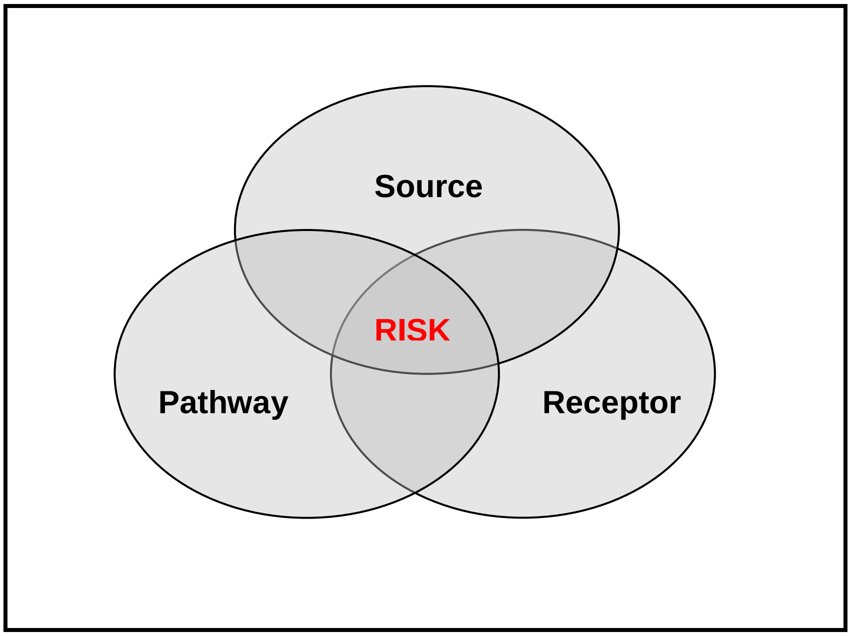

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Figure 2-18. Vulnerability Layers for the Surficial Deposits

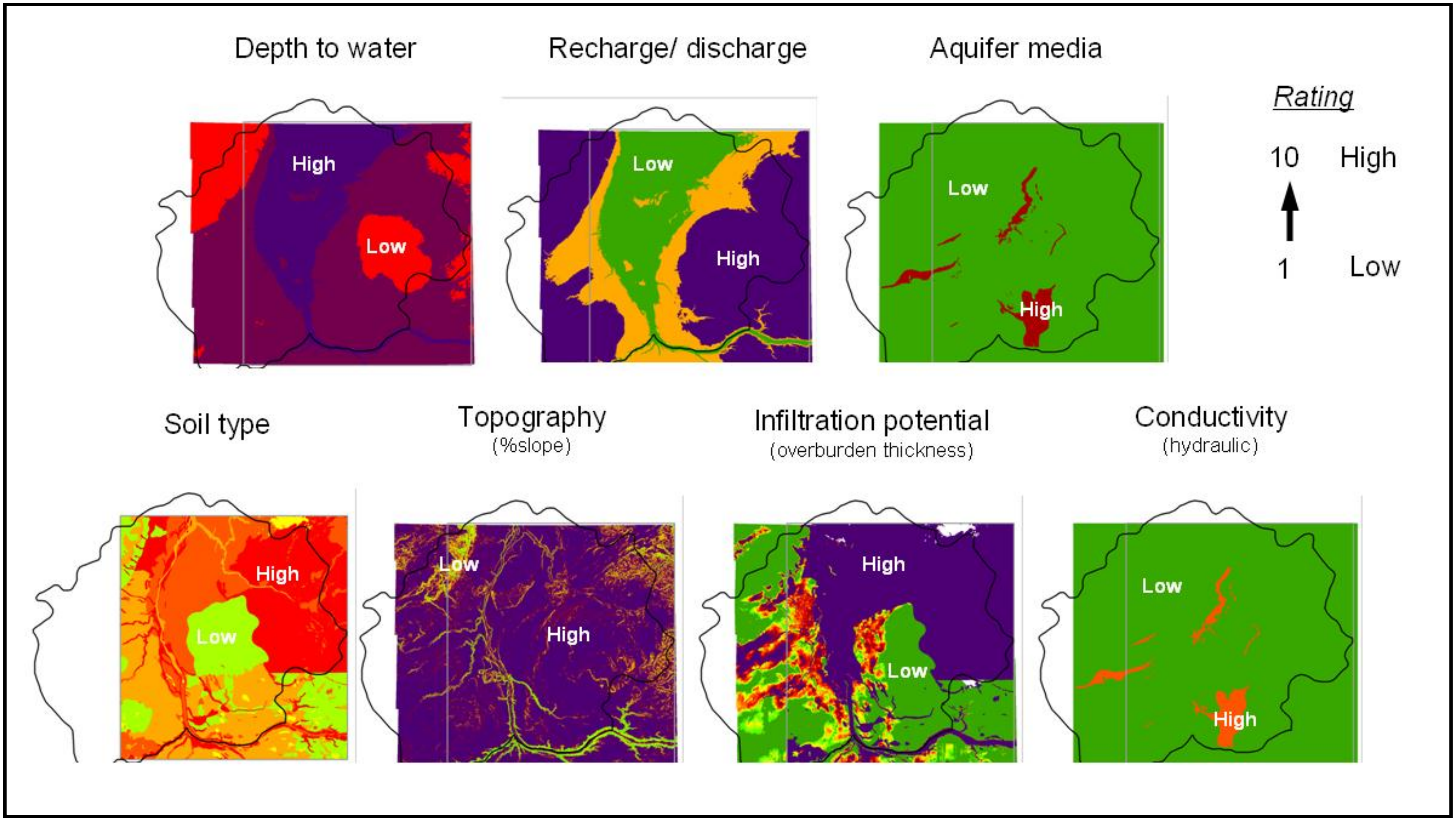

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Figure 2-19. Vulnerability Layers for the Basal McMurray

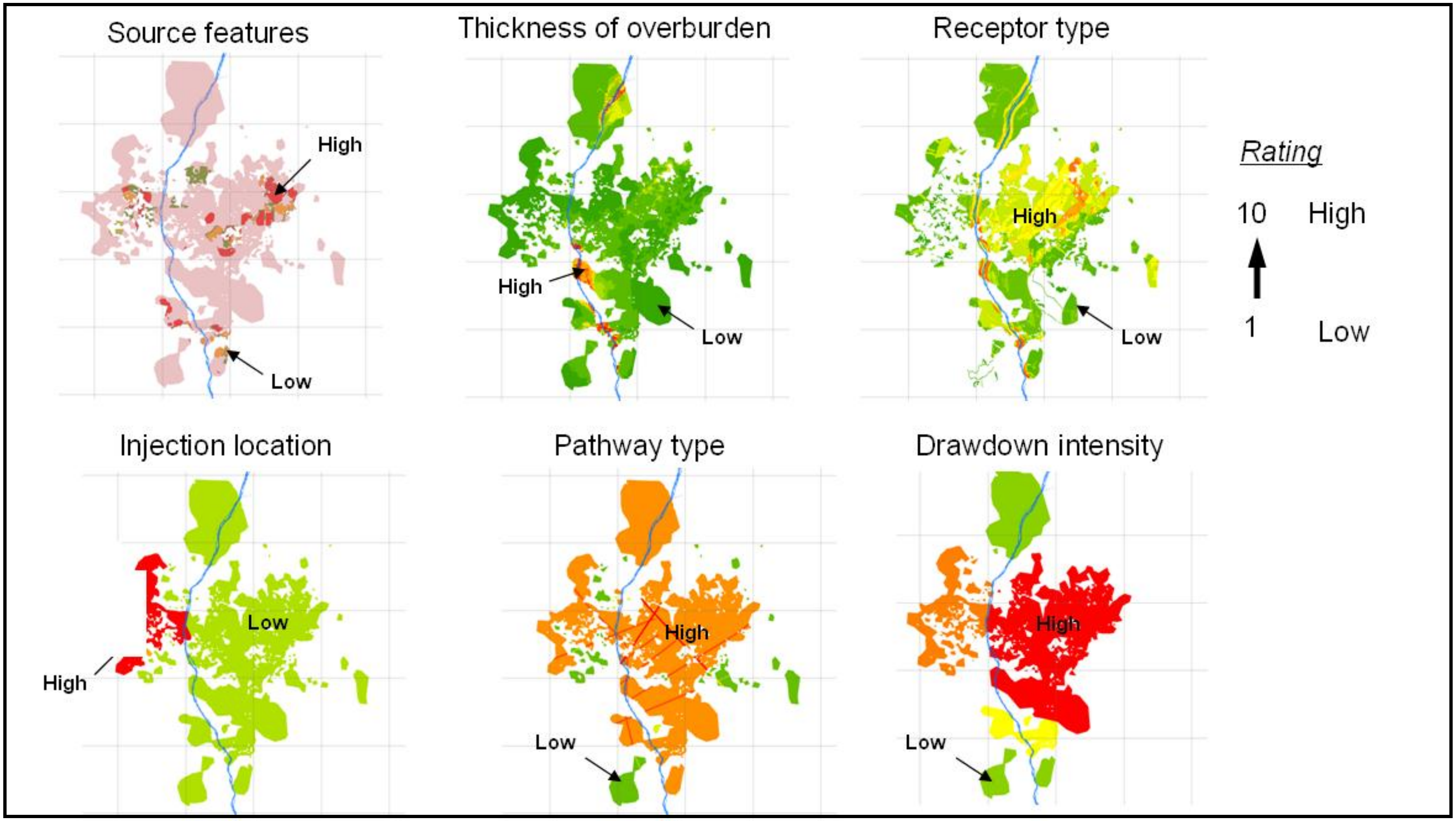

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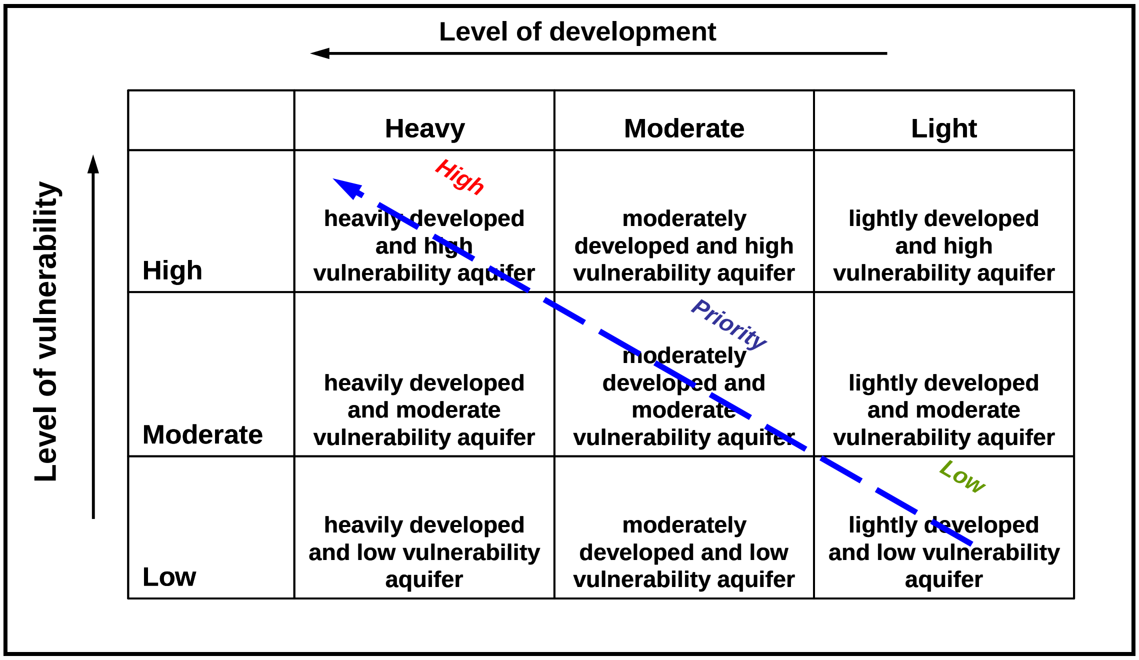
Figure 2-20. Groundwater Risk Approach



	Heavy	Moderate	Light
High	heavily developed and high vulnerability aquifer	moderately developed and high vulnerability aquifer	lightly developed and high vulnerability aquifer
Moderate	heavily developed and moderate vulnerability aquifer	moderately developed and moderate vulnerability aquifer	lightly developed and moderate vulnerability aquifer
Low	heavily developed and low vulnerability aquifer	moderately developed and low vulnerability aquifer	lightly developed and low vulnerability aquifer

Source: Berardinucci and Ronneseth 2002

Figure 2-21. Vulnerability and Risk in the Surficial Deposits

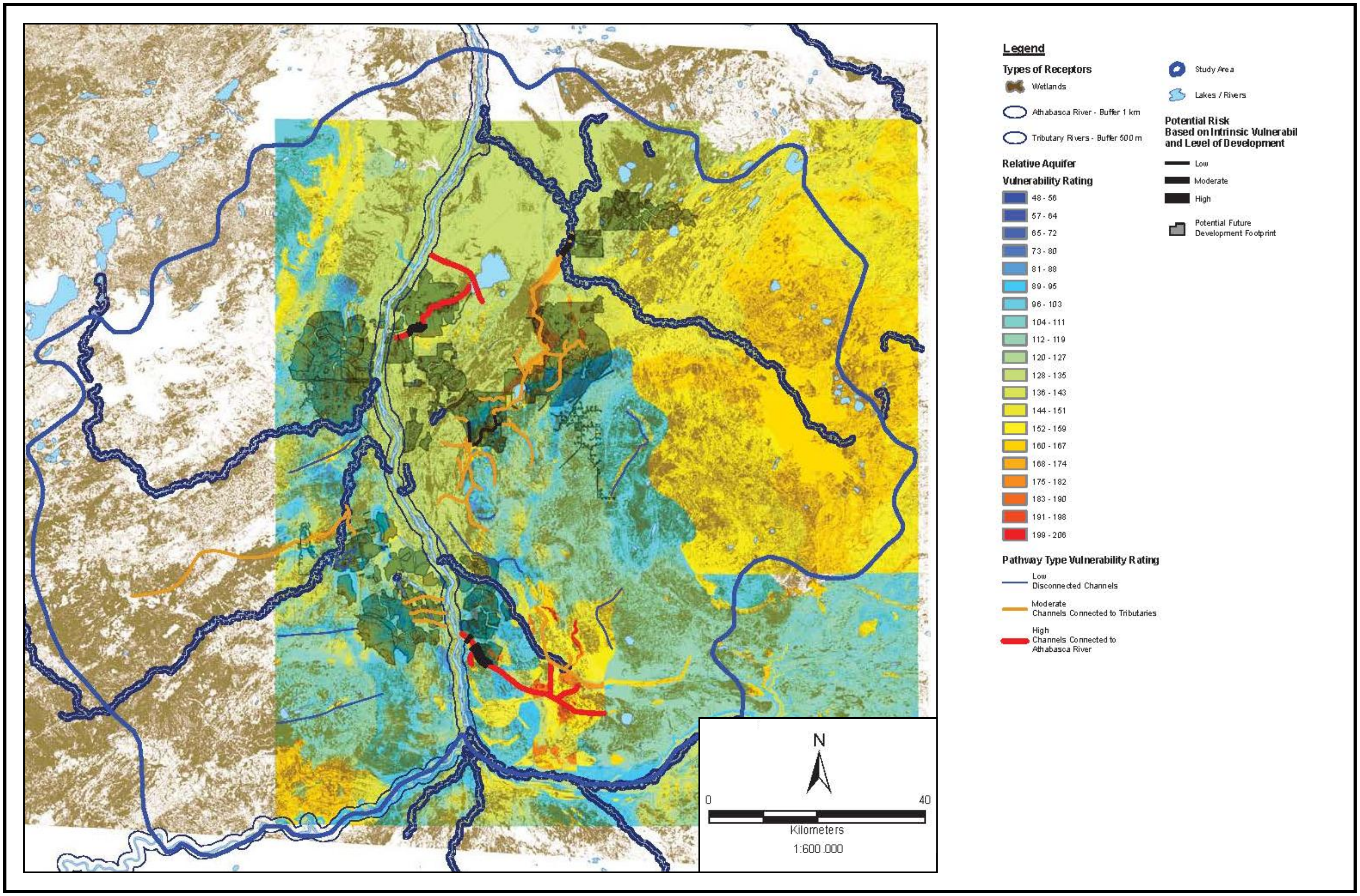


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Figure 2-22. Vulnerability Rating in the Basal McMurray Formation

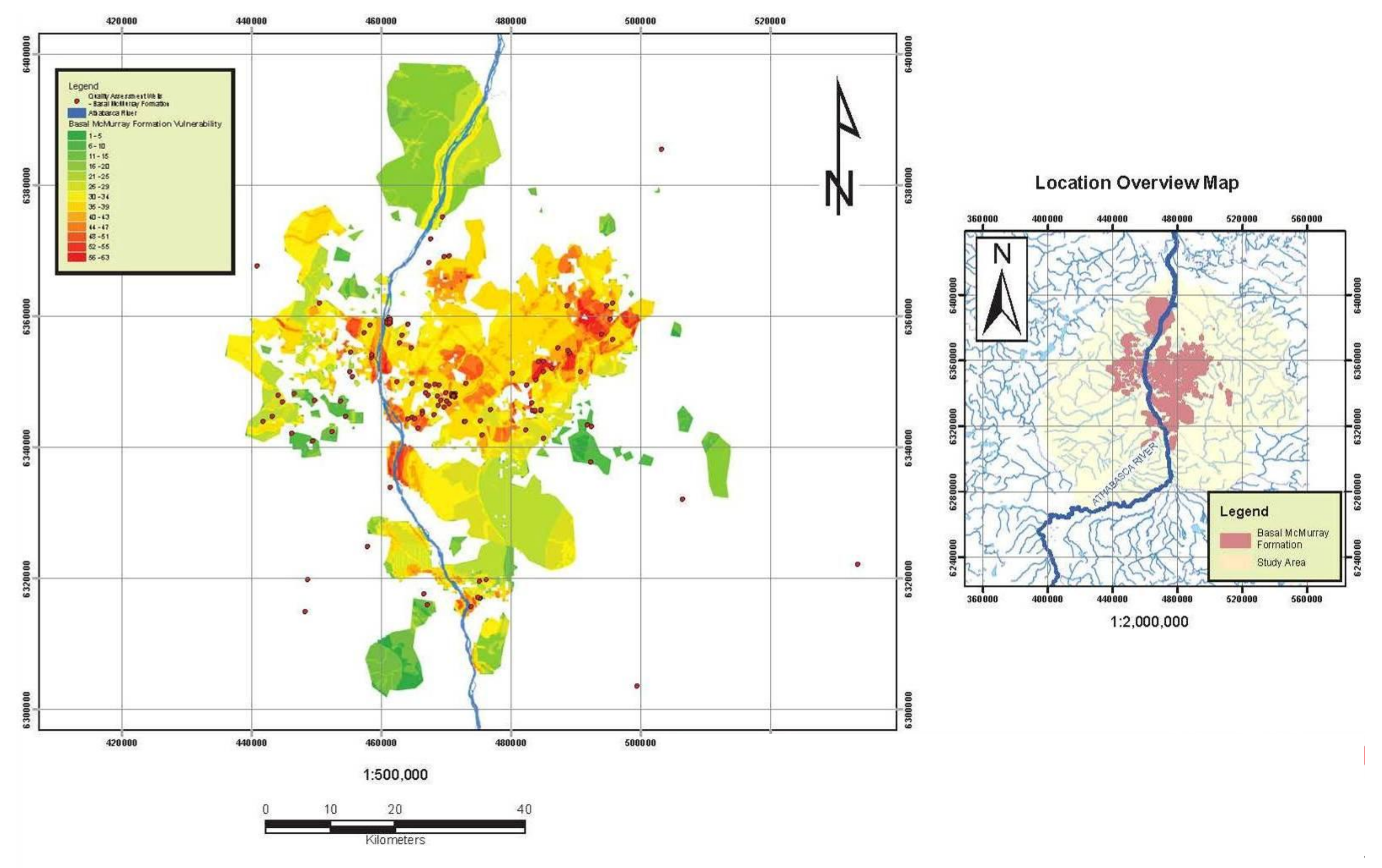

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Figure 2-23. Aquifer Management Units within Basal McMurray Formation

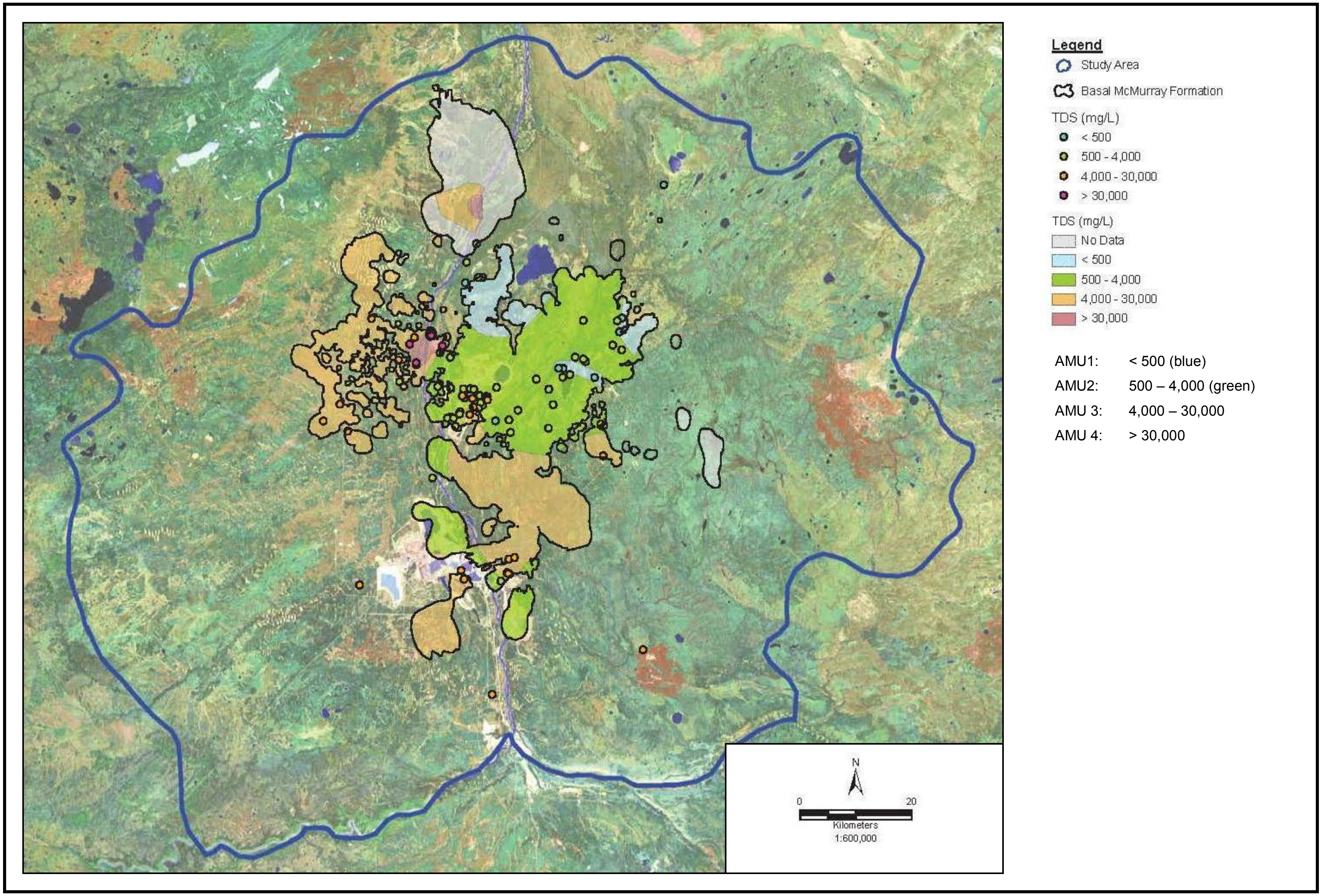

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Figure 4-1. Regional Groundwater Monitoring Network (2009 and Proposed)

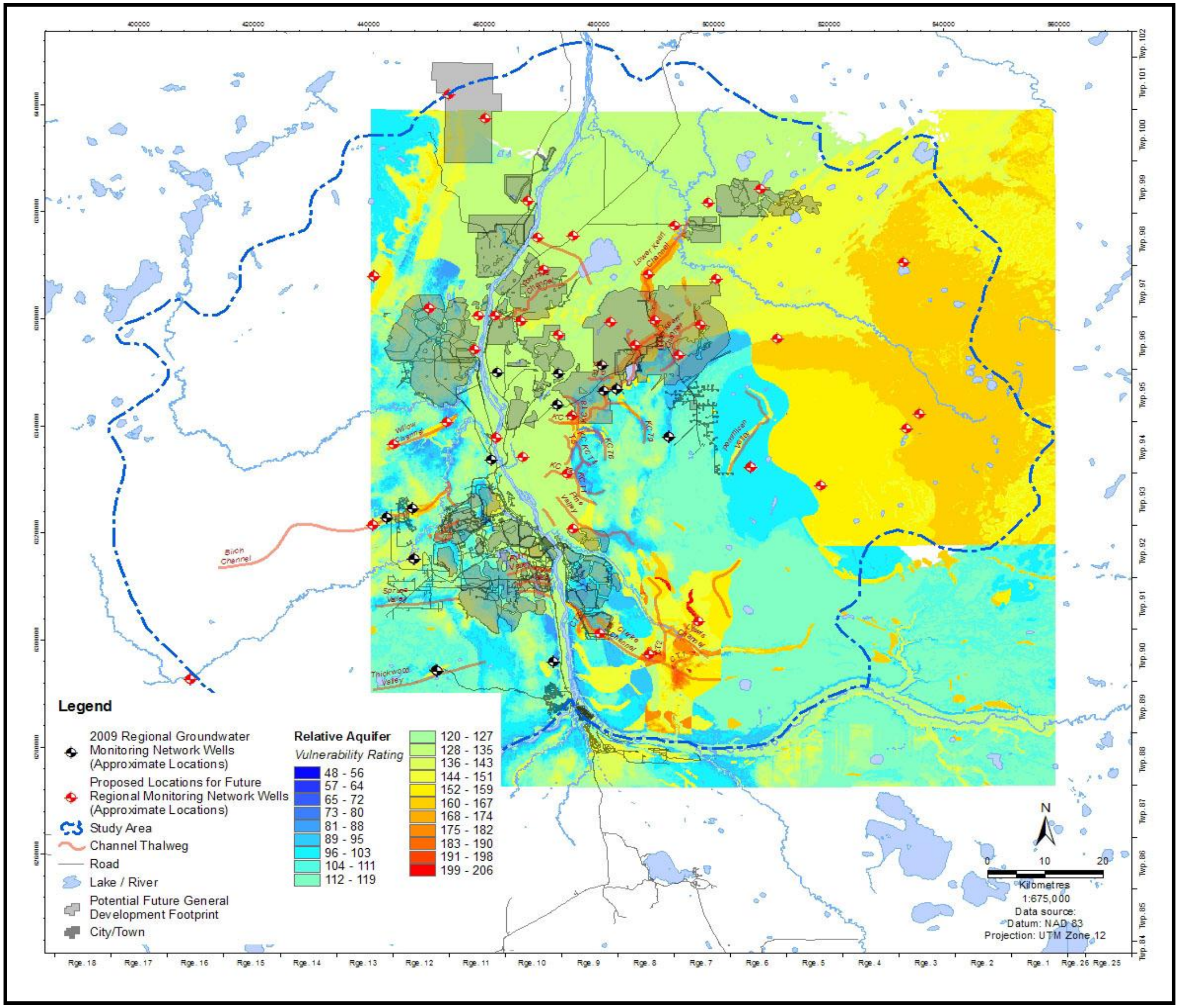

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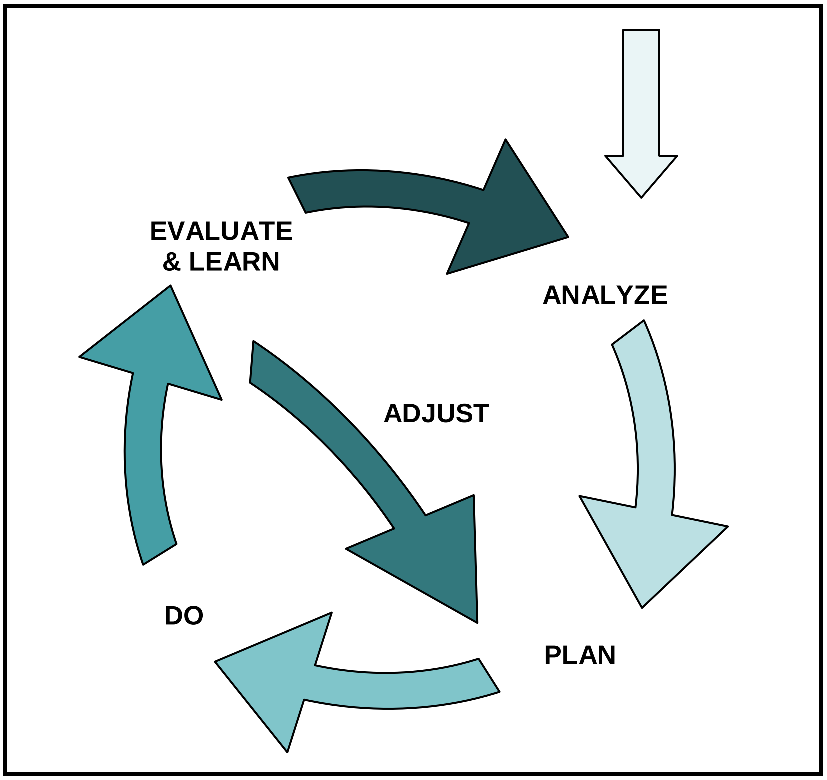
Figure 5-1: Adaptive Management Approach for Groundwater in the Lower Athabasca Region



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APPENDIX B - Tables

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Table 2-1. Summary of the Hydrostratigraphic Column in the NAOS Area

Period	Formation	Classification	Hydrostratigraphic System
Quaternary	Undifferentiated	Aquifer/Aquitard	Surficial Sands; Buried Channel and Valley Systems
Lower Cretaceous	Grand Rapids Formation	Aquifer	McMurray-Wabiskaw Aquifer/Aquitard System
	Clearwater Formation	Aquifer/Aquitard	
	Basal McMurray Formation	Aquifer/Aquitard	
Upper Devonian	Grosmont Formation	Aquifer	Beaverhill Lake-Cooking Lake Aquifer System
	Ireton Formation	Aquitard	
	Cooking Lake Formation	Aquifer	
	Waterways Formation	Aquifer/Aquitard	
	Slave Point Formation	Aquifer	
	Fort Vermillion Formation	Aquiclude	
Middle Devonian	Watt Mountain Formation	Aquitard	Prairie Watt Mountain Aquiclude System
	Prairie Evaporite Formation	Aquiclude	
	Methy Formation	Aquifer/Aquitard	
	Contact Rapids Formation	Aquifer/Aquitard	Lower Elk Point Group Aquitard/Aquiclude System
	Cold Lake Formation	Aquiclude	
	Ernestina Lake Formation	Aquifer/Aquitard	
	Lotsberg Formation	Aquiclude	
	Granite Wash / La Loche	Aquifer	
Precambrian	-	Aquiclude	-

Table 2-2. Potential Groundwater/Surface Water Interactions

Groundwater Formation	Potential Interaction Point
Kearl Channel and associated tributaries	Muskeg and Firebag rivers
Fort Hills Channel	McClelland Lake and associated fen complex
Birch Channel	MacKay River
North & South Spruce channels	MacKay River
Clark and Lewis channels	Upper Steepbank River

Table 2-3. Data Quality Rating Descriptions

Data Quality Rating	Description
Good	Good spatial and temporal data available for aquifer class; good knowledge of aquifer extent
Fair	Some spatial and temporal data available for aquifer class; some knowledge of aquifer extent
Poor	No or few data available; limited knowledge of aquifer extent

Table 2-4. Data Used in Interim Trigger Development (Aquifers Only)

Aquifer Scheme	Number of Wells with Chemistry Records	Number of Wells with Greater than 6 Measurements	Data Quality Rating
Surficial sands	184	22	Fair
Buried channels, Birch	18	8	Fair
Buried channels, Kearl (main)	12	0	Poor
Buried channels, Kearl (upper)	2	0	Poor
Buried channels, Thickwood	1	0	Poor
Bedrock aquifers, Grand Rapids	1	0	Poor
Bedrock aquifers, Wabiskaw	5	1	Poor
Bedrock aquifers, Basal McMurray	183	14	Fair
Bedrock aquifers, mid Devonian/Keg River	13	1	Poor
Total	**419**	**46**	**Fair to Poor**

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Table 2-5. Baseline Statistics – Summary

Interval	Statistic	TDS	Chloride	Ammonia	Arsenic	Naphthenic Acids	Phenols
Surficial sands	Range (mg/L)	62 – 3,470	12 – 1,550	0.005 – 2.0	0.0001 – 0.0144	0.5 – 6.6	0.00005 – 0.77
	Median	380	1.7	0.2	0.0006	0.5	0.001
	Count	166	139	63	91	74	106
Birch channel	Range (mg/L)	109 – 1,150	1 – 46	0.11 – 1.98	0.0002 – 0.0033	0.50 – 1.0	0.0005 – 0.002
	Median	689.5	4	1.39	0.0002	0.5	0.0005
	Count	16	16	8	9	15	14
Kearl channel (main)	Range (mg/L)	384 – 1,101	2 – 54	--	0.0001 – 0.002	5.0 – 8.6	0.0005 – 0.054
	Median	477	11	--	0.002	6.8	0.006
	Count	9	11	--	2	2	8
Kearl channel (upper)	Range (mg/L)	399	2.8	--	0.0025	3.7	0.003
	Median	--	--	--	--	--	--
	Count	1	1	--	1	1	1
Wabiskaw Member	Range (mg/L)	577 – 22,400	52 – 13,400	18.8 – 19.4	0.0012 – 0.0025	3.0 – 4.0	0.0005 – 0.005
	Median	22,100	12,800	19.1	0.002	3	0.003
	Count	4	4	2	2	3	2

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Table 2-5 Continued. Baseline Statistics – Summary

Interval	Statistic	TDS	Chloride	Ammonia	Arsenic	Naphthenic Acids	Phenols
Basal McMurray	Range (mg/L)	182 – 529	2.6 – 53.3	--	0.0001 – 0.068	0.5 – 6.3	0.001 – 0.02
(AMU 1)	Median	452	12.7	--	0.0005	5.05	0.002
	Count	14	14	--	9	6	12
Basal McMurray	Range (mg/L)	356 – 3,973	7 – 1,540	0.89 – 1.22	0.0001 – 0.071	3 – 32	0.0001 – 0.72
(AMU 2)	Median	2,170	567	1.06	0.0025	12	0.004
	Count	82	76	2	23	16	37
Basal McMurray	Range (mg/L)	4,351 – 23,300	500 – 13,350	2.07 – 9.90	0.0002 – 0.0055	12 - 24	0.0005 – 0.09
(AMU 3)	Median	9,190	3,145.1	6.38	0.001	15	0.005
	Count	42	41	7	10	7	4
Basal McMurray	Range (mg/L)	36,500 – 278,340	21,600 – 171,800	5.6 - 23	0.0001 – 0.006	7	0.005
(AMU 4)	Median	52,500	29,850	14.3	0.001	7	0.005
	Count	18	17	2	10	1	1
Methy Formation	Range (mg/L)	482 – 337,600	105 – 43,563	--	0.005	5.0 – 7.0	0.005
	Median	20,638	7,670.5	--	0.005	6.0	0.005
	Count	13	12	--	1	2	1

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Table 2-6. Baseline Summary Statistics – Surficial Aquifers

Unit = mg/L unless noted	Surficial Sands – some areas not potable				Birch Channel				Kearl Main Channel			
	Min	Max	Ave	Count	Min	Max	Ave	Count	Min	Max	Ave	Count
Cations, Anions & Ion Balance												
pH units	6.6	8.4	7.55	186	7.0	8.4	7.7	16	7.3	8.5	7.79	11
Chloride: D	0.3	1550.1	58.6	139	1.0	46.0	10.3	16	2.0	54.0	17.38	11
Sulphate: D	0.0015	1890	60.5	151	5.6	405	187.6	16	0.5	97.0	20.90	11
TDS	62	52480	916.1	166	109	1150	719	16	384	1101	603.22	9
Calcium: D	12.1	410	90.1	139	11.3	179	88.1	17	64.4	142	91.95	10
Magnesium:D	2.3	124	22.5	139	3.7	72.6	36.3	17	16.4	35.8	25.07	10
Potassium: D	0.1	233	7.4	138	3.9	12.4	6.9	17	1.88	15.6	5.79	10
Sodium: D	0.5	1110	59.7	139	5	332	120.4	17	9.7	103	61.96	10
Flouride: D	0.025	13	0.5	80	0.1	0.76	0.3	16	0.2	1.06	0.54	9
DOC												
DOC	0.8	83	13.1	79	ID				ID			
Nutrients												
TotAmm N	0.005	2.0	0.4	63	0.11	1.98	1029	8	ID			
Dissolved Metals and Trace Elements												
Arsenic: D	0.0001	0.0144	0.0015	91	0.0002	0.0033	0.0010	9	ID			
Barium: D	0.005	1.09	0.17	127	0.005	0.1	0.04	8	ID			
Boron: D	0.005	1.59	0.15	127	0.025	0.8	0.38	8	ID			
Mercury: D	0.000025	0.0002	0.000053	53	0.0001	0.0004	0.000163	8	ID			
Selenium: D	0.0001	0.035	0.0018	90	0.0002	0.0007	0.000263	8	ID			

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Strontium: D	0.01	2.04	0.29	118	0.166	1058	0.92	8	ID		
Select Hydrocarbons											
Benzene	0.002	0.0005	0.00024	69	0.00025	0.00025	0.00025	14	ID		
Toluene	0.0002	0.00177	0.00032	68	0.00025	0.00025	0.00025	14	ID		
Ethylbenzene	0.0002	0.0019	0.0003	69	0.00025	0.00025	0.00025	14	ID		
Xylenes	0.0002	0.0242	0.0012	125	0.00025	0.00025	0.00025	14	ID		
Phenols	0.00005	0.77	0.03	106	0.0005	0.002	0.0007	14	0.0005	0.054	0.013	8
LMW (PAH)	0.00001	0.0031	0.00051	15	ID				ID		
Napthalenes	0.000005	1	0.057	70	0.00001	0.00002	0.000018	8	ID		
Naphthenic Acids	0.5	6.6	1.34	74	0.5	1	0.6	15	ID		

ID = Insufficient Data

Note: insufficient data were available for Kearl Upper Channel and the Lewis Channel. No data were available for the buried valley wells.

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Table 2-7. Baseline Summary Statistics – Bedrock Aquifers, Part A

Unit = mg/L unless noted	Basal McMurray (TDS <500)				Basal McMurray (TDS 500- 4,000)				Basal McMurray (TDS 4,000 – 30,000)			
	Min	Max	Ave	Count	Min	Max	Ave	Count	Min	Max	Ave	Count
Cations, Anions & Ion Balance												
pH units	6.6	8.5		154	6.6	8.5		154	6.6	8.5		154
Chloride: D	2.6	53.3	19.5	14	7.0	1540.0	557.1	76	500.0	13350.0	5217.1	41
Sulphate: D	0.1	35.0	7.4	14	0.2	133.0	22.1	76	0.1	944.0	43.3	42
Iron: D					0.2	133.0	22.1					
TDS	182	529	429	14	356	3973	2129	82	4351	23300	11334	42
Calcium: D	37.9	83.6	67.1	13	4.5	112.0	42.8	48	16.0	166.0	62.8	33
Magnesium:D	15.5	32.6	26.4	13	1.0	84.1	24.9	48	18.0	293.0	97.1	33
Potassium: D	0.3	19.1	9.7	13	3.6	253.0	32.3	48	11.0	157.0	48.7	32
Sodium: D	7.3	117.0	57.2	13	48.8	1490.0	563.6	48	1610.0	9062.0	4877.3	32
Flouride: D	0.20	1.70	1.03	8	0.10	2.00	1.28	63	0.20	1.20	0.55	12
DOC												
DOC	ID				0.5	136	23.2	17	ID			
Nutrients												
TotAmm N	ID				ID				2.07	9.90	6.54	7
Dissolved Metals and Trace Elements												
Arsenic: D	0.0001	0.0680	0.0079	9	0.0001	0.0710	0.0110	23	0.0002	0.0055	0.0015	10
Barium: D	0.045	1.990	0.444	12	0.060	1.230	0.449	31	0.028	10.000	0.890	13
Boron: D	0.030	0.960	0.630	12	0.430	5.080	1.631	31	2.710	7.650	4.834	13
Mercury: D	0.000025	0.000100	0.000033	9	0.000025	0.000300	0.000065	32	0.000100	0.002400	0.000330	10
Selenium: D	0.0001	0.0390	0.0047	9	0.0001	0.1280	0.0156	23	0.0002	0.0035	0.0009	5
Strontium: D	0.20	1.95	1.21	12	0.50	3.20	1.20	31	12.80	21.80	18.94	10

Select Hydrocarbons												
Benzene	ID				0.0002	0.0029	0.0005	20	ID			
Toluene	ID				0.0002	0.0005	0.0003	19	ID			
Ethylbenzene	ID				0.0002	0.0005	0.0003	20	ID			
Xylenes	0.0003	0.0004	0.0003	8	0.0003	0.0037	0.0007	30	ID			
Phenols	0.00100	0.02000	0.00500	12	0.00010	0.72000	0.05360	63	ID			
LMW (PAH)	ID				ID				ID			
Napthalenes	0.000150	0.000400	0.000200	5	ID				ID			
Naphthenic Acids	0.50	6.30	3.95	6	3.0	32.0	14.7	16.0	ID			

Table 2-8. Baseline Summary Statistics – Bedrock Aquifers, Part B

Unit = mg/L unless noted	**Basal McMurray (TDS > 30,000)**				**Mid Devonian/Methy**			
	Min	**Max**	**Ave**	**Count**	**Min**	**Max**	**Ave**	**Count**
Cations, Anions & Ion Balance								
pH units	6.6	8.5		154	7.3	8.4	0.4	14
Chloride: D	21600.0	171800.0	38829.4	17	105.0	43563.0	12951.05	12
Sulphate: D	8.1	4540.0	2825.3	18	11.0	4737	1741.49	13
Iron: D								
TDS	36500	278340	66436	18	482	337600	106643.23	13
Calcium: D	159.0	1460.0	883.0	18	57.7	3870	1700.51	5
Magnesium:D	216.0	415.0	297.6	18	28.5	91	25.91	5
Potassium: D	29.8	156.0	76.0	18	4	19.3	5.65	5
Sodium: D	13200.0	101563.0	23553.5	18	75.3	91500	40845.17	5
Flouride: D	ID				ID			
DOC								
DOC	ID				ID			
Nutrients								
TotAmm N	ID				ID			
Dissolved Metals and Trace Elements								
Arsenic: D	0.0001	0.006	0.001	10	ID			
Barium: D	0.028	10	0.89	13	ID			
Boron: D	2.71	7.65	4.834	13	ID			
Mercury: D	0.000025	0.0024	0.00033	10	ID			
Selenium: D	0.0002	0.0035	0.0009	5	ID			

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Strontium: D	12.8	21.8	18.94	10	ID			
Select Hydrocarbons								
Benzene	ID				ID			
Toluene	ID				ID			
Ethylbenzene	ID				ID			
Xylenes	ID				ID			
Phenols	ID				ID			
LMW (PAH) units?	ID				ID			
Napthalenes units?	ID				0.00002	0.00018	0.000057	8
Naphthenic Acids	ID				ID			

Note: insufficient data were available for Grand Rapids Wells and for the Wabiskaw aquifer.

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Table 2-9. Baseline Summary Statistics – Tailings and Process-affected Ranges

Unit = mg/L unless noted	Sand Swale and Process-affected Ranges				Consolidated Tailings				Mature Fine Tailings			
	Max	95th Percentile	Median	Count	Max	95th Percentile	Median	Count	Max	95th Percentile	Median	Count
Cations, Anions & Ion Balance												
Chloride: D	795	120	53	145	795	120	53	145	250	139	68	110
Sulphate: D	1530	1106	616	146	1530	1106	616	146	255	233	140	110
Iron: D	2.3	0.28	0.022	38	9.5	2.1	0.44	40	9.5	2.1	0.44	40
TDS	4090	2289	1532	76	4090	2289	1532	76	2641	2012	1249	69
Calcium: D	506	188	56	103	506	188	56	103	39	17	7.4	103
Magnesium:D	93	47	20	106	93	47	20	106	28	8.7	4.7	102
Sodium: D	1310	622	435	110	1310	622	435	110	660	452	333	104
DOC												
DOC	95	74	48	35	95	74	48	35	207	79	57	60
Nutrients												
TotAmm N	17	11	5.1	69	17	11	5.1	69	77	24	6	70
Dissolved Metals and Trace Elements												
Arsenic: D	0.0081	0.0067	0.0051	11	0.073	0.0074	0.0038	28	0.073	0.0074	0.0038	28
Barium: D	14	0.18	0.13	27	0.31	0.22	0.12	38	0.31	0.22	0.12	38
Boron: D	4.8	3.9	2.7	27	4.8	3.9	2.7	38	4.8	3.9	2.7	38
Mercury: D	7.9E-05	6.1E-05	4.0E-05	23	7.9E-05	6.1E-05	4.0E-05	2.3E+01	7.9E-05	6.1E-05	4.0E-05	23
Selenium: D	0.0064	0.0045	0.0022	12	0.038	0.006	0.0016	40	0.038	0.006	0.0016	40
Strontium: D	3.4	2.2	1.3	28	6.2	2.4	0.75	37	6.2	2.4	0.75	37
Select Hydrocarbons												
Naphthenic Acids	115	94	68	60	115	94	68	60	120	118	100	60

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Table 2-10. Summary of Wells and Records for each Aquifer Unit

Formation or Interval	**Number of Wells**	**Number of Records**
Till	183	1,206
Surficial sands	151	1,802
Buried Channels	5	11
Birch Channel	16	109
Kearl Channel (main)	11	14
Kearl Channel (upper)	2	6
Lewis Channel	1	1
Clearwater	21	68
Wabiskaw	68	14
McMurray Formation Oil Sand	54	485
Basal McMurray	152	612
Upper Devonian/Beaverhill Lake Group/Waterways	13	952
Prairie Evaporite	2	2
Mid Devonian/Methy	1	14
Granite Wash	2	1
Precambrian	1	3
Unclassified	1	180
Total	**684**	**5,480**

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Table 2-11. Groundwater Licences as of 2009

Assigned Aquifer	Number of Licences	Total Licenced Volume (million m^3/yr)	Average Volume Withdrawn (million m^3/yr)
Surficial Deposits	15	5.1	0.34
Kearl Channel	1	26	26
Birch Channel	1	0.5	0.5
South Spruce Channel	5	1.3	0.25
Basal Aquifer	7	19	2.7
Total	**29**	**51.9**	**29.79**

Table 2-12. Summary of Recharge Rates in the Plains Region of North America

Location	Surface Lithology	Recharge (% of Annual Precipitation)	Reference
Dalmeny, Saskatchewan	Glacial Till (clay, silt and fine-grained deposits)	1.5	Fortin et al. 1991
North Dakota	Glacial Till (sandy deposits)	9	Rehm et al. 1982
14 sites in Manitoba and Saskatchewan	Various Glacial Tills	0.5 to 7.5 (average = 4.4%)	Meyboom 1967
Utikuma Lake, Alberta	Sandy, glacial outwash soils	5 to 17	Smerdon 2007

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Table 2-13. Recharge Estimate for Surficial Deposits

Areas of each of the surficial geology units, classification and estimated groundwater recharge

DESCRIPTION	Classified as Surf Aquifer	AREA (Hectares)	AREA (m2)	ONLY Surf Sand Area Term (m2)	Surfical Sand Volume (Assume 2 m thick) m3	LOW Est Recharge (mm/yr)	LOW Est Vol of Rech (m3/year)	AVE Est Recharge (mm/yr)	AVE Est Vol of Rech (m3/year)	HIGH Est Recharge (mm/yr)	HIGH Est Vol of Rech (m3/year)
Clay and silt (bedded)	N	4.24E+04	4.24E+08	0.00E+00		**7**	**2.79E+06**	**23**	**9.77E+06**	**40**	**1.68E+07**
Clay and silt (with pebbles)	N	7.22E+04	7.22E+08	0.00E+00		**7**	**4.75E+06**	**23**	**1.66E+07**	**40**	**2.85E+07**
Colluviated ground moraine	N	1.36E+04	1.36E+08	0.00E+00		**7**	**8.98E+05**	**23**	**3.14E+06**	**40**	**5.39E+06**
Gipsy till - ground moraine	N	2.10E+03	2.10E+07	0.00E+00		**7**	**1.39E+05**	**23**	**4.85E+05**	**40**	**8.32E+05**
Gipsy till - hummocky moraine	N	5.94E+02	5.94E+06	0.00E+00		**7**	**3.91E+04**	**23**	**1.37E+05**	**40**	**2.35E+05**
Granite, gneiss and metasedimentary rocks	N	3.40E+02	3.40E+06	0.00E+00		**7**	**2.24E+04**	**23**	**7.85E+04**	**40**	**1.35E+05**
Ground moraine	N	1.26E+05	1.26E+09	0.00E+00		**7**	**8.31E+06**	**23**	**2.91E+07**	**40**	**4.99E+07**
Gully, creek valley	N	2.82E+04	2.82E+08	0.00E+00		**7**	**1.86E+06**	**23**	**6.51E+06**	**40**	**1.12E+07**
Horse River till - ground moraine	N	2.42E+04	2.42E+08	0.00E+00		**7**	**1.59E+06**	**23**	**5.58E+06**	**40**	**9.57E+06**
Horse River till - hummocky moraine	N	1.35E+02	1.35E+06	0.00E+00		**7**	**8.91E+03**	**23**	**3.12E+04**	**40**	**5.35E+04**
Hummocky moraine	N	1.56E+04	1.56E+08	0.00E+00		**7**	**1.03E+06**	**23**	**3.60E+06**	**40**	**6.16E+06**
Kinosis till - ground moraine	N	2.90E+04	2.90E+08	0.00E+00		**7**	**1.91E+06**	**23**	**6.69E+06**	**40**	**1.15E+07**
Mixed	N	3.93E+04	3.93E+08	0.00E+00		**7**	**2.59E+06**	**23**	**9.05E+06**	**40**	**1.55E+07**
Organic	N	5.45E+03	5.45E+07	0.00E+00		**7**	**3.59E+05**	**23**	**1.26E+06**	**40**	**2.15E+06**
Silt	N	6.20E+03	6.20E+07	0.00E+00		**7**	**4.08E+05**	**23**	**1.43E+06**	**40**	**2.45E+06**
Silt and clay	N	4.28E+04	4.28E+08	0.00E+00		**7**	**2.82E+06**	**23**	**9.87E+06**	**40**	**1.69E+07**
Slump	N	1.82E+04	1.82E+08	0.00E+00		**7**	**1.20E+06**	**23**	**4.18E+06**	**40**	**7.17E+06**
Aeolian sand	Y	2.46E+04	2.46E+08	2.46E+08	4.91E+08	**22**	**5.39E+06**	**48**	**1.19E+07**	**75**	**1.83E+07**
Aeolian sand, dunes	Y	3.96E+04	3.96E+08	3.96E+08	7.92E+08	**22**	**8.70E+06**	**48**	**1.91E+07**	**75**	**2.96E+07**
Alluvial fan	Y	3.37E+04	3.37E+08	3.37E+08	6.74E+08	**22**	**7.40E+06**	**48**	**1.63E+07**	**75**	**2.52E+07**
Ice-contact deposits	Y	3.94E+04	3.94E+08	3.94E+08	7.87E+08	**22**	**8.64E+06**	**48**	**1.90E+07**	**75**	**2.94E+07**
Kame, kame moraine	Y	1.01E+03	1.01E+07	1.01E+07	2.01E+07	**22**	**2.21E+05**	**48**	**4.85E+05**	**75**	**7.50E+05**
Meltwater channel outwash	Y	8.92E+03	8.92E+07	8.92E+07	1.78E+08	**22**	**1.96E+06**	**48**	**4.31E+06**	**75**	**6.66E+06**
Meltwater channel sediment	Y	2.22E+04	2.22E+08	2.22E+08	4.45E+08	**22**	**4.88E+06**	**48**	**1.07E+07**	**75**	**1.66E+07**
Outwash sand	Y	1.98E+05	1.98E+09	1.98E+09	3.97E+09	**22**	**4.35E+07**	**48**	**9.58E+07**	**75**	**1.48E+08**
Outwash sand and gravel	Y	1.74E+05	1.74E+09	1.74E+09	3.48E+09	**22**	**3.82E+07**	**48**	**8.40E+07**	**75**	**1.30E+08**
Outwash sand and gravel overridden by glacier	Y	1.10E+05	1.10E+09	1.10E+09	2.20E+09	**22**	**2.42E+07**	**48**	**5.32E+07**	**75**	**8.22E+07**
Sand and silt	Y	6.26E+04	6.26E+08	6.26E+08	1.25E+09	**22**	**1.37E+07**	**48**	**3.02E+07**	**75**	**4.67E+07**
Stream alluvium	Y	4.17E+04	4.17E+08	4.17E+08	8.33E+08	**22**	**9.14E+06**	**48**	**2.01E+07**	**75**	**3.11E+07**
Grand Total		1.223E+06	1.223E+10	7.561E+09	1.512E+10		**1.967E+08**		**4.726E+08**		**7.486E+08**

TILL	1.5% to 9%	5.25%
SAND	5% to 17%	11%

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Table 2-14. Attributes Used in Vulnerability Mapping

Vulnerability Attributes for Surficial Deposits	Vulnerability Attributes for Basal McMurray Aquifer
• Depth to water • Recharge (net) • Aquifer media • Soil media • Topography • Impact of vandose zone • Conductivity (hydraulic) • Buried channels	• Source features • Thickness of surficial deposit • Receptor type • Injection location • Pathway type • Drawdown intensity

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Table 2-15. Preliminary Aquifer Classification for the NAOS Area. Part 1

	Physical and hydrogeological aquifer characteristics									Aquifer use					Groundwater quality				Groundwater quantity					Groundwater risk		
	Yield capability	Score	Approx. TDS range (mg/L)	Hydrocarbon detections	Estimated Potability Score	potential GW-SW interaction	Score	Aquifer size (km2)	Score	Demand for water	Score	type of water use - withdrawal	Score	type of water use -disposal	Quality concerns	Quality concerns	Quality Score	Quality data gaps (3=ND)	Potential quantity concerns	Quantity concerns	Quantity Concern Score	Quantity data gaps -water level (3=ND)	Quantity data gaps -volume (3=ND)	Vulnerability score	Potential Development score (2065)	Total Score
A Surficial sands																										
outwash deposits, kames, recent alluvium	Mod	2	100 to 5300	ND	3	wetlands, fens, shallow lakes	3	wide-spread	3	Mod	2	dewatering	3		seepage	local	1	1	dewatering	No	0	2	3	3	3	29
B Buried channels																										
Birch	High	3	100 to 1200	ND	3	MacKay	2	129	3	Low	1	steam generation	2		SAGD operations	local	1	2	dewatering & overuse	Yes	1	1	3	2	3	27
Clark	High	3	ND	ND	1	Athabasca	1	62	2	None	0	NCU	0		SAGD operations, mine pits and seepage	local	1	3	overuse	No	0	3	3	2	2	21
Fort Hills	Mod	3	ND	ND	1	McLelland	3	25	2	None	0	NCU	0		mine-pit backfill, seepage	no	0	2		No	0	3	3	2	2	21
Kearl (main)	High	3	400 to 1100	ND	2	Muskeg; Firebag	3	60	2	Mod	2	dewatering	3		mine-pit backfill, seepage	no	0	2	dewatering & overuse	No	0	2	3	3	3	28
Kearl (upper)	High	3	250 to 400	ND	3	Muskeg	1	17	1	Mod	2	NCU	0		mine-pit backfill, seepage	no	0	3	dewatering & overuse	No	0	3	3	3	2	24
Lewis	High	3	400	ND	3	Steebank	2	50	2	None	0	NCU	0		SAGD operations	no	0	3	overuse	No	0	3	3	3	2	24
North Spruce	Mod	2	ND	ND	3	MacKay	2	4	1	None	0	NCU	0		mine-pit backfill, seepage	no	0	3		No	0	3	3	2	2	21
South Spruce (N branch)	Mod	2	ND	ND	3	MacKay	2	2	1	None	0	NCU	0		mine-pit backfill, seepage	local	1	3		No	0	3	3	3	3	24
South Spruce (S branch)	Mod	2	ND	ND	3	MacKay	1	3	1	None	0	NCU	0		mine-pit backfill, seepage	local	1	3		No	0	3	3	3	3	23
Willow	Mod	2	ND	ND	3	Dover	1	14	1	None	0	NCU	0		mine-pit backfill, seepage	no	0	3	dewatering	No	0	3	3	2	2	20
C Buried valleys																	0									
Inglis	ND	3	ND	ND	3	ND	0	5	1	Low	1	NCU	0			no	0	3		No	0	3	3	2	3	22
Pemmican	ND	3	ND	ND	3	ND	0	68	3	Low	1	NCU	0			no	0	3		No	0	3	3	2	2	23
South Pemmican	ND	3	ND	ND	3	ND	0	24	2	Low	1	NCU	0			no	0	3		No	0	3	3	2	1	21
Pine	ND	3	ND	ND	3	ND	0	22	2	Low	1	NCU	0			no	0	3		No	0	3	3	2	3	23
Ruth	ND	3	ND	ND	3	ND	0	10	2	Low	1	NCU	0			local	1	3		No	0	3	3	2	3	24
Spruce	ND	3	ND	ND	3	ND	0	30	3	Low	1	NCU	0			no	0	3		No	0	3	3	1	2	22
Stony	ND	3	ND	ND	3	ND	0	8	1	Low	1	NCU	0			no	0	3		No	0	3	3	2	2	21
Thickwood	ND	3	ND	ND	3	ND	0	21	2	Low	1	NCU	0			no	0	2		No	0	3	3	1	2	20
D Bedrock Aquifers																										
Grand Rapids	Mod	2	1,100	Yes	1	Dover	1	regionally extensive	3	Low	1	NCU	0		SAGD operations	no	0	3	overuse	No	0	3	3	2	3	22
Wabiskaw	Low	1	1100 to 22100	Yes	1	MacKay	2	regionally extensive	3	Low	1	steam generation	1	waste injection	disposal	local	2	3	overuse	No	0	1	3	2	1	21
Basal McMurray	Mod	2	200 to 278500	Yes	1	Athabasca	3	regionally extensive	3	Mod	2	steam generation	1	waste injection; depressurization water	disposal	local	2	1	overuse	No	0	2	3	2	3	25
Methy	Mod	2	500 to 337600	Yes	1	Athabasca, Firebag, Clearwater	3	patchy; unknown	1	Low	1	NCU	0	waste injection	disposal	local	2	3	overuse	No	0	3	3	1	2	22

Notes:

1. Rating scheme: 1 = low 2 = moderate 3 = high (or no data)
2. ND = no data (or not detected); NCU = not currently used

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Table 2-16. Aquifer Management Unit Descriptions

Basal McMurray Formation	Mineralization (mg/L TDS)	Comment
AMU 1	Less than 500	Potentially potable quality; may still require treatment prior to intended use
AMU 2	500 to 4,000	Useable or treatable; may be rendered potable following adequate treatment

Table 3-1. Indicators for Mining Operations

Indicators		Condition indicator
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, LMW PAHs.
	Tertiary	GC-MS, stable or radiogenic isotopes.
Quantity	Primary	Temporal change in groundwater surface elevation in an aquifer management unit at an established monitoring location.
	Secondary	Impact to sensitive water body or wetland as demonstrated by water level changes. Accuracy of modeled versus measured conditions in established monitoring wells.

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Table 3-2 Indicators for In Situ Operations

Indicators		**Condition**
Quality	Primary	Temperature, redox, total dissolved solids, chloride, silicon, arsenic, boron, phenols.
	Secondary	All other major ions + remaining trace elements, naphthenic acids BTEX, PHC F1 and F2, LMW PAHs.
	Tertiary	GC-MS, stable or radiogenic isotopes.
Quantity	Primary	Temporal change in groundwater surface elevation in a regional aquifer at an established monitoring location.
	Secondary	Impact to sensitive water body or wetland as demonstrated by water level changes. Accuracy of modeled versus measured conditions at established monitoring wells.

Table 3-3. Indicators for Other Influences

Indicators		**Condition**
Quality	Primary	pH, TDS, chloride, nitrate, BTEX.
	Secondary	All other major ions, trace elements, pesticides, low molecular weight PAHs.
	Tertiary	GC-MS, stable or radiogenic isotopes.
Quantity	Primary	Temporal change in groundwater surface elevation in an aquifer management unit at an established monitoring location.
	Secondary	Measureable impact to sensitive water body or wetland as demonstrated by water level changes. Accuracy of modeled predictions versus measured conditions at established monitoring wells.

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Table 3-4. Examples of Development Indicators

Groundwater Quality	Groundwater Quantity
Mining Operations	
• density of mine-related seepage sites for relevant aquifers • density of disposal operations in a given area	• density of dewatering activity in overburden and basal aquifer for mine development
In-situ Operations	
• proximity of SAGD operations to aquifers and water bodies or wetlands • density of steam injection wells or disposal operations in a given area.	• density of SAGD operations per area • number of licenced water wells per aquifer and area • quantity of water withdrawals in a given area (water use index)
Other Development Activities	
• proximity of development to high priority aquifers and water bodies or wetlands	• density of population in a given area • proportion of cut block and/or forest fire burn relative to a given catchment. • density of gravel extraction operations in a given catchment

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APENDIX C. Vulnerability Assessment and Risk Mapping

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1 Vulnerability Assessment for Surficial Sands and Buried Channels

Vulnerability assessment and risk mapping was completed for the entire Lower Athabasca Region using the following methodology (WorleyParsons, 2009).

A modified version of the U.S. Geological Survey (USGS) model DRASTIC (Aller et al. 1987) was used to map the intrinsic vulnerability of the surficial sands, buried channels and valleys. This approach is a qualitative indexing method that takes into consideration the vulnerability of the subsurface to surface activities. Vulnerability mapping is a management tool and should be used to complement and not replace on-site hydrogeological investigations.

DRASTIC is a point counting method which assesses groundwater vulnerability via a system of weighted parameters (Aller et al. 1987). It consists of seven weighted layers that when aggregated provide an overall intrinsic vulnerability for a given location. A numerical score is obtained by multiplying the score assigned to a parameter by the weighting factor assigned to the parameter and summing the results. The model is based on the following assumptions:

- the contaminant is introduced at the ground surface
- the contaminant is flushed into the groundwater by precipitation
- the contaminant has the mobility of water
- the area of evaluation is 100 acres or larger.

The general approach of the DRASTIC model was followed, but some modifications were required due to lack of certain data and consideration of the regional hydrogeological setting. A modified rating table was used to improve the spatial representation at the local scale. A similar approach has been used by Liggett et al. (2006). The model consisted of a 100 metre pixel spacing for all DRASTIC layers, and was limited in areas to the north and northwest due to lack of available data, primarily surficial geology which has not been mapped to date.

There are seven attributes included in the method which make up the acronym DRASTIC, with the addition of a buried channel attribute in the modified DRASTIC approach. The modified approach assesses groundwater vulnerability in deeper laying features like buried channels. The attributes for the modified DRASTIC model are depicted in Figure C-1 and include.

- **D**epth to water
- **R**echarge (net)
- **A**quifer media
- **S**oil media
- **T**opography
- **I**mpact of vadose zone
- **C**onductivity (hydraulic)
- **B**uried channel.

The approach used to assess vulnerability is to rate each attribute depending on its characteristics and distribution within the study area. The attributes are ranked generically on a scale of one to five based on their relative importance. This is the number in front of each of the DRASTIC attributes in the formula below. The attribute weighting (w) represents the relative severity of each attribute for a specific location. The following equation is then used to determine the vulnerability rating of a given area (V).

$$V = 5\mathbf{D}w + 4\mathbf{R}w + 3\mathbf{A}w + 2\mathbf{S}w + 1\mathbf{T}w + 5\mathbf{I}w + 3\mathbf{C}w + 2\mathbf{B}w$$

(w= attribute weighting)

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Once a final vulnerability value has been computed for a given location it is possible to spatially identify areas more susceptible to groundwater contamination relative to others. Aggregate values obtained using this method typically range from high to low indicating areas with increased potential for effect from area activities (high values) or area of lesser vulnerability (lower values). Further details on the model conceptualization and attribute weighting are provided in WorleyParsons (2009). Each attribute is discussed in more detail below. As an example, results of vulnerability mapping of each of the 7 primary attributes for the surficial deposits in the NAOS area are shown in Figure 2-18 of the main document.

1.1 Depth to Water

The spatial distribution of available groundwater level data was plotted by major aquifer interval (where available). Unfortunately the spread of data was insufficient to use an interpolative method to determine the general "Depth to Water" across the area. Instead, a method similar to that of Liggett et al. (2008) was followed using the relationship between water elevation (h) and ground surface elevation (z). In a previous study executed by WorleyParsons (2010a) the following correlation was determined between depth to water and ground elevation. Given the complexity introduced by using water levels from the surficial sands (i.e., unconfined versus confined conditions), the decision was made to use data from monitoring wells completed within the upper five metres of the surficial till. Water level data were used from the oil sands area only, since in other areas no meaningful relationship could be derived from the groundwater data.

By running a linear regression through the resulting data points, the following equation was identified.

$$h = 0.0157z - 3.8537$$

(h = measured water level and z = ground elevation)

This regression coefficient associated with this equation is 0.39 (Figure C-2). Although this regression coefficient would appear a bit low, there was an obvious trend for deeper water levels at higher elevation (recharge zone) and artesian conditions at lower elevation (discharge zone). Using this equation as a reasonable approximation of depth to water below ground surface, the digital elevation model (DEM) was converted into a continuous depth to water surface for the area assessed.

1.2 Recharge

Recharge in the DRASTIC model is defined as a broad value for a region equal to the total quantity of water which is applied to the ground surface and infiltrates to reach the aquifer (Aller et al. 1987). To assess recharge conditions in the study area, predicted recharge values based on elevation were used instead of estimated net recharge and in the more southern areas based on professional judgment as well.

The DEM (digital elevation model) was used to define zones of recharge, discharge and the transition zone based on the elevation of the topographical surface. For the mineable area the review of the histogram of elevation data along with professional judgment resulted in a cut-off value of 343 metres above sea level (masl) for the top of the "discharge zone" and 449 masl for the top of the "transition zone." The top of the "recharge zone" was defined by the highest elevation in the regional dataset (859 masl). For the remaining areas recharge and discharge areas were assessed based on the DEM data and professional judgment.

1.3 Aquifer Media

Data available from the Alberta Geological Survey was used to define the presence of buried channel aquifers beneath the study area (Andriashek and Atkinson 2007). Based on this information a rating of eight (high vulnerability) was applied to the major channels with accumulations of sands and gravel, while all other zones outside of the defined channels were assigned a rating of one (low vulnerability).

1.4 Soil Media

Data defining the soil media underlying the study area was accessed using the surficial geology provided through the Alberta Geological Survey. Data for a portion of the NAOS area to the west and north has yet to be

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mapped and thus was not available for assessment. As a result, the final vulnerability map was reduced in extent to only cover the area where surficial geology exists (i.e., the coloured area of DRASTIC seen on the maps demonstrates the extent of coverage). Vulnerability ratings values were assigned to the different surficial geology types in the study area using professional judgment. For example, a rating of seven (higher vulnerability) was applied to the more permeable outwash sand deposits and kames as opposed to a value of three (low vulnerability) for lower permeability till deposits.

1.5 Topography (per cent Slope)

The topographic layer of the DRASTIC model was derived from the DEM data obtained for use in this study. The degree of slope (as per cent) was calculated from the information provided using the spatial analyst “slope” tool available in the ArcGIS version 9.3 software. Higher vulnerability was associated with low per cent slope as opposed to areas with a higher per cent slope. The reasoning behind this is that water on steeper slopes will tend to run off versus infiltrate, thus the potential for any constituents within the runoff water to enter the subsurface is less.

1.6 Impact of Vadose Zone

Instead of using the traditional DRASTIC parameter “Impact of Vadose Zone,” a layer characterizing the thickness of protective cover above the aquifer was created. Using the surficial geology GIS layer, hydraulic conductivity values (K in m/s) were identified for the various units using measured values provided by existing oil sands applications, government reports and/or professional judgment. A bias toward overestimating the most probable hydraulic conductivity was used. Table C-1 summarizes the various types of deposits and assigned K values.

Aggregate overburden thickness was calculated by subtracting the thickness of the buried channels from the overall drift thickness (both obtained from Andriashek and Atkinson 2007). Surficial deposits with the highest K values were assumed to have a zero metres thickness of protective cover. The resulting layer was combined with the layer of zero metres thickness for surficial sands to create a final “thickness of protective cover” layer.

1.7 Conductivity (hydraulic)

Hydraulic conductivity values measured from shallow wells in the area were overlain on the outline map of the buried channels. Using available data and professional judgment, a hydraulic conductivity value was averaged for the aquifers, and given a vulnerability rating based on one of the tables in Liggett et al. (2006). All other locations (where there were no buried channels) were given a rating of one.

1.8 Buried Channel

The USGS DRASTIC model has a tendency to underestimate the groundwater vulnerability in areas where there are buried channels. These channels can form a conduit for vertical and lateral groundwater movement towards receptors, and thus make the area more vulnerable to impacts from subsurface. Where channels are present a weighting of four was used for the buried channel attribute, and a value of one where channels are absent.

2 Vulnerability Assessment for Basal McMurray Aquifer

Vulnerability in the Basal McMurray Aquifer was assessed for the NAOS area. The modified DRASTIC model, which is a “top down” type of assessment, does not include “bottom up” or “side-in” type of influences. The following additional factors were therefore used to accommodate the occurrence of “bottom-up” types of influences such as dewatering, injection and mine depressurization:

- potential source areas (end pit lakes, mine pit backfill, waste injection wells, and active and future tailings ponds)
- thickness of low permeability overburden material above the Basal Aquifer
- nearby receptor type (surficial water body, tributary to Athabasca, useable aquifer, potable aquifer, and the Athabasca River itself)

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- waste injection site locations and the degree of potential interconnectedness of the Basal Aquifer in the surrounding area
- inferred pathway types (faults, degree of interconnection to the Athabasca River)
- drawdown intensity (based on the number of existing and planned mine de-watering systems).

Table C-2 provides the ranking system applied to each of these attributes, which ultimately led to the aggregate vulnerability value. Figure 2-19 of the main document shows the results of vulnerability mapping for these attributes for the Basal McMurray Aquifer in the NAOS area.

3 Risk Mapping

In order to assess risk to groundwater resources in the study area, development features were added to the modified DRASTIC model. The definition of risk, in the context of groundwater resources, can be described as follow.

Intrinsic vulnerability + Development intensity = Risk

Development intensity was dealt with by adding two data layers to the process.

1) a layer identifying potential source areas, ranked pathways and potential receptors in the area
2) a "development" layer indicating the additive summary of ranked contaminant sources, age of proximal infrastructure and overall development footprint in the area.

Table C-3 provides a summary of data sources used for the risk mapping approach. GIS layers were created and summed to yield the final maps, which help identify risk of potential cumulative effects in the area. A ranking system (i.e., one to ten) was developed to determine the level of vulnerability associated with each major attribute, pathway and receptor type, contaminant source and age of infrastructure, and intensity of activity. Each of these attributes are discussed in detail below. The final potential risk map is a superimposition of the development intensity layers over the vulnerability maps. It is instrumental in identifying areas at highest risk from area development, and thus worthy of future monitoring to assess for potential cumulative effects.

3.1 Pathway and Receptor Type

The pathway type shape file was made using two polyline files, one of the buried channels provided by the Alberta Geological Survey (AGS) and the EUB/AGS, and the other from postulated fault lineaments identified in Cotterill and Hamilton (1995). Buried channels were ranked based on their potential connection to themajor rivers (direct, indirect or no connection) and associated tributary streams. Channels with potential for connection to major wetland areas were also identified. Weighting for the various pathway types identified is provided in Table C-4.

Wetlands were mapped using two sources. The first was the Alberta Ground Cover Classification (AGCC) from Alberta Sustainable Resource Development (ASRD). This data set was generated by ASRD from satellite imagery of the province, with ground-truthing done on different areas to verify results. Anything classified as a wetland by the AGCC data was mapped as such.

The other data source used in this process was shape files from the Government of Canada's Natural Resources Canada national topographic (NTS) database files, where 1:50,000 scale topographic shape file data was downloaded for use. These wetland polygons did not differentiate between vegetation types like the AGCC imagery. Areas within one kilometre of rivers with channels potentially interacting with them were identified as high risk. A similar approach was used for major tributary rivers and stream, only a 500 metre buffer distance was used. Table C-5 summarizes the ranking associated with each receptor type.

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3.2 Contaminant Source Type and Age of Infrastructure

Contaminant source types and their related age were included in the risk mapping approach given their potential for effect. This was achieved using a combination of points for different facilities and polygons for different footprints in the area. Weighting applied to the various contaminant source types is summarized in Table C-6. Age of infrastructure was considered in the attribute ranking approach, with increased weighting being given to older facilities.

The bedrock geology of the Devonian and McMurray formations were trimmed using a 300 metre buffer around major rivers and a 200 metre buffer about the tributary rivers. This approximates the boundary zone where the slopes of the river valleys significantly decrease and flatten out based on the DEM data for the area.

3.3 Intensity of Activity

Polygons identifying other area infrastructure were digitized from publicly available Environmental Impact Assessments that included the proposed development footprint plans. Only footprints up to and including the year 2065 were used to generate the shape files. Existing tailings ponds identified on the Digital Globe satellite image were also digitized and included in the development footprint layer. For in-situ operations, lease boundaries were used. Linear corridors (such as roads and cut lines) were included in the intensity of activity as well.

The resulting footprints are a combination of all proposed disturbances gathered from the various oil sands applications accessed. Footprints associated with these developments were amalgamated into a GIS layer for assessment along with the aggregate vulnerability layer.

3.4 Results of Risk Mapping

The results of the risk mapping exercise for each of the three Athabasca Oils Sands areas are given in the main text of the respective *Supporting Document*.

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Appendix C Figures and Tables

Figure C-1 Attributes for DRASTIC Model

(Source. B. Turner and R. Franklin [GSC] and modified by C. Médard Chardon [SFU])

Figure C-2. Relationship Between Ground Elevation and Depth to Groundwater

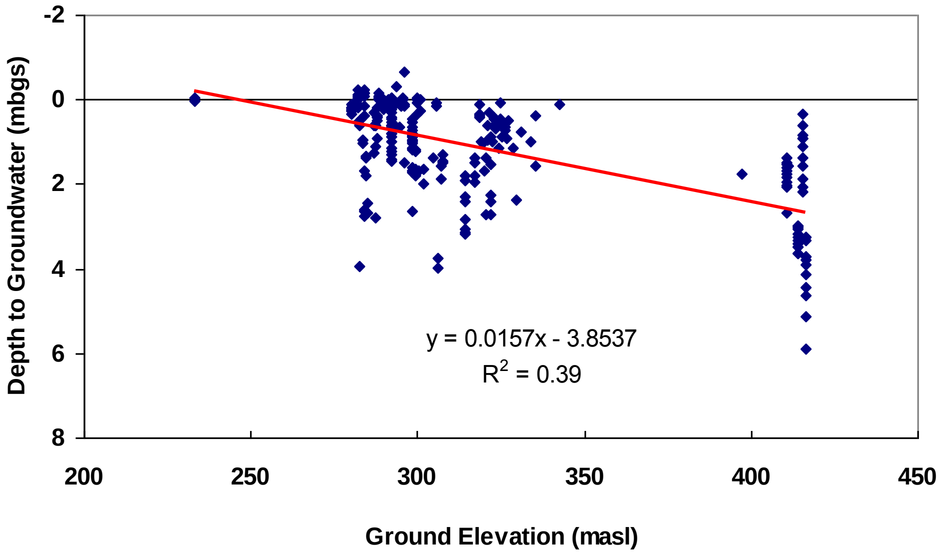

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Table C-1 Summary of K-values Used for “Impact of Vadose Zone”

Map Code	Group	Age	Description	K (m/s)
17	Aeolian Deposits	Not shown	Loess	1×10^{-6}
18	Aeolian Deposits	Not shown	Aeolian sand	1×10^{-5}
12	Aeolian Deposits	Recent	Aeolian sand, dunes	1×10^{-5}
13	Alluvial Deposits	Recent	Stream alluvium	1×10^{-5}
19	Alluvial Deposits	Not shown	Stream alluvium	1×10^{-5}
5	Glaciofluvial Deposits	Pleistocene	Ice-contact deposits	1×10^{-5}
9	Glaciofluvial Deposits	Pleistocene	Kame, kame moraine	1×10^{-5}
11	Glaciofluvial Deposits	Pleistocene	Outwash sand	1×10^{-5}
14	Alluvial Deposits	Recent	Alluvial fan	1×10^{-4}
12	Glaciofluvial Deposits	Pleistocene	Meltwater channel outwash	2×10^{-4}
9	Glaciofluvial Deposits	Pleistocene	Meltwater channel sediment	2×10^{-4}
7	Glaciofluvial Deposits	Pleistocene	Outwash sand & gravel	2×10^{-4}
6	Glaciofluvial Deposits	Pleistocene	Outwash sand & gravel overridden by glacier	2×10^{-4}

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Table C-2. Attribute Ranking for Basal McMurray Formation Vulnerability

Ranking	Source Area	Thickness of Surficial Deposit Metre\(m)	Receptor Type – Adjacent to or Connected	Injection Location	Pathway Type	Drawdown Intensity
1		>100		Into isolated pod away from Athabasca R. (>2 km)	Precambrian fault	
2	Pit lake	100			Isolated pod away from Athabasca R. (>2 km)	One planned + existing operator
3		50	Major wetland complex		Devonian fault	
4		40	Surficial water body		Isolated pod near Athabasca R. (<2 km)	Two planned + existing operators
5		30	Tributary to Athabasca			
6	Mine pit backfill	20	Useable aquifer (Grand Rapids, Basal Useable AMU)			
7		15	Potable aquifer (Basal Potable AMU, surficial sands & buried channels			
8	Waste injection well	10		Into fault connected to Athabasca R.		
9		5				
10	Tailings pond	<5	Athabasca River	Into interval connected to Athabasca R.	Connected to Athabasca River	Five planned + existing operators

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Table C-3. Data Sources for Development Activity, Potential Receptors and Pathways

Parameter	Shapefile Type(s)	Data Sources
Contaminant Source	Point - Oil and Gas Facilities (including SAGD and CSS facilities)	Ensight IHS Energy
	Point - Golf Courses	Addresses Found on the Internet and Spatial Location Digitized
	Polygons - Footprints	Digitized from EIA Reports/Digital Globe Satellite Image
	Polygons - Bedrock Geology	Alberta Geological Survey
Age of Proximal Infrastructure	Polygons - Footprints	Digitized from EIA Reports/Digital Globe Satellite Image
Pathway Type	Poly-lines - Faults	ARC Open File Report, 1995-07 Fig 22
	Poly-lines - Buried Channels	Alberta Geological Survey
Intensity of Activity	N/A	N/A
Type of Receptor	Raster - Alberta Ground Cover Classification (AGCC)	Alberta Sustainable Resource Development
	Polygons - 1.50,000 National Topographic Database (NTDB) Wetlands	Natural Resources Canada

Table C-4. Ranking of Pathway Types

Ranking	Pathway Type
1	Disconnected channel
3	Disconnected channel with potential for effect on major wetland area
4	Devonian fault and post Devonian faults
5	Channel potentially connected to tributary discharging to Athabasca River
10	Channel potentially connected to Athabasca River (i.e. Clarke channel, Fort Hills); bedrock formation in contact with major river or tributary

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Table C-5. Ranking of Receptor Types

Ranking	Receptor Type
6	Wetland
8	COSEWIC area
9	Tributary to Athabasca River
10	Athabasca River

Note. COSEWIC = Committee on the Status of Endangered Wildlife in Canada

Table C-6. Ranking of Contaminant Source Type

Ranking	Contaminant Source Type	Age of Proximal Infrastructure
1	Satellite, injection well, terminal, gas gathering system, tank farm, line heater, pump/metering station	Husky Sunrise, Shell Jackpine, CNRL Horizon; Petro-Canada Fort Hills, Total Joslyn and other SAGD; Undeveloped mines (less than 5 years)
2	Compressor station, battery	Suncor Firebag (less than 5 years)
3	Waste water treatment plant, golf course	Syncrude Aurora N; Petro-Canada Dover & MacKay, Albian Sands (4 to 10 years)
4	End pit lake, open mine pit, gas plant	
5	Forestry disturbance	
6	Overburden dump/ stockpile	
7	Reclamation landform	
8	External tailings area	Syncrude Mildred Lake (16 to 36 years)
9	Tailings pond	
10	Discharge from Devonian/McMurray	Suncor Lease 86/17, Steepbank and Millennium (36 to 40 years)

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