Preliminary State of Groundwater Knowledge in the Transboundary Region of the Mackenzie River Basin, Northwest Territories

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Jamie VanGulck, Ph.D., P.Eng., Principal
ARKTIS Solutions Inc.
vangulck@arktissolutions.com

Phone: 867.446.4129
Facsimile: 866.475.1147

EXECUTIVE SUMMARY

The Mackenzie River Basin covers roughly 1.8 million square kilometers, nearly 20% of the landmass of Canada, including areas within Alberta, British Columbia, Saskatchewan, the Yukon, and the Northwest Territories. In 1997 these provinces and territories signed the Mackenzie River Basin Transboundary Waters Master Agreement, which commits all six governments to work together to manage the water resources of the whole Mackenzie River Basin. The Master Agreement also makes provisions for neighboring jurisdictions to negotiate Bilateral Water Management Agreements to address water issues at jurisdictional boundaries on transboundary water bodies and to provide objectives on the quality, quantity and flow of water.

This preliminary State of Groundwater Knowledge Report for the transboundary groundwater of the Mackenzie River Basin bordering the Northwest Territories is intended to aid in implementation of the aforementioned Bilateral Water Management Agreements. Currently, there is limited knowledge about groundwater classification, quality and quantity in the Transboundary Area of the Mackenzie River Basin. Advancing the knowledge of groundwater in the Transboundary Area is critical with respect to the implementation of existing Bilateral Agreements, and the negotiation of future agreements. The Bilateral Agreements stipulate the development of Learning Plans to improve the understanding of aquifers that have moderate levels of existing or proposed development and/or are considered vulnerable (e.g., low water), support sensitive uses (e.g., drinking water), experience high degree of conflict, or show negative impact trends. The Learning Plans are to include issue scoping, compilation of baseline data, collection of additional baseline data, monitoring, data analysis, and investigations into potential effect pathways. This report consolidated existing knowledge on groundwater resources, groundwater uses, potential impacts to groundwater, groundwater monitoring, and groundwater-surface water interaction to support the future development of Learning Plans.

The hydraulic properties of geological materials control, in large part, the flow of groundwater and location of aquifers. The surficial and bedrock geology can be broadly divided into three categories that align with these physiographic regions straddled by the Mackenzie River Basin:

- Canadian Shield: The pervasive crystalline rocks of the Canadian Shield are characterized by low primary porosity and permeability, with variable fracture patterns, and generally have a low water yield and poor water quality. The glacial sediments in the Canadian Shield, in particular, the coarse-grained high yield glaciofluvial deposits (e.g., eskers) can be an important location for aquifers.
- Interior Platform: The near horizontal bedrock stratigraphy in the Interior Platform is commonly assigned to three categories, a lower clastic unit, a middle unit of carbonates and evaporites, and an upper clastic unit, with groundwater quantity and quality commonly controlled by depth and the nature of shallower, overlying units. Surficial aquifers, namely buried valley aquifers, are some of the most important freshwater aquifers in the southern portions of the Mackenzie River Basin.
- Cordillera: Bedrock groundwater flow in the intensely deformed rocks of the Cordillera region typically occurs through secondary fractures, or porous rock types, with artesian conditions commonly occurring in intermontane valleys. Shallow unconfined glaciofluvial and fluvial aquifers located in river valleys may have a direct connection with the surface water; these aquifers are highly vulnerable to contamination, and are also an important water source for many communities. Groundwater recharge is seasonally dependent, occurring in late spring to early summer as a result of freshet.

Permafrost covers the northern part of the Mackenzie River Basin extending across all three physiographic regions extending to depths greater than 500 m. The southern boundary of the permafrost region is irregular, as it is influenced by secondary features, such as aspect, vegetation cover and snow depth. Permafrost in the mountainous terrain of the Cordillera is particularly complex, in addition to the secondary features listed above, air movement may also influence distribution. Permafrost acts as a barrier to groundwater flow, reducing groundwater recharge, and groundwater-surface water interaction. The active layer of permafrost functions as an unconfined aquifer for shallow groundwater, seasonally when thawed.

There have been a limited number of studies completed on delineating aquifers in the transboundary region of the Mackenzie River Basin. Aquifers have been characterized in four areas related to oil and gas exploration: Norman Wells, Northwest Territories, near Fort Liard, Northwest Territories, near Fort Nelson, British Columbia and near Cameron Hills, Northwest Territories and Alberta.

In each Transboundary Area stakeholder jurisdiction, groundwater users were identified, where applicable, in applications related to: community uses, domestic (private) uses, mining uses, oil and gas production uses, commercial uses, industrial uses and agricultural uses. Table 1 summarizes the state of knowledge for each category by jurisdiction. Alberta and British Columbia are by far the largest groundwater users by jurisdiction. Alberta has excellent information on groundwater use, while groundwater use in British Columbia has not been regulated previously, and will not be until sometime in 2016. Saskatchewan had no identified groundwater users. Oil and gas are the largest groundwater user by industry, and in particular oil sands mining in the Athabasca and Peace sub-basins.

Each jurisdictional stakeholder in the Transboundary Area have their own unique developments that may impact groundwater, which may include environmental remediation sites, landfills (community and industrial), mining undertakings, and/or oil and gas production undertakings. Table 2 summarizes the state of knowledge for potential impact source by jurisdiction. Data on the potential impacts from oil and gas production, mining, and new landfills is typically readily available due to environmental assessments. Historically contaminated sites tend to have less data available until remediation and long term monitoring occurs.

Groundwater monitoring programs in the Transboundary Area were reviewed, including both provincial/territorial observation well networks and local monitoring programs. The state of knowledge for groundwater monitoring is summarized by jurisdictions in Table 3. Provincial/territorial monitoring programs have been implemented by all jurisdictions except for the Northwest Territories; however, the monitoring programs have no wells, or a limited number of wells in the Transboundary Area. Groundwater monitoring is required by water licences for licensed mine sites in the Northwest Territories and Yukon. Oil and gas projects in care and maintenance within the Northwest Territories were not required to monitor groundwater. Regulatory monitoring requirements of oil and gas and mining projects in the three provinces was not reviewed due to time constraints.

Identified areas of groundwater and surface water interaction were located for each Transboundary Area stakeholder jurisdiction. These areas include surface water bodies, karst landforms, springs, and abandoned mine adits. Table 4 summarizes the state of knowledge for each category by jurisdiction. Areas of karst topography were inferred from geological maps and reports for all applicable jurisdictions. The location of springs was limited or not available for all jurisdictions. The interaction of groundwater and surface water at the bottom of surface water bodies was not investigated, and should be informed by the surface water learning plans, which are not yet available.

A summary of the state of groundwater knowledge required to develop Learning Plans is provided in Table 5 for each of the jurisdictions of the Transboundary Area of the Mackenzie River Basin.

Table 1. Summary of the state of knowledge for groundwater uses by stakeholder jurisdiction.

Groundwater Use	Summary of the State of Knowledge for Groundwater Uses by Stakeholder Jurisdiction				
	Northwest Territories	**Alberta**	**British Columbia**	**Saskatchewan**	**Yukon**
Community and Domestic	Limited number of users. Some communities record quantity of groundwater used as required by Water Licence.	Large number of wells and high use. Estimates of total groundwater use by area, and database of groundwater users.	Large number of wells and high use. No estimate of total groundwater use. Water use to be regulated, but no reporting on quantities removed. Database of water wells locations.	No known users. Surface water is the primary water source.	Limited number of users. Environment Yukon has water well registry but does not track volume of water used in domestic wells.
Mining	Prairie Creek is the only known mine using groundwater as a water source, and are required to record the volume of water used. Most mines extract large volumes of water through dewatering. Water licences may require this volume of water to be recorded.	Alberta combines water use for mining, and oil and gas. Largest user of groundwater for the entire Mackenzie River basin, in particular oil sands mining in the Athabasca and Peace sub-basins. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. No active mines. Surface water has historically been the primary water source.	Two of three mines are using groundwater. Water licences limit the volume used, and require the volume used to be reported annually.
Oil and Gas	Oil and gas exploration and production is limited by current oil prices. Oil and gas production is a major user of groundwater in the NT during production. Some water licences limit volume of water used, and require annual reporting of quantities.		Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Limited exploration has been completed.	No known users. Oil and gas exploration and production is limited by current oil prices and regulatory framework. A potential major user of groundwater in the YK.
Commercial	No known users. Region has low population and limited infrastructure.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region has low population and limited infrastructure.	No known users. Region has low population and limited infrastructure.
Industrial	No known users. Region has low population and limited infrastructure.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region has low population and limited infrastructure.	No known users. Region has low population and limited infrastructure.

Groundwater Use	Summary of the State of Knowledge for Groundwater Uses by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
		use by area, and database of groundwater users.			
Agricultural	There is limited agriculture in the Hay River sub-sub-basin. No known groundwater users due to abundant surface water.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region is not ideal for agricultural practices	No known users. Region is not ideal for agricultural practices
Local Community Information	Information from local communities on groundwater is available for some locations. Not all communities had responded at the time of writing.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.
Other	No known users.	Alberta uses groundwater for water management and habitat enhancement. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users.	No known users.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;
Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
Red = Data is unavailable or not recorded and will result in gaps within Learning Plans.
Tan = Not applicable.

Table 2. Summary of the state of knowledge for potential impacts to groundwater by stakeholder jurisdiction.

Source of Impact	Summary of the State of Knowledge for Potential Impacts to Groundwater by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Environmental Remediation Sites	Database of federal contaminated sites. Does not include private or territorial contaminated sites. Potential impact to groundwater not assessed in this report.	Provincial database of contaminated sites. Database of federal contaminated sites. Potential impact to groundwater not assessed in this report.	Provincial database of contaminated sites. Database of federal contaminated sites. Potential impact to groundwater not assessed in this report.	Database of federal contaminated sites. Does not include private or provincial contaminated sites. Potential impact to groundwater not assessed in this report.	Database of federal contaminated sites. Does not include private or territorial contaminated sites. Potential impact to groundwater not assessed in this report.
Landfills	This report has assumed landfills to be associated	Database of active landfills and historic dump sites.	Database of active landfills and waste disposal	This report has assumed landfills to be associated	One landfill was identified in YK portion of the basin.

Source of Impact	Summary of the State of Knowledge for Potential Impacts to Groundwater by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
	with communities in the NT. Impacts would likely be restricted to shallow aquifers due to the prevalence of permafrost. Potential impact to groundwater not assessed in this report.	Potential impact to groundwater not assessed in this report.	facilities. Potential impact to groundwater not assessed in this report.	with communities in northern SK. Impacts may be reduced due to permafrost. Potential impact to groundwater not assessed in this report.	Historic landfills and dump sites may be located elsewhere. Impacts may be reduced due to permafrost. Potential impact to groundwater not assessed in this report.
Mining	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	No licensed mines in region. The locations of advanced exploration projects were not identified in this report. Impacts to groundwater would be predicted during environmental assessment and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.
Oil and Gas	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment and assessed during production phase.	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment and assessed during production phase.	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment and assessed during production phase.	Database of historic, and exploration oil and gas wells. No production has occurred in the region. . Impacts to groundwater would be predicted during environmental assessment and assessed during production phase.	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment and assessed during production phase.

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Table 3. Summary of the state of knowledge for groundwater monitoring by stakeholder jurisdiction.

Monitoring	Summary of Groundwater Monitoring by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Regulatory (Users)	Groundwater users are required by water licences to report the volume of groundwater used, but not necessarily the water level of the aquifer or water quality.	Regulatory monitoring requirements were not assessed as part of this report.	No regulations on groundwater use in province until 2016.	No known users.	Groundwater users are not required to monitor quantity or quality.
Regulatory (Impacts)	Active mining projects and mining projects under remediation are typically required by water licences to monitor groundwater quality if there is a potential for impact. Oil and gas facilities in care and maintenance are often not required to monitor groundwater.	Regulatory monitoring requirements were not assessed as part of this report.	Regulatory monitoring requirements were not assessed as part of this report.	Regulatory monitoring requirements were not assessed as part of this report.	Active mining projects and mining projects under remediation are typically required by water licences to monitor groundwater quality if there is a potential for impact. No oil and gas projects are active.
Provincial or Territorial Monitoring Network	No territorial groundwater monitoring network.	Provincial monitoring network, but limited number of wells in north. Continuously monitors groundwater level, and periodically water quality.	Provincial monitoring network, but limited number of wells in north. Continuously monitors groundwater level, and periodically water quality.	Provincial monitoring network, but no wells in basin. Continuously monitors groundwater level, and periodically water quality.	Territorial monitoring network, but no wells in basin. Continuously monitors groundwater level, and periodically water quality.

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Table 4. Summary of state of knowledge for groundwater-surface water interaction by stakeholder jurisdiction.

Type of interaction	Summary of State of Knowledge for Groundwater-Surface Water Interaction by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Surface water bodies	Interaction between surface water bodies and groundwater was not investigated. No database of talik locations.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.

Type of interaction	Summary of State of Knowledge for Groundwater-Surface Water Interaction by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Karst landscapes	Regional study identifying known and potential karst landscapes. Karst landscapes have been identified locally.	Regional study identifying known and potential karst landscapes. Karst landscapes have been identified locally.	Regional study identifying potential karst landscapes. Karst landscapes have been identified locally.	No known karst landscapes.	Karst landscapes have been identified locally.
Springs	Local studies of spring locations and water quality. No territorial database of spring locations.	Limited provincial database of spring locations.	No provincial database of spring locations. Locations of protected hot springs identified.	No provincial database of spring locations.	No territorial database of spring locations. Locations of protected springs identified.
Abandoned mine adits (mountains)	Federal database of contaminated sites contains abandoned mines.	Federal and provincial database of contaminated sites contains abandoned mines.	Federal and provincial database of contaminated sites contains abandoned mines.	Not applicable.	Federal database of contaminated sites contains abandoned mines.

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Table 5. Summary of groundwater knowledge and relevant notes required to develop Learning Plans.

Learning Plan Item	Data Gaps and Relevant Notes Per Stakeholder				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Groundwater Resources	Limited number of hydrogeological studies available.	Limited number of hydrogeological studies available.	Limited number of hydrogeological studies available.	No hydrogeological studies were identified during writing of this report.	No hydrogeological studies were identified during writing of this report; however, one study occurred south of the border in British Columbia.
Groundwater Uses	Limited users due to sparse population of the area. Groundwater uses well defined and groundwater quantity reporting regulated.	Groundwater uses well defined and studies performed to examine groundwater quantity per water use category. Data available to public.	Groundwater use has not been regulated in past, and quantities have not been reported. New legislation is expected to be instituted in 2016 requiring water licences for non-domestic use. This will also require water use quantities to be reported.	Limited users due to sparse population of the area.	Limited users due to sparse population of the area. Incomplete list of users and associated quantities

Groundwater Impacts	List of federal contaminated sites is available. A complete list of landfills is available.	Risks to groundwater are well defined and available to public.	At the time of this report, limited data was available about environmental remediation sites. Other risks including landfills, mining and oil and gas production are well known.	List of federal contaminated sites is available. A complete inventory/ list of landfills and their status is unavailable,	List of federal contaminated sites is available. A complete list of landfills is available.
Groundwater Monitoring	Groundwater quality monitoring is required by the water license(s) issued to communities and mine sites. No network of monitoring points is maintained.	Groundwater levels and chemistry routinely monitored and data available to public. Relatively few wells are located in Transboundary Area despite significant oil and gas, mining, and other undertakings in the area.	Groundwater levels and chemistry routinely monitored and data available to public. Relatively few wells are located in Transboundary Area despite significant oil and gas, mining, and other undertakings in the area.	No network of monitoring points is maintained.	Groundwater quality monitoring is required by the water license(s) issued to mine sites. No network of monitoring points is maintained.
Groundwater – Surface Water Interaction	Karst locations are well documented. No territorial database for springs available.	Limited data available about karstic features across Alberta. A limited database of springs is available and updated routinely.	Limited data available about karstic features across Transboundary Area of British Columbia. No provincial database for springs available.	Limited data available about karstic features across Saskatchewan. No provincial database for springs available.	Limited data available about karstic features across Yukon. No territorial database for springs available.

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1.0 INTRODUCTION

The Government of the Northwest Territories (GNWT), Environment and Natural Resources (ENR), has contracted ARKTIS Solutions Inc. (ARKTIS) to develop a preliminary State of Groundwater Knowledge Report for the transboundary groundwater of the Mackenzie River Basin bordering the Northwest Territories (NWT). The NWT is the ultimate downstream jurisdiction in the Mackenzie River Basin.

The Mackenzie River Basin covers roughly 1.8 million square kilometers, nearly 20% of the landmass of Canada (Figure 1). The Mackenzie River Basin can be sub-divided into six major sub-basins: the Athabasca, the Peace, the Liard, the Great Slave, the Peel, and the Great Bear (Figure 1). Watershed boundaries at the sub-basin level will be used as surrogates for delineating transboundary groundwater, as proposed by Alberta and the Northwest Territories (2015), since few studies have delineated groundwater and aquifers in the region. Where additional information is provided, transboundary groundwater may be identified by aquifer or delineated at the sub-sub-basin level. Figure 1 shows the general flow of water in the Transboundary Area assuming that the groundwater flows from topographic high to low elevations.

The Mackenzie River Basin has the potential to be impacted by management decisions in the upper basin which includes, areas within Alberta, British Columbia, Saskatchewan and the Yukon Territory (herein called the Transboundary Area). In 1997 these provinces and territories signed the Mackenzie River Basin Transboundary Waters Master Agreement (The Government of Canada et al., 1997), which commits all six governments to work together to manage the water resources of the whole Mackenzie River Basin. The Master Agreement also makes provisions for neighboring jurisdictions to negotiate Bilateral Water Management Agreements (Bilateral Agreement) to address water issues at jurisdictional boundaries on transboundary water bodies and to provide objectives on the quality, quantity and flow of water.

The NWT-Alberta Bilateral Agreement was signed in March 2015, and the NWT-British Columbia Bilateral Agreement was signed in October 2015. Negotiations are currently underway to complete a NWT-Saskatchewan Bilateral Agreement and to update the NWT-Yukon Bilateral Agreement that was signed in 2002. In the future, the NWT-Nunavut Agreement may also be negotiated. The purpose of the Bilateral Agreements is to ensure an adaptive approach in determining what actions should be taken, and when, based on scientific monitoring. They will also respect the jurisdiction of governments and ensure water is collaboratively managed to maintain the ecological integrity of the aquatic ecosystems, people and the economy.

Currently, there is limited knowledge about groundwater classification, quality and quantity in the Transboundary Area of the Mackenzie River Basin. Advancing the knowledge of groundwater in the Transboundary Area is critical with respect to the implementation of existing Bilateral Agreements, and the negotiation of future agreements. Table 1 provides a description of transboundary groundwater classes (Government of Alberta & Government of the Northwest Territories, 2015). Learning Plans will be developed by the stakeholders for Class 2 and Class 3 transboundary groundwater as stipulated by the respective Bilateral Agreements; Learning Plans are intended to improve understanding of groundwater sources, and include scoping, compilation of baseline data, collection of additional baseline data, monitoring, data analysis, and investigations into potential effect pathways. The Learning Plans are developed to learn about Transboundary Area Waters to proactively address any negative trends, and to prepare for, in accordance with the Risk Informed Management (RIM) approach, the setting and assessment of the achievement of the Transboundary objectives. The RIM approach guides the identification and implementation of Jurisdictional and Bilateral Water Management actions, which is informed by an understanding of the risks to, and uses of, Transboundary Waters (Government of Alberta & Government of the Northwest Territories, 2015).

Table 1. Transboundary classes (Government of Alberta & Government of the Northwest Territories, 2015).

Class	Description	Key Commitments
Class 1: Reporting	Groundwater sources characterized by no or very little existing and projected development.	• Ensure each stakeholder's jurisdictional water management practices meet transboundary agreement commitments, including identification of transboundary impacts. • Report on developments and activities, and share available information on transboundary groundwater sources. • No additional Bilateral Water Management actions required.
Class 2: Learning	Groundwater sources with moderate levels of existing and/or projected development. Groundwater sources that are stressed or vulnerable (e.g., low water), support sensitive uses (e.g., traditional uses, drinking water), experience a high degree of conflict, and/or show negative impact trends.	• Initiate a Learning Plan to improve understanding of the groundwater source. • The Learning Plan includes issue scoping, compilation of baseline data, collection of additional baseline data, monitoring, data analysis, and investigations into potential effect pathways. • The Learning Plan forms the basis for setting Transboundary Objectives. • Triggers may be established to initiate additional management or action.
Class 3: Objective Setting	Groundwater sources with high levels of development, or a combination of moderate development levels and natural vulnerabilities, sensitive uses, use conflicts, and/or negative impact trends.	• Set objectives or firm conditions for the stakeholders to meet. • Initiate additional Bilateral Water Management to address specific issues. • Conduct site-specific analysis to assess the needs for protecting the groundwater resource and to establish Triggers and Transboundary Objectives. • Establish joint and/or stakeholder monitoring programs and investigations. • Prepare action plans to ensure the Transboundary Objectives are achieved.
Class 4: Objectives not met	Groundwater sources failed to meet Transboundary objectives. The RIM approach taken in the previous classes is intended to prevent any groundwater sources from reaching this class.	• Initiate immediate action in support of achieving Transboundary Objectives and report progress on and agreed schedule. • Additional actions may be taken to address the situation, including mitigation.

ARKTIS has developed this report to consolidate existing knowledge and studies that will ultimately contribute to Learning Plans, and subsequently inform the classification (i.e. Class 1 through 4) of transboundary groundwater. Organization of the data and reporting follows the Groundwater Learning Plan table of contents, as listed in Appendix H2 of Government of Alberta & Government of the Northwest Territories (2015). Organization of the report is as follows:

- Section 1.0 Introduction: provides the background, objective, and scope of work for the report, in addition to identifying the Transboundary Area of the Mackenzie River Basin;
- Section 2.0 Groundwater Resources: identification and description of the geological framework. This includes a brief summary of surficial geology, bedrock geology, and permafrost and their respective influences on regional hydrogeology. Section 2.4 provides a more detailed summary of known aquifers in the Transboundary Area;
- Section 3.0 Groundwater Uses: identification of groundwater users, and estimates of groundwater quantity used. This section is subdivided by stakeholder jurisdiction, with a summary of the state of knowledge provided in Section 3.6;
- Section 4.0 Potential Impacts to Groundwater: identification of possible sources of point and non-point discharges. This section is subdivided by stakeholder jurisdiction, with a summary of the state of knowledge provided in Section 4.6;
- Section 5.0 Groundwater Monitoring: identification of groundwater monitoring networks in the Transboundary Area. This section is subdivided by stakeholder jurisdiction, with a summary of the state of knowledge provided in Section 5.6;
- Section 6.0 Groundwater–Surface Water Interaction: identification and summary of groundwater-surface water interactions This section is subdivided by stakeholder jurisdiction, with a summary of the state of knowledge provided in Section 6.6;
- Section 7.0 Summary: summarizes the state of knowledge available in each of the stakeholder jurisdictions and identifies data gaps.

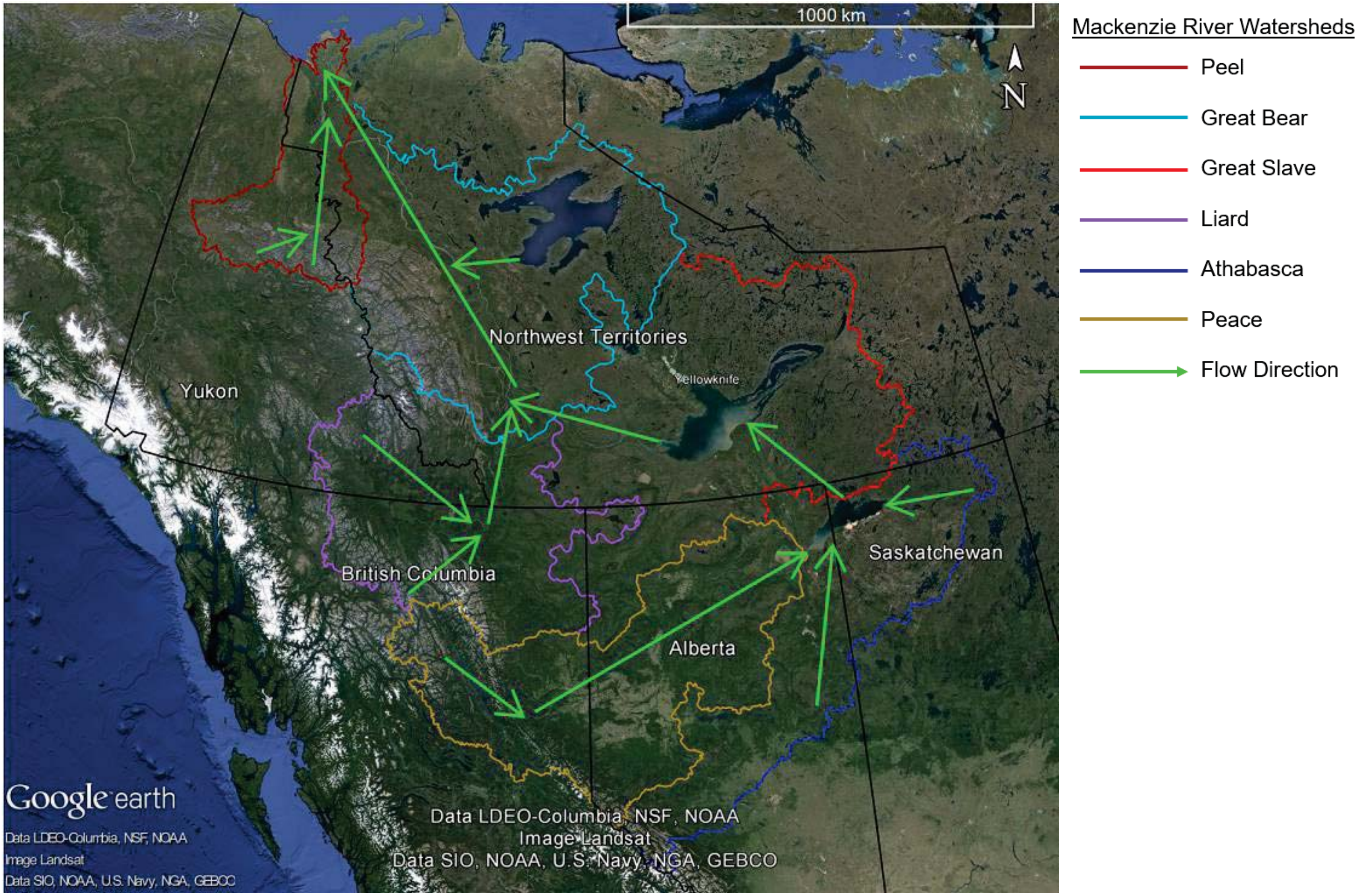


Figure 1. Generalized water flow direction in the Mackenzie Valley Basin at the sub-basin level. Watershed boundaries provided by the Mackenzie River Basin Board (Pittman, 2016).

2.0 GROUNDWATER RESOURCES

The hydraulic properties of geological materials control, in large part, the flow of groundwater and location of aquifers. A brief description of the geology for the entire Mackenzie River Basin is included in the sections below. Section 2.4 provides additional details for select transboundary areas where aquifers have been identified. More detailed geology can be examined on a local scale for the entire Mackenzie River Basin using data available from federal, provincial and territorial governments (Table 2). Appendix A provides geological maps for each of the provinces and territories located in the Mackenzie River Basin.

Table 2. Sources of geological data in the Mackenzie River Basin.

Stakeholder	Organization	Link
Canada	Natural Resources Canada	http://geoscan.nrcan.gc.ca/
		http://geogratis.gc.ca/
Northwest Territories	Northwest Territories Geological Survey	http://www.nwtgeoscience.ca/
Alberta	Alberta Geological Survey	http://ags.aer.ca/
British Columbia	British Columbia Geological Survey	http://www.empr.gov.bc.ca/mining/geoscience
Saskatchewan	Saskatchewan Geological Survey	http://www.economy.gov.sk.ca/geopub
Yukon	Yukon Geological Survey	http://www.geology.gov.yk.ca/

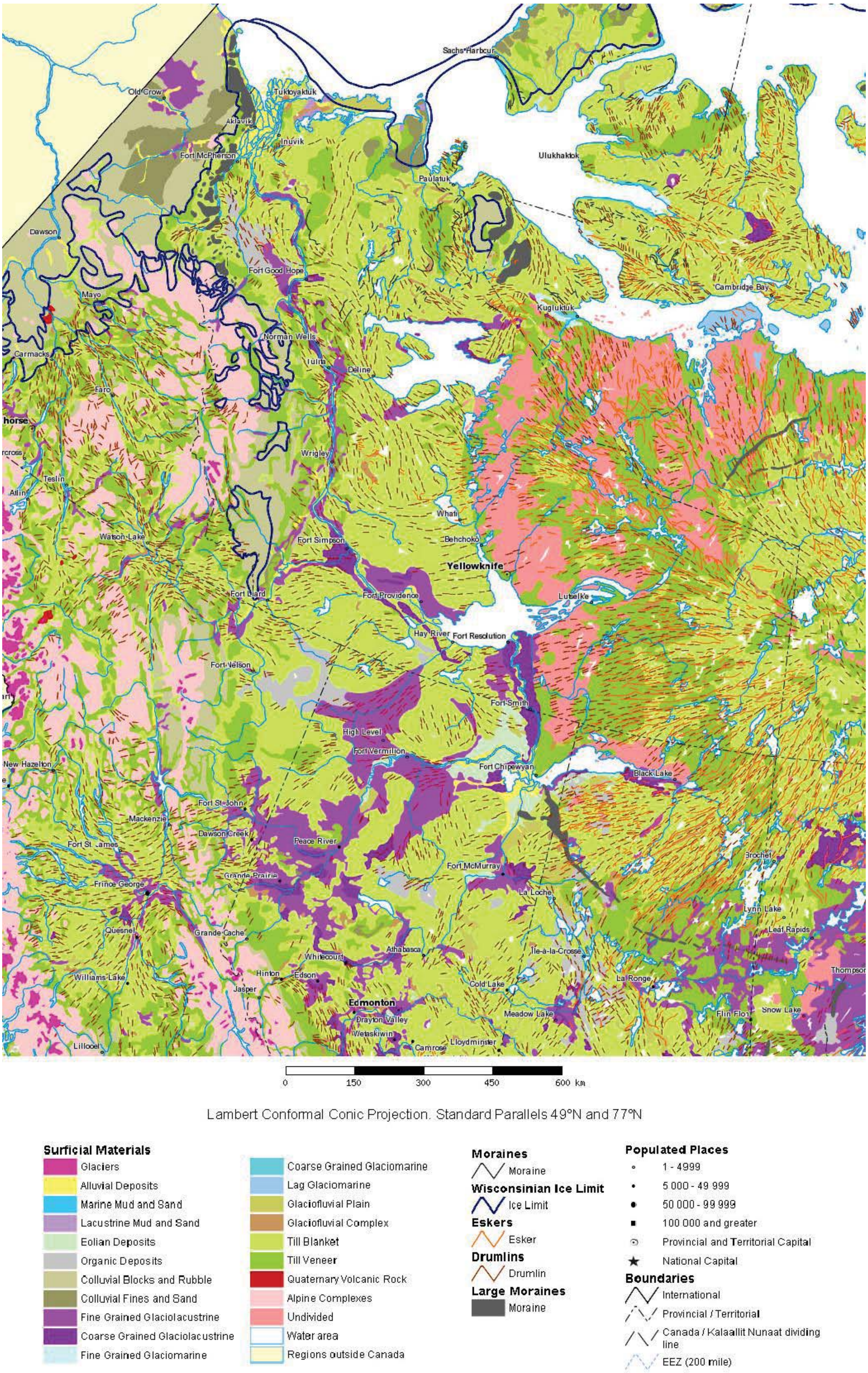
2.1 Regional Surficial Geology

The Mackenzie River Basin straddles three physiographic regions: the Canadian Shield, the Interior Platform, and the Cordillera. The surficial geology can be broadly divided into three categories that align with these physiographic regions (Figure 2). The storage of groundwater in these unconsolidated surficial sediments is related to the intergranular porosity (Todd & Mays, 2005). Surficial deposits of coarser material (e.g., fluvial and glaciofluvial sand and gravels) yield more groundwater and have higher hydraulic conductivities than surficial deposits of finer material (e.g., glaciolacustrine and glaciomarine silts and clays).

Much of the Canadian Shield has a discontinuous cover of thin glacial sediment (Groundwater Information Network, 2014). Thicker deposits occur in correlation to glacial landforms, such as drumlins, eskers and moraines. Extensive glaciolacustrine deposits occur in parts of the Canadian Shield and form clay basins with underlying sand and gravel deposits. The glacial sediments in the Canadian Shield, in particular, the coarse-grained high yield glaciofluvial deposits (e.g., eskers) can be an important location for aquifers.

Surficial sediment thickness in the Interior Platform is variable, with the thickest sediment occurring along buried valleys, and only a thin veneer occurring along most of the western margin, and up to several 100 metres thick elsewhere (Groundwater Information Network, 2014). Large glaciolacustrine deposits may be found across the region. Surficial aquifers, namely buried valley aquifers, are some of the most important freshwater aquifers in the southern portions of the Mackenzie River Basin.

In the Cordillera, surficial deposits can be up to 100 m thick in the intermontane and major river valleys (Groundwater Information Network, 2014). The deposits include glaciofluvial, glaciolacustrine, and glaciomarine sediments at elevations below the marine limit, as well as alluvial fans and valley aprons. Shallow unconfined glaciofluvial and fluvial aquifers located in river valleys may have a direct connection with the surface water; these aquifers are highly vulnerable to contamination. Shallow aquifers in the Cordillera are an important water source for many communities across the Mackenzie River Basin.



Source(s):
Eskers
Location of eskers in Canada from the last glaciation. Eskers are sinuous ridges consisting of glacial material laid down by subglacial meltwater streams. Their orientation is generally parallel to ice flow. Fulton, R.J. 1995. Surficial Materials of Canada, Geological Survey of Canada, Map
Surficial Materials
Fulton, R.J. 1995. Surficial Materials of Canada, Geological Survey of Canada, Map 1880A.

Figure 2. Surficial geology of the Mackenzie River Basin. Modified from Natural Resources Canada (2010).

2.2 Regional Bedrock Geology

The Mackenzie River Basin covers an extensive area (Figure 1) with portions included in several geological provinces (Figure 3). Geology is an important control on the characteristics of both groundwater quantity and quality in aquifers. The storage of groundwater in these materials is directly related to porosity; in crystalline metamorphic and igneous rocks, porosity is related to fractures, and in sedimentary and volcanic rocks both intergranular and fracture porosity must be considered (Todd & Mays, 2005). A brief summary of the geology in each geological province and a discussion of its potential influence on groundwater is provided in the sections below.

2.2.1 Canadian Shield

Precambrian rocks of the Canadian Shield are exposed along the eastern reaches of the Mackenzie River Basin, including rocks from the Slave, Churchill, and Bear Provinces. The structurally complex Canadian Shield is composed of intensely deformed metamorphic, meta-intrusive and meta-volcanic rocks of Archean and Proterozoic age, and overlain in part by Neoproterozoic meta-sedimentary rocks (Hannigan, Morrow, & MacLean, 2011). Along the western edge of the Precambrian rocks, several significant northeast-southwest structural trends extend southwesterly beneath the overlying Proterozoic and Phanerozoic sedimentary rocks of the Great Bear and Great Slave Plain areas of the Interior Platform (Morrow, MacLean, Miles, Tzeng, & Pană, 2006). These ancient fault structures may influence deep groundwater in the overlying sedimentary rocks.

The pervasive crystalline rocks of the Canadian Shield are characterized by low primary porosity and permeability, with variable fracture patterns, and generally have a low water yield (Groundwater Information Network, 2014). Fracture zones may yield potable water to depths of around 100 m, however, at greater depths the groundwater quality degrades, progressively becoming more saline, reducing and old. High concentrations of total dissolved solids occur in fractures at greater depths, up to 50,000 to 100,000 mg/L. Recharge and discharge is characterized by local fracture patterns. Water quality may be also impacted in these fracture systems due to bedrock mineralization. Elevated hydraulic heads are common in the Canadian Shield rocks as a result of surface loading from the Laurentide Ice Sheet. The undulating, and low to modest relief, of the Canadian Shield leads to slow groundwater movement and reduced mixing at depth (Groundwater Information Network, 2014).

2.2.2 Interior Platform

Much of the Mackenzie River Basin within the Northwest Territories is underlain by a Proterozoic sedimentary succession, 13 to 16 km thick, composed primarily of siliciclastic rocks. The Proterozoic sedimentary rocks are absent to the east of the Interior Platform, where the Phanerozoic sedimentary rocks directly overlay the Precambrian crystalline basement (Hannigan et al., 2011). The siliciclastic succession is broken intermittently by discontinuous igneous sheets, and may include lesser amounts of carbonate, evaporite, and volcanic rocks (Hannigan et al., 2011).

The widespread sub-Cambrian unconformity separates the Proterozoic sedimentary succession from the overlying Paleozoic sedimentary rocks. The Paleozoic strata is dominated by siliciclastic rocks during the early to mid-Cambrian, followed by evaporites during the late Cambrian, carbonates from the Ordovician through to the mid-Devonian. Siliciclastic units are again dominant in the late Devonian. The sub-Cretaceous unconformity superimposes the Cretaceous siliciclastic rocks onto the Paleozoic sequences (Hannigan et al., 2011).

The Interior Platform has a major northeasterly-trending structural pattern related to the underlying Precambrian structures. Northwesterly-striking linear grabens have also been interpreted near Cameron Hills and Great Slave Lake (Morrow et al., 2006).

The bedrock hydrostratigraphy in the Interior Platform is commonly assigned to three categories: a lower clastic unit, a middle unit of carbonates and evaporites, and an upper clastic unit (Groundwater Information Network, 2014). Groundwater quantity and quality in the region is commonly controlled by depth and the nature of shallower, overlying units. Shallow bedrock aquifers hosted in marine and fluvial sandstone are an important groundwater source in the region. Aquifers in older units that are found at shallow depths in the eastern Interior Platform may be used as a potable water source, however moving westward these units are found at greater depths in the west where total dissolved solids can exceed 600,000 mg/L. As a result of low topography, horizontal stratigraphy, and high bedrock heterogeneity, local groundwater flow systems are driven by the minor topographic variations found across the region. Topography near the basin edge can influence regional groundwater flow by introducing fresh meteoric water as recharge from isolated uplands (Groundwater Information Network, 2014).

2.2.3 Cordilleran Orogen

The Mackenzie River Basin is bounded on the west by the Mackenzie Mountains and the northern parts of the Canadian Rocky Mountains. Many of the Proterozoic and Mesozoic stratigraphic units from the Interior Platform are also found in the Cordilleran Orogeny, however, the rocks are intensely deformed. Structural trends in the northern Canadian Rocky Mountains are northwest-trending, but are north-northeast-trending in the Mackenzie Mountains (Hannigan et al., 2011).

Bedrock groundwater flow in the region typically occurs through secondary fractures, such as bedding planes, joints or faults. Flow may also occur through porous volcanic rocks, karstic units, and along dissolution channels. Artesian conditions are common in intermontane valleys as confined aquifers may be connected to elevated bedrock systems that provide substantial hydraulic head. Groundwater recharge is seasonally dependent, occurring in late spring to early summer as a result of freshet.

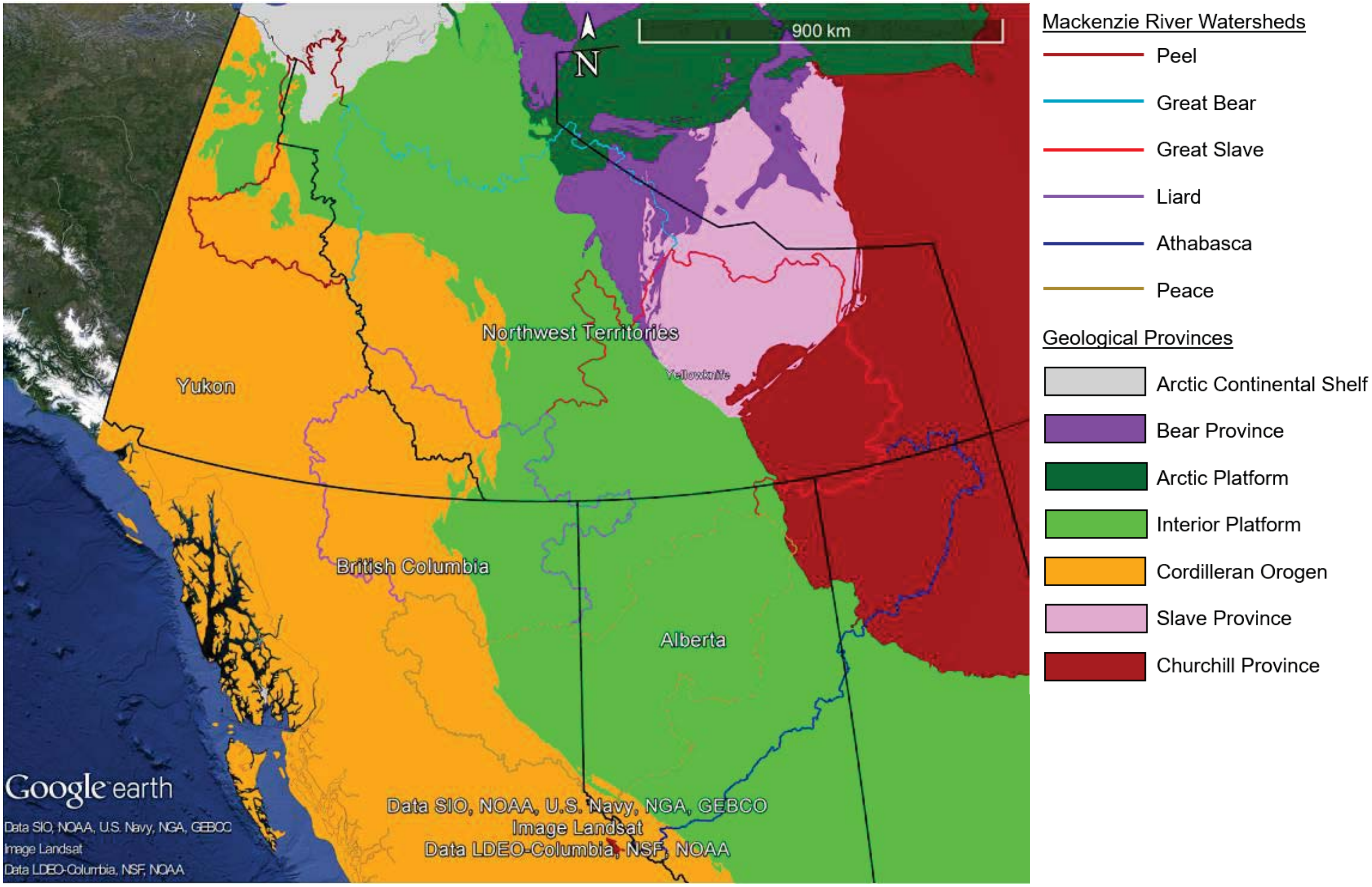


Figure 3. Geological provinces in the Mackenzie River Basin. The Canadian Shield includes the Slave, Bear and Churchill Provinces. Data for the geological provinces provided by Natural Resources Canada (Jean Pinard, 2016)

2.3 Permafrost

Permafrost covers the northern part of the Mackenzie River Basin (Figure 4), where rock and soil temperatures remain at or below 0°C year round and water in pores and fractures is typically frozen. Permafrost extends across the northern part of all geological provinces in the Mackenzie River Basin. The southern boundary of the permafrost region is irregular, as it is influenced by secondary features that influence heat exchange, such as vegetation cover and snow depth. Consequently, discontinuous permafrost occurs further south in certain landscapes, such as peat bogs and on northern facing slopes (Groundwater Information Network, 2014). This means that permafrost in the discontinuous zone occurs in scattered regions ranging in size from a few square metres to several hectares, with a thickness that can vary from a few centimetres at the southern limit of the discontinuous permafrost zone to as much as 100 m near the boundary with the continuous permafrost zone (Andersland & Ladanyi, 2004). Permafrost in the mountainous terrain of the Cordillera is particularly complex, where air movement may also influence distribution (Gruber et al., 2015).

With respect to hydrogeology, permafrost may be considered an aquiclude; the pores and fractures of the medium are filled with ice, acting as a barrier to groundwater flow (Groundwater Information Network, 2014). Permafrost may act as both the base of an unconfined aquifer and the cover for a confined aquifer. The active layer of permafrost functions as an unconfined aquifer for shallow groundwater, seasonally when thawed. Unfrozen ground in vicinity of waterbodies within the permafrost is referred to as a talik:

- Open taliks – unfrozen ground connected to the surface, but otherwise enclosed in permafrost. Often associated with small deep lakes.
- Closed taliks – unfrozen ground entirely encapsulated in permafrost. Often associated with wetlands.
- Through taliks – unfrozen ground open at surface that extends through the permafrost to the unfrozen ground beneath. Often associated with large deep lakes.

In the Cordilleran Orogen, permafrost is thought to confine coarse valley fill aquifers, which many communities in southern Yukon rely on for community water supply. Confined aquifers beneath permafrost may also occur on north-facing slopes in the southern reaches of the permafrost zone. Moving northward, permafrost becomes thicker, extending to depths greater than 500 m, precluding the use of sub-permafrost aquifers for community water supply (Groundwater Information Network, 2014).

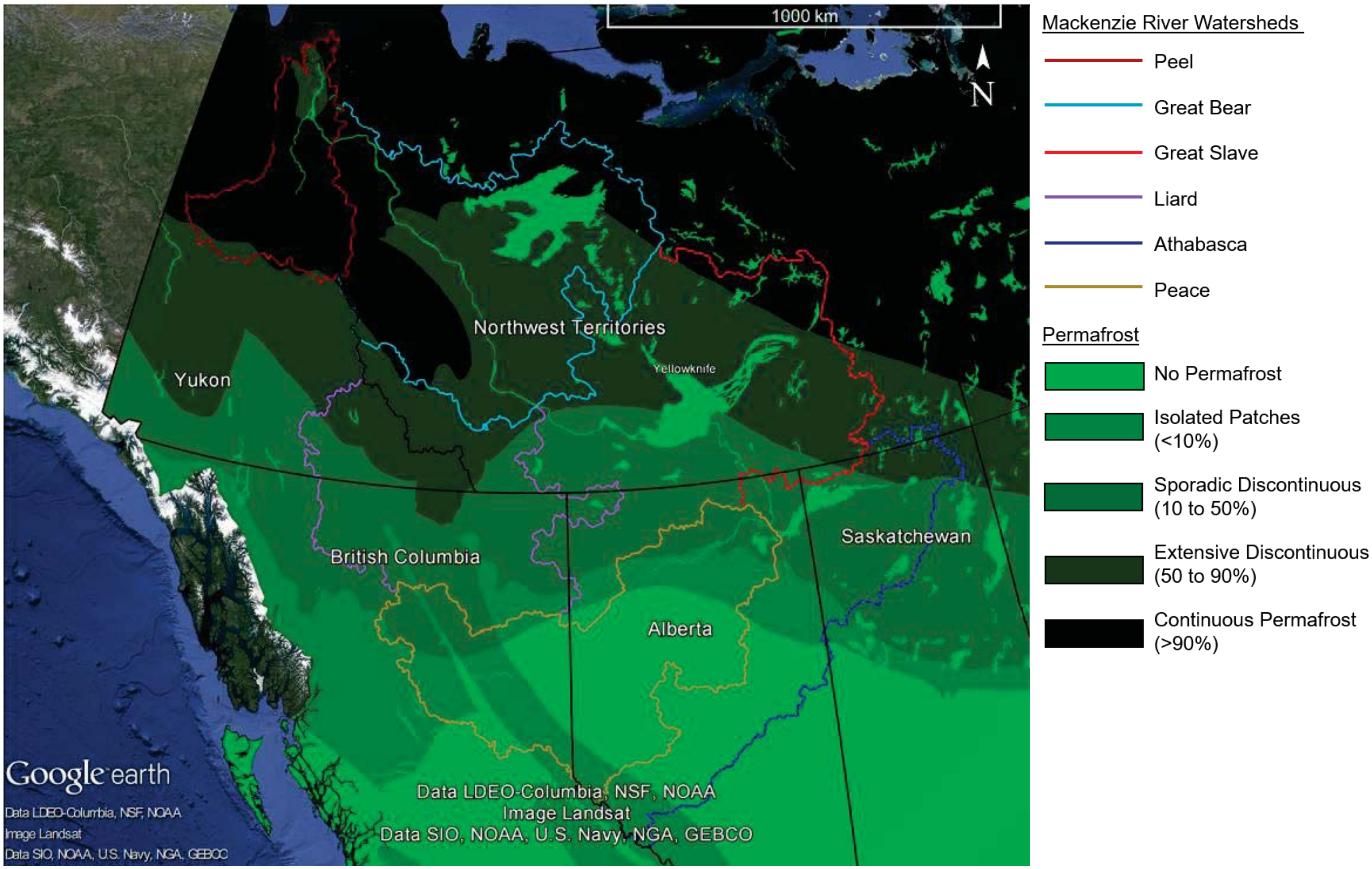


Figure 4. Permafrost in the Mackenzie River Basin (Natural Resources Canada, 2000).

2.4 Known Aquifers in the Transboundary Region

2.4.1 Central Mackenzie Valley (Norman Wells)

Detailed reviews of the hydrogeology in the Central Mackenzie Valley, near Norman Wells, were recently completed by AMEC (2014) and Golder (2015). The study areas are located within the Great Bear sub-basin. Both studies intended to identify potential aquifers for industry use, and to aid in assessment of possible impacts to groundwater from future industrial development. Although the aquifers described in the studies are distant from bordering jurisdictions, the detailed knowledge on subsurface geology and hydrogeology may be applicable to describing aquifers at other locations in the Transboundary Areas.

The surficial geology in the region consists of peat, muskeg, and organic soils at surface, immediately overlying glacial deposits of clay-rich till, glaciolacustrine clays and silts, and minor glaciofluvial sands and gravels. Alluvial and colluvial sand and gravel deposits are located along the Mackenzie River and its tributaries. The total thickness of overburden typically ranges from 0 m to 10 m, with local deposits up to 30 m (AMEC, 2014; Golder, 2015). The Central Mackenzie Valley is located in the extensive discontinuous permafrost zone (Figure 4). The depth of permafrost, where present in the Norman Wells area, ranges from 52 m to 143 m thick. The local variations in permafrost are related to factors such as topography, surface materials, vegetation, drainage, and proximity to large water bodies. The active layer in the region ranges from 0.5 m to 3 m (AMEC, 2014; Golder, 2015).

Bedrock in the Central Mackenzie Valley near Norman Wells is largely controlled by a broad east-west oriented syncline of the Mackenzie fold belt. Thrust faults are present in the southern parts of the region. Paleozoic strata is unconformably overlain by westward thickening units of Cretaceous and Tertiary age (AMEC, 2014; Golder, 2015; Hannigan et al., 2011). The Paleozoic strata is unconformably overlying thick, highly deformed, Proterozoic sedimentary successions (Golder, 2015; Morrow et al., 2006). Table 3 presents a stratigraphic column of the key units in the Central Mackenzie Valley near Norman Wells.

There have been limited studies investigating the aquifer potential of surficial sediments. Unconsolidated coarse-grained sediments offer high hydraulic conductivities and aquifer potential, but deposits of these materials in the region have limited spatial distribution, insufficient thickness, and have limited groundwater flow due to permafrost (AMEC, 2014; Golder, 2015). The aquifer potential and aquifer characteristics of key geological formations in the Central Mackenzie Valley is outlined in Table 3. Sandstone units of the Little Bear Formation have been identified as being an optimal aquifer in the Central Mackenzie Valley in terms of both quantity and quality. The younger Summit Creek Formation has been identified as the best source of freshwater in the region (AMEC, 2014; Golder, 2015). Isotope analysis of groundwater from the two aquifers indicated that water in the deeper Little Bear Formation had a long residence time and was on the order of 20,000 years old, whereas the water in the Summit Creek Formation was closer to meteoric water in composition and was only five to ten years old (AMEC, 2014).

The evolution of major ion chemistry in the Central Mackenzie Valley groundwater suggests that there is a deep circulation flow pathway from recharge areas on the valley sides (i.e., karst terrains of the Bear Rock Group) to discharge areas in the valley centre. Groundwater becomes increasingly saline with depth, and more diluted in the near surface strata (Golder, 2015). It has also been suggested that recharge to the shallowest units (i.e., Summit Creek Formation) may be a result of recharge though local areas of low ice content (e.g., coarse sands and gravel) that may be possible talik zones.

Table 3. Stratigraphic column and aquifer properties for units in the Central Mackenzie Valley (AMEC, 2014; Golder, 2015).

<table>
<tr><th>Era</th><th>Period</th><th colspan="2">Formation</th><th>Lithology</th><th>Average Porosity (%)</th><th>Hydraulic Conductivity (m/s)</th><th>TDS (mg/L)</th><th>Aquifer Characteristics</th></tr>
<tr><td rowspan="2">Cenozoic</td><td>Quaternary</td><td colspan="2">Overburden</td><td>Unconsolidated sediments</td><td>-</td><td>-</td><td>-</td><td>Unlikely due to limited presence and depth of coarser sediments and permafrost</td></tr>
<tr><td>Late Cretaceous to Paleocene</td><td colspan="2">Summit Creek</td><td>conglomerate, sandstone, coal</td><td>-</td><td>10^{-6} to 10^{-5}</td><td><370</td><td>Most viable aquifer for freshwater.</td></tr>
<tr><td rowspan="7">Mesozoic</td><td rowspan="3">Late Cretaceous</td><td colspan="2">East Fork</td><td>shale</td><td>-</td><td>-</td><td>-</td><td>Aquitard</td></tr>
<tr><td colspan="2">Little Bear</td><td>sandstone, coal</td><td>14 to 22</td><td>10^{-4-}</td><td>177 to 3,482</td><td>Optimal aquifer quality and water chemistry in the CMV.</td></tr>
<tr><td colspan="2">Slater River</td><td>shale, sandstone</td><td>-</td><td>-</td><td>-</td><td>Aquitard</td></tr>
<tr><td rowspan="4">Early Cretaceous</td><td colspan="2">Mahoney Lake</td><td>sandstone siltstone, shale</td><td>-</td><td>-</td><td>-</td><td>Aquitard</td></tr>
<tr><td colspan="2">Sans Sault Member</td><td>sandstone siltstone, shale</td><td>-</td><td>-</td><td>-</td><td>Not identified</td></tr>
<tr><td colspan="2">Arctic Red</td><td>shale, sandstone</td><td>-</td><td>-</td><td>-</td><td>Aquitard</td></tr>
<tr><td>Basal Cretaceous Group</td><td>Martin House</td><td>sandstone, siltstone</td><td>10 to 21</td><td>-</td><td>3,208 to 40,212</td><td>Thick locally continuous sandstones in the northeast of the CMV with variable water quality.</td></tr>
<tr><td rowspan="3">Paleozoic</td><td>Late Devonian</td><td colspan="2">Imperial</td><td>shale, siltstone, sandstone, limestone</td><td>-</td><td>-</td><td>-</td><td>Aquitard</td></tr>
<tr><td>Middle to Late Devonian</td><td rowspan="2">Horn River Group</td><td>Canol</td><td>black shale, siltstone</td><td>-</td><td>-</td><td>-</td><td>Contains porous intervals, petroliferous.</td></tr>
<tr><td>Middle Devonian</td><td>Kee Scarp-Ramparts</td><td>limestone, siltstone, black shale</td><td>5 to 8</td><td>10^{-9} to 10^{-8}</td><td>7,437 to 14,412</td><td>Marginal matrix permeability where natural fractures</td></tr>
</table>

Era	Period	Formation		Lithology	Average Porosity (%)	Hydraulic Conductivity (m/s)	TDS (mg/L)	Aquifer Characteristics
								enhance the permeability in the Norman Wells area. Contains porous intervals, petroliferous.
			Hare Indian	shale, black shale, siltstone	-	-	-	Contains porous intervals.
		Hume		fossiliferous limestone, shale	3 to 28	-	16,394	Formation waters are modestly saline with average permeability.
	Early to Middle Devonian	**Bear Rock Group**	Landry	limestone breccia	1 to 15	-	18,364 to 41,912	High porosity and permeability. Presence of solution channels. The major bedrock aquifer in the CMV.
			Arnica	dolostone breccia	3 to 14	-	1,616 to 28,940	
			Fort Norman	gypsum and anhydrite breccias	-	-	-	May contain porous intervals.
	Late Silurian – Early Devonian	Tsetso		siltstone, sandstone, dolostone	-	-	-	Aquitard
	Late Ordovician – Early Silurian	Mount Kindle		fossiliferous dolostone, sandstone	-	-	-	Karstic with river sink development. Source of groundwater supply.
	Late Cambrian – Middle Ordovician	Franklin Mountain		sparsely fossiliferous dolostone	-	10^{-11} to 10^{-4}	-	
	Middle-Late Cambrian	Saline River		evaporite, shale, siltstone, dolostone	-	-	-	Secondary porosity from dissolution of evaporite minerals. Major aquifer with poor water quality.

Era	Period	Formation	Lithology	Average Porosity (%)	Hydraulic Conductivity (m/s)	TDS (mg/L)	Aquifer Characteristics
	Middle Cambrian	Mount Cap	shale, siltstone, dolostone, sandstone	-	10^{-10} to 10^{-5}	-	Possibly locally important
		Nainlin	shale, sandstone, conglomerate	-	-	-	Not identified
	Early-Middle Cambrian	Mount Clark	sandstone	-	-	-	Not identified
Precambrian	Neoproterozoic	Little Dal Group	carbonate, shale, gypsum	-	-	-	Not identified
		Katherine Group	sandstone, mudstone, carbonate	-	-	-	Not identified
		Undefined	gabbro, diabase	-	-	-	Not identified
	Proterozoic	Mackenzie Mountain Supergroup	shale, sandstone, dolostone				Not identified

Notes:
Double line borders represent an unconformity
TDS = total dissolved solids
CMV = Central Mackenzie Valley

2.4.2 Liard Basin (Fort Liard)

The Liard Basin (geological) is located at the confluence of northern British Columbia, southeastern Yukon and southwestern Northwest Territories, entirely within the Liard sub-basin (watershed) of the Mackenzie River. The basin hosts numerous oil and gas fields, and is now the target of exploration for unconventional sources. A recent estimate suggested that the Upper Besa and Lower Besa Formations in the Liard Basin may contain 219 trillion cubic feet (Tcf) of marketable, unconventional natural gas. The estimate would make the Liard Basin Canada's second largest known gas resource behind the Montney Formation, located in the Peace sub-basin and contains an estimated 449 Tcf (Government of Northwest Territories, 2016).

The Liard Basin hosts relatively undeformed sedimentary stratigraphy measuring several thousand metres thick (Figure 5) (Morrow & Shinduke, 2003). The Liard Basin has been described as a late Paleozoic and Cretaceous depocentre. Extensional faulting during the Carboniferous and Early Cretaceous provided for additional space for westward thickening of the Carboniferous and Cretaceous formations. The basin is bounded on the east by the complex Bovie fault zone, which displays structural elevation drops of over 1000 m (Morrow & Shinduke, 2003).

The Government of British Columbia produced a compilation map of the Liard Basin geology (Walsh, 2004). The map includes locations of drill stem tests, and includes identification of the formation, the depth, and a brief description of the water encountered.

Hayes and Costanzo (2014) were contracted by Geoscience BC to complete a study of deep sub-surface aquifers in the Liard Basin that may be used for sourcing and disposal of waters (e.g., brines) related to unconventional hydrocarbon development. The study investigated four aquifer intervals in detail: the early Carboniferous carbonate rocks (Rundle Group and the younger Fantasque Formation), the late Carboniferous sandstone (Mattson Formation), Lower Cretaceous sandstone (Chinkeh and Scatter Formations), and the Upper Cretaceous sandstone and conglomerate (Dunvegan Formation) (Hayes & Costanzo, 2014) (Figure 5). Hayes and Costanzo (2014) made the following observations regarding the four investigated areas:

- The Rundle Group and Fantasque Formation have moderate aquifer potential locally. Tight and brittle rocks dominate both, however, moderate potential comes in dolomitized intervals, sandstone and fractured intervals.
- The Mattson Formation sandstone has very good to excellent water source and disposal potential in the north and northeastern portions of the Liard Basin, The Mattson Formation is at approximately 500 m depth in the Bovie Fault zone, but depth increases rapidly to over 2 km moving southward and westward. Testing indicates hydrogeological connectivity between the Mattson Formation and the underlying Rundle Group suggesting potentially large aquifer volumes.
- The Dunvegan Formation sandstone and conglomerate has the potential to be an excellent water source in the north-central part of the basin. The shallow depth of the formation, approximately 200 m, makes it an ideal water source, but precludes it from use for water disposal.
- The Chinkeh Formation sandstone has poor to moderate aquifer potential. The Formation is limited in extent, restricted to just east of the Bovie fault zone in the northeastern part of the basin. In this location, the thick basal Cretaceous sandstone appears to have very good aquifer potential.
- The Scatter Formation sandstone has poor aquifer potential in the Liard Basin.

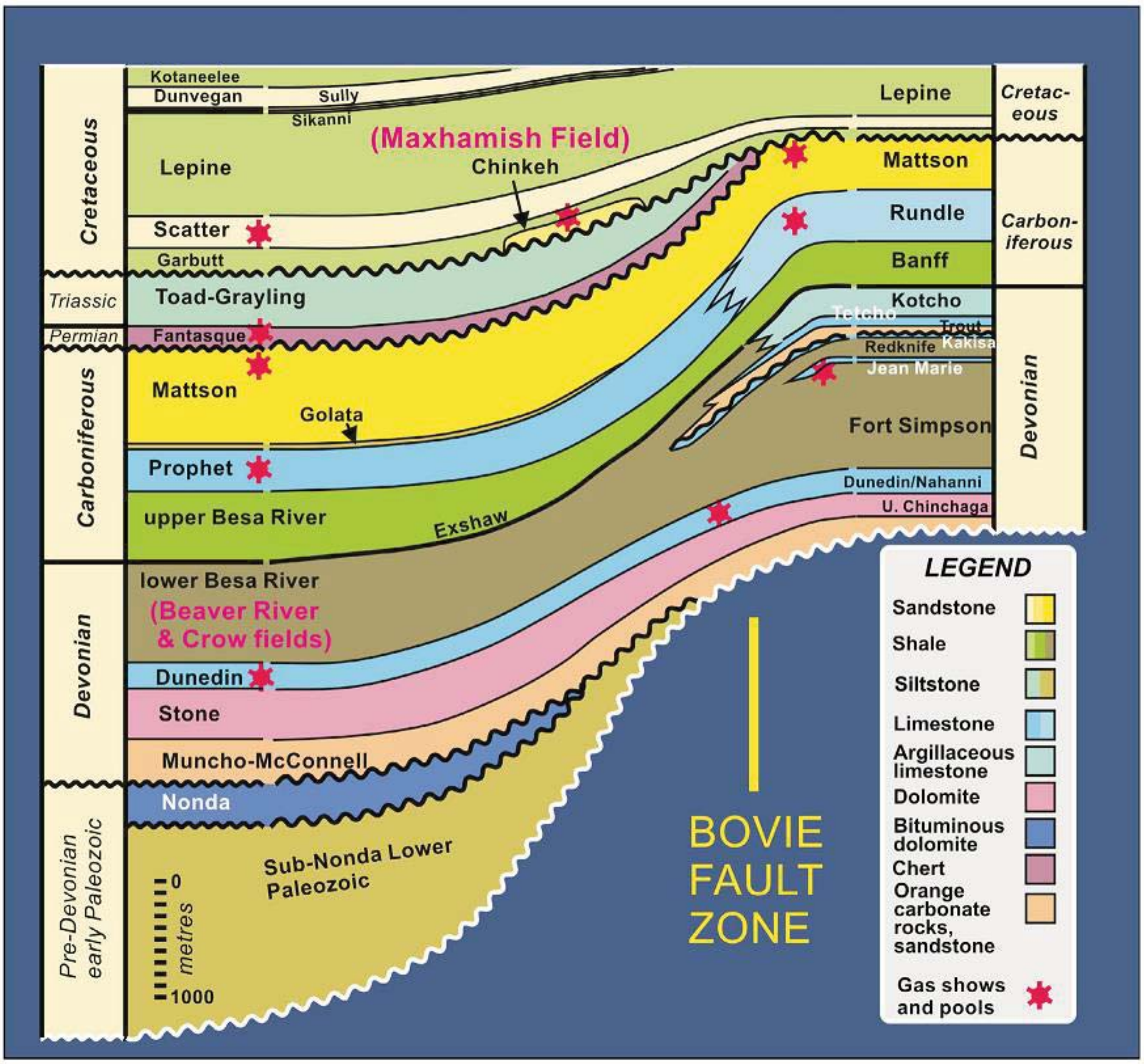


Figure 5. Cross section of Liard Basin (Morrow & Shinduke, 2003).

2.4.3 Horn River Basin (Fort Nelson)

The Horn River Basin is located in northeastern British Columbia, and the southwestern Northwest Territories. The Horn River Basin is bounded to the south and east by the Devonian carbonate Keg River, Sulphur Point, and Slave Point Formation; in the west is the Bovie Fault Zone, separating the Horn River Basin from the previously discussed Liard Basin (Petrel Robertson Consulting Ltd., 2010).

The sedimentary sequences of the Horn River Basin are relatively undeformed with a fairly uniform north-northeasterly dip in the eastern half of the basin. There is a high level of structural complexity near the Bovie Fault Zone in the west; structural elevations in the Horn River Basin are much higher than those in the Liard Basin (Figure 6). Glacial deposits up to 100 m to 150 m thick overly the bedrock (Petrel Robertson Consulting Ltd., 2010).

The principal aquifer of the Horn River Basin for use as a water source in oil and gas exploration is located in the carbonate Rundle and Debolt Formations (Petrel Robertson Consulting Ltd., 2010). The Rundle Formation within the Horn River Basin has limited porosity (< 5%), permeability (0.5 mD), and hydraulic conductivity[1] (10^{-9} m/s), as does the Debolt Formation which exhibits comparable qualities. The Rundle and Debolt Formations are beveled by a pre-Cretaceous unconformity in the east (Figure 7). The principal aquifer for the region is associated with an intensively leached and dolomitized zone (detrital zone) associated with the base of this unconformity. This zone is characterized by fine to coarse crystalline dolomite with a sucrosic texture and vuggy pores, and is fractured locally (Petrel Robertson Consulting Ltd., 2010). The detrital zone has been estimated to have a porosity in excess of 10%, permeability ranging from several millidarcys to as high as 30,000 millidarcys, and hydraulic conductivity[1] between 10^{-8} m/s and 10^{-4} m/s (Canadian Discovery Ltd., 2009; Petrel Robertson Consulting Ltd., 2010). The aquifer is best developed in the upper Rundle and lower Debolt rocks along the eastern and southern margins of the Horn River Basin (Petrel Robertson Consulting Ltd., 2010). Water quality samples from the aquifer indicated total dissolved solids concentrations in the Rundle and Debolt formations ranging from 15,000 mg/L to 40,000 mg/L, as well as measurable concentrations of hydrogen sulphide (H_2S) (Canadian Discovery Ltd., 2009).

Overlying the beveled unconformity are basal Cretaceous sandstones of the Gething Formation filling valleys along the eastern basin margin and of the Bluesky Formation as a shoreface along the southern basin margins (Figure 7). Both formations are named based on their relative stratigraphy and depositional setting, but have not been directly correlated to more southern formations of the same names. The Gething Formation is predominantly medium- to coarse-grained sandstone. The Bluesky Formation is predominantly a very fine-grained sandstone with porosity in excess of 25% and permeability ranging to hundreds of millidarcys, , and hydraulic conductivity[1] up to 10^{-6} m/s (Petrel Robertson Consulting Ltd., 2010). Water quality in the basal Cretaceous sandstones have total dissolved solids concentrations between 15,000 mg/L and 35,000 mg/L, as well as measurable concentrations of H_2S. Formation pressure and water chemistry between the basal Cretaceous sandstones and the underlying Rundle and Debolt Formations are very similar suggesting they form a single hydrostratigraphic unit with no significant aquitard in between (Canadian Discovery Ltd., 2009).

[1] $K = (k\rho g)/(\mu)$, where K is the hydraulic conductivity, k is the intrinsic permeability, ρ is the fluid density, g is acceleration of gravity (9.81 m/s^2), and μ is the dynamic viscosity. Assume that the fluid is water, so that ρ = 1000 kg/m3, and μ = 0.000894 Pa·s.

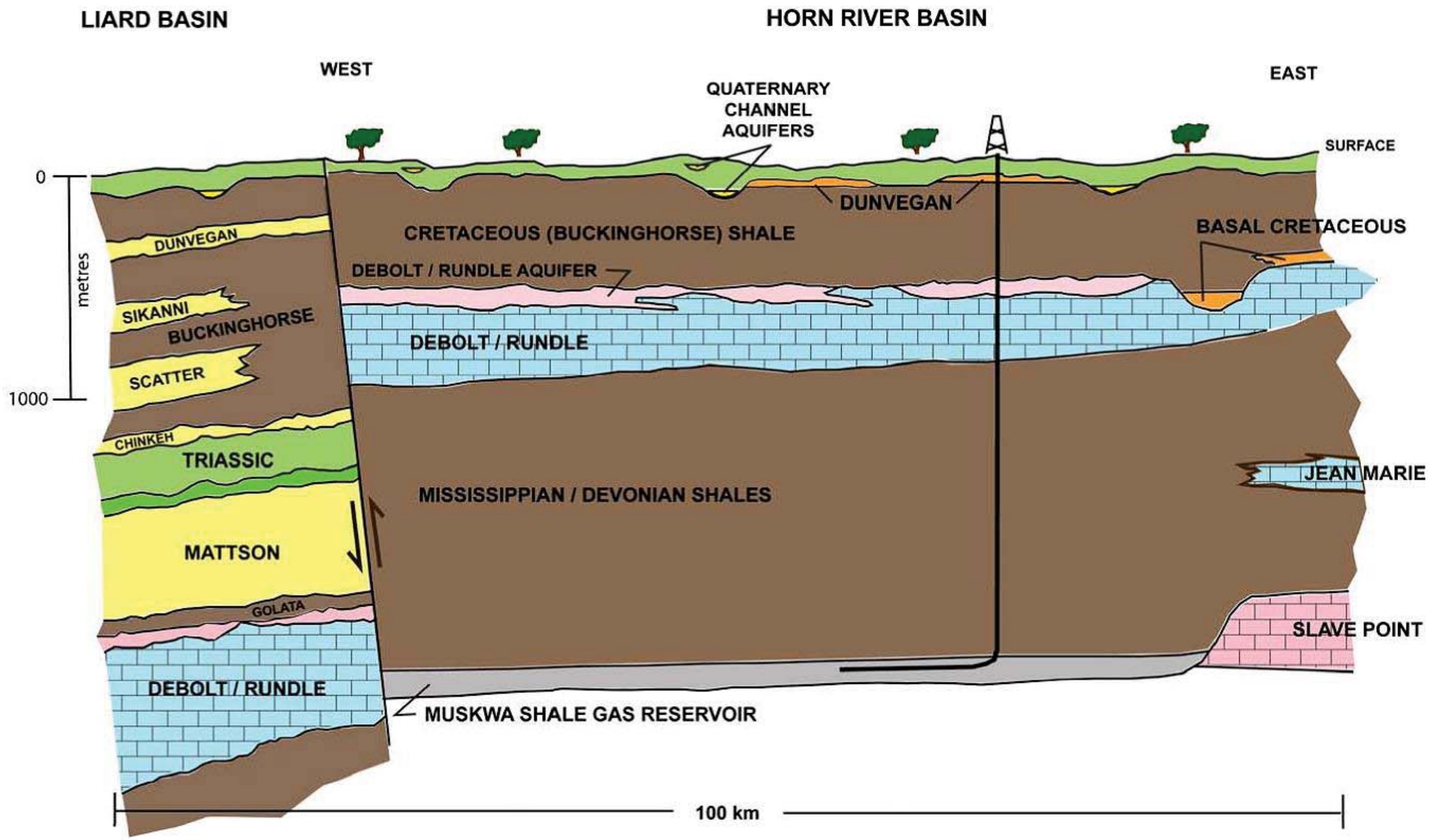


Figure 6. Cross-section of the Horn River Basin, and the Liard Basin (Petrel Robertson Consulting Ltd., 2010).

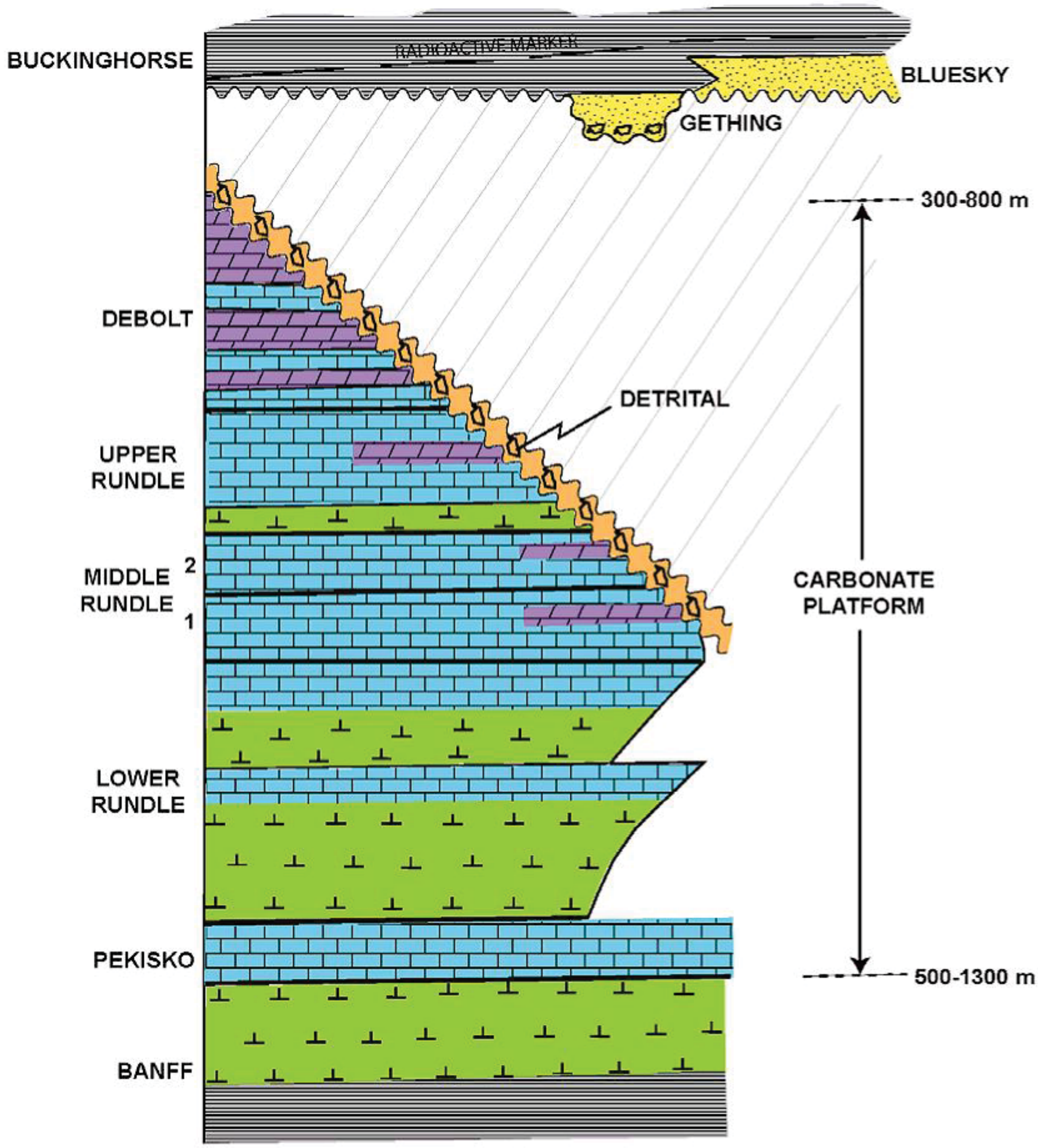


Figure 7. Stratigraphic column of the Mississippian and Cretaceous section of the Horn River Basin showing the beveled unconformity between the Mississippian carbonates (Debolt and Rundle Formations) and the overlying Cretaceous units (Petrel Robertson Consulting Ltd., 2010).

2.4.4 Northwestern Alberta (Cameron Hills)

Borneuf and Pretula (1980), and Ozoray (1980) mapped the hydrogeology of the Zama-Bistcho Lakes and Steen River-Whitesand River areas, northwestern Alberta, bordering British Columbia and the Northwest

Territories. The mapped regions extends across the Liard sub-basin, the Peace sub-basin, and the Great Slave sub-basin, and includes the southern extents of the Cameron Hills oil and gas field.

2.4.4.1 Zama-Bistcho Lakes Area

The Zama-Bistcho Lakes area shares borders with British Columbia and the Northwest Territories (Borneuf & Pretula, 1980). The area has had numerous producing oil and gas fields, and the oil and gas pipelines from the Norman Wells and Cameron Hills oil and gas fields in the Northwest Territories pass through the region. The Liard sub-basin drains the northern third of the mapped area. Despite the water table in the drainage area being located close to surface, surficial sediments are typically well drained. Many of the small lakes and streams are believed to be hydrogeologically connected to Bistcho Lake based on similar concentrations of total dissolved solids (Borneuf & Pretula, 1980). The Great Slave sub-basin drains the remaining two-thirds of the area. Surficial sediments in this region of the sub-basin exhibit poor drainage, and lowlands are often subject to flooding (Borneuf & Pretula, 1980). Discontinuous permafrost can be found in the northern half of the map area (Figure 4).

Surficial sediments are thin in the southern portion of the map, thickening northwards, and reaching a maximum thickness of 363 m around Bistcho Lake. In the south of the map, topographic highs are related to bedrock topography, however, in the north topographic highs are attributed to thick deposits of surficial sediments (Borneuf & Pretula, 1980).

The study investigated the bedrock stratigraphy of this Interior Platform region as deep as the Paleozoic sedimentary sequences. A major unconformity separates the Paleozoic carbonate rocks from the overlying clastic rocks of the Cretaceous. The Cretaceous successions are primarily composed of siltstones and shales, along with lesser abundant sandstone units. The uppermost unit of the Cretaceous stratigraphy is the Dunvegan Formation (Borneuf & Pretula, 1980); this formation was also found in the Liard Basin and the sandstones were identified as a promising aquifer (Hayes & Costanzo, 2014).

The study did not collect any samples from potential bedrock aquifers. The study identified one aquifer hosted in sands and gravels with a thickness between 30 m and 60 m located adjacent to Zama Lake. The aquifer provided yields between 15 L/s and 450 L/s. This aquifer has been used by the oil and gas industry as a water source for injection into the underlying oil reservoirs to enhance recoveries. Another aquifer was hypothesized to be located adjacent to Bistcho Lake further north with estimate yields between 2 L/s and 8 L/s based on lithology and thickness of sediments (120 m to 360 m), as no wells were drilled. Concentration of total dissolved solids in groundwater ranges from about 200 mg/L to 300 mg/L in the one identified aquifer, and range from 500 mg/L to 3000 mg/L in groundwater collected from other surficial deposits (Borneuf & Pretula, 1980).

2.4.4.1 Steen River-Whitesand River Area

The Steen River-Whitesand River area is located immediately to the east of the Zama-Bistcho Lakes area, and shares a border with the Northwest Territories to the north. The Great Slave sub-basin drains the majority of the map area, with the Liard sub-basin and the Peace River sub-basin each draining a small portion in the northwest and southeast, respectively. Discontinuous permafrost can be found across most of the map area (Figure 4) (Ozoray, 1980).

Surficial sediments vary greatly in thickness, ranging from 170 m to an estimated 400 m thick within a buried valley in the Cameron Hills, and 15 m to 45 m in the lowlands and Caribou Mountains. Bed moraine till is widespread over the area. Coarser grained sand and gravel deposits have been noted within the buried valleys in the Cameron Hills, in other fluvioglacial deposits in the Cameron Hills, in kames along the plateau of the Cameron Mountains, and in terraces along the Hay River (Ozoray, 1980). The bedrock geology in the area is comparable to that described above by Borneuf and Pretula (1980), with the exception that an additional shale unit may be found overlying the Dunvegan Formation (Ozoray, 1980).

The primary aquifers in the region were identified as being located in the surficial sediments. The buried valleys of the Cameron Hills have an estimated yield of 8 L/s to 32 L/s, while other sand and gravel aquifers in the region are estimated to have yields between 2 L/s and 8 L/s (Ozoray, 1980). Bedrock in the region was not viewed favourably for potential aquifers, typically with low estimated yields and high concentrations of total dissolved solids. Where the Devonian carbonate rocks outcrop are near surface in the northern central parts of the region, and there is potential for karstic features, they may be considered for a potential aquifer. Additionally, the Dunvegan Formation is estimated to have yields between 0.4 L/s to 2 L/s and may be a suitable aquifer in some locations. Concentration of total dissolved solids in groundwater ranges 100 mg/L to 500 mg/L in surficial sediments, and from 10,000 mg/L to 30,000 mg/L for samples collected from bedrock (Ozoray, 1980).

3.0 GROUNDWATER USES

Groundwater use in each Transboundary Area stakeholder jurisdiction is discussed subsequently for various groundwater users identified. Where, available, quantities of groundwater use are described, which includes, but is not limited to: community uses, domestic (private) uses, mining uses, oil and gas production uses, commercial uses, industrial uses and agricultural uses where appropriate.

3.1 Northwest Territories

Groundwater uses in the Northwest Territories is limited to communities, oil and gas production, and mining.

3.1.1 Community

The only communities that rely on groundwater are Fort Liard, Nahanni Butte, Whatì, and Wrigley. Fort Liard and Nahanni Butte are located in the Liard sub-basin; the former is permitted to withdraw 40,000 m^3 of groundwater annually (Mackenzie Valley Land and Water Board, 2010), while the latter currently has no water licence and therefore does not have a withdrawal limit. Whatì, located in the Great Slave sub-basin, is permitted to withdraw 30,000 m^3 of groundwater annually (Mackenzie Valley Land and Water Board, 2007). Wrigley, located in the Great Bear sub-basin currently has no water licence and therefore has no withdrawal limit.

3.1.2 Mining

Mines in the Northwest Territories predominantly use surface water as a water source. One notable exception is the Canadian Zinc Corporation Prairie Creek Mine that is permitted to withdraw up to 14,600 m^3 of water annually from the shallow Prairie Creek Alluvial Aquifer. Although not considered a water use with respect to licensing, nearly all mines extract large quantities of groundwater through the dewatering of open pits and underground workings.

3.1.3 Oil and Gas

Petroleum exploration and production (including both conventional oil and gas, as well as shale gas) occurs, or has occurred, across the entire Mackenzie River Basin, but primarily in four areas within the Northwest Territories: near Cameron Hills, Fort Liard, Norman Wells, and Inuvik (Figure 9). Although nearly all petroleum exploration and production has been put on hold due a decline in the price of oil, many of these locations remain prospective producers in the future.

3.1.4 Local Community Information

The following members of the Aboriginal Steering Committee who helped guide the implementation of the Northwest Territories Water Stewardship Strategy and Transboundary work were contacted:

- K'atl'odeeche First Nation (KFN) – Peter Redvers
- Northwest Territories Métis Nation (NWT Métis Nation) – Tim Heron
- Dehcho First Nations (DFN) – Dahti Tsetso
- Salt River First Nation (SRFN) – Jeff Fraser
- Gwich'in Tribal Council (GTC) – David Krutko

A response was received from the KFN, NWT Métis Nation, and the DFN.

The KFN indicated that there was extensive Traditional Knowledge (TK) regarding groundwater, in particular, springs and underground rivers. An assessment of TK on groundwater was completed as part of the Mackenzie Gas Project; however, the report is confidential, and was not available at time of preparation of this report.

The NWT Métis Nation is currently collecting land use information from the three NWT Metis Tribal Councils: Fort Resolution, Fort Smith, and Hay River. The NWT Métis Nation forwarded the information request to the three councils to identify the availability of TK on groundwater. At the time of writing, an update regarding the amount of information available had not yet been received. Additionally, it is the Elder's preference that TK be communicated orally, in person, rather than through written documents. The NWT Métis Nation did not provide any TK on groundwater, however, observations from community members on groundwater in the region were shared with the GNWT ENR as part of the Slave River and Delta Partnership.

The DFN forwarded the information request to the member communities to identify the availability of TK on groundwater and areas that are sensitive or high risk. At the time of writing, an update regarding the amount of information available had not yet been received. The DFN identified the Edéhzhié Protected Area, or Horn Plateau, as an important groundwater source area where additional groundwater studies are required.

An exhaustive review of local community information was not completed in this report, but may be achieved through further correspondence with the Aboriginal Steering Committee members.

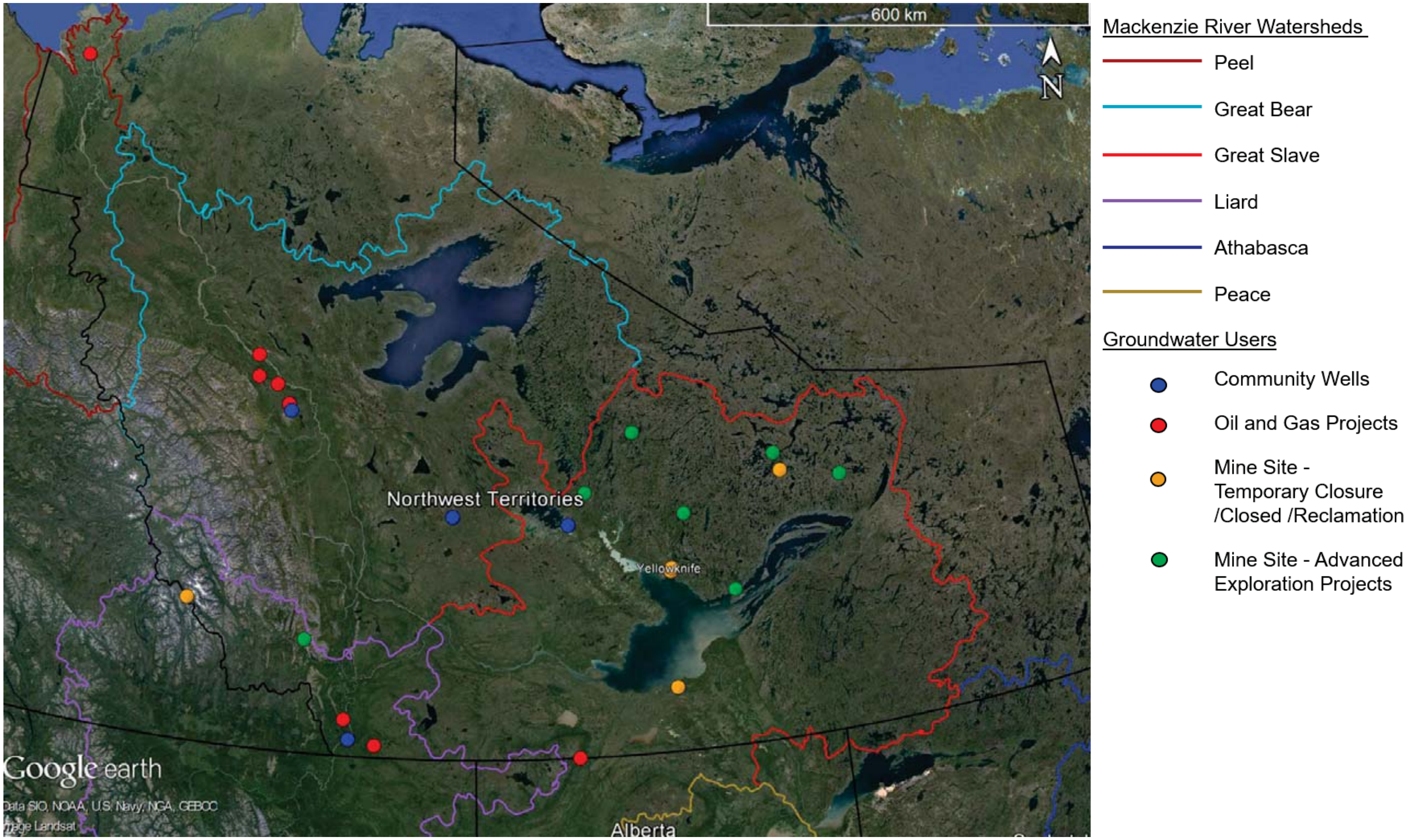


Figure 8. Groundwater users and potential sources of contamination in the Northwest Territories.

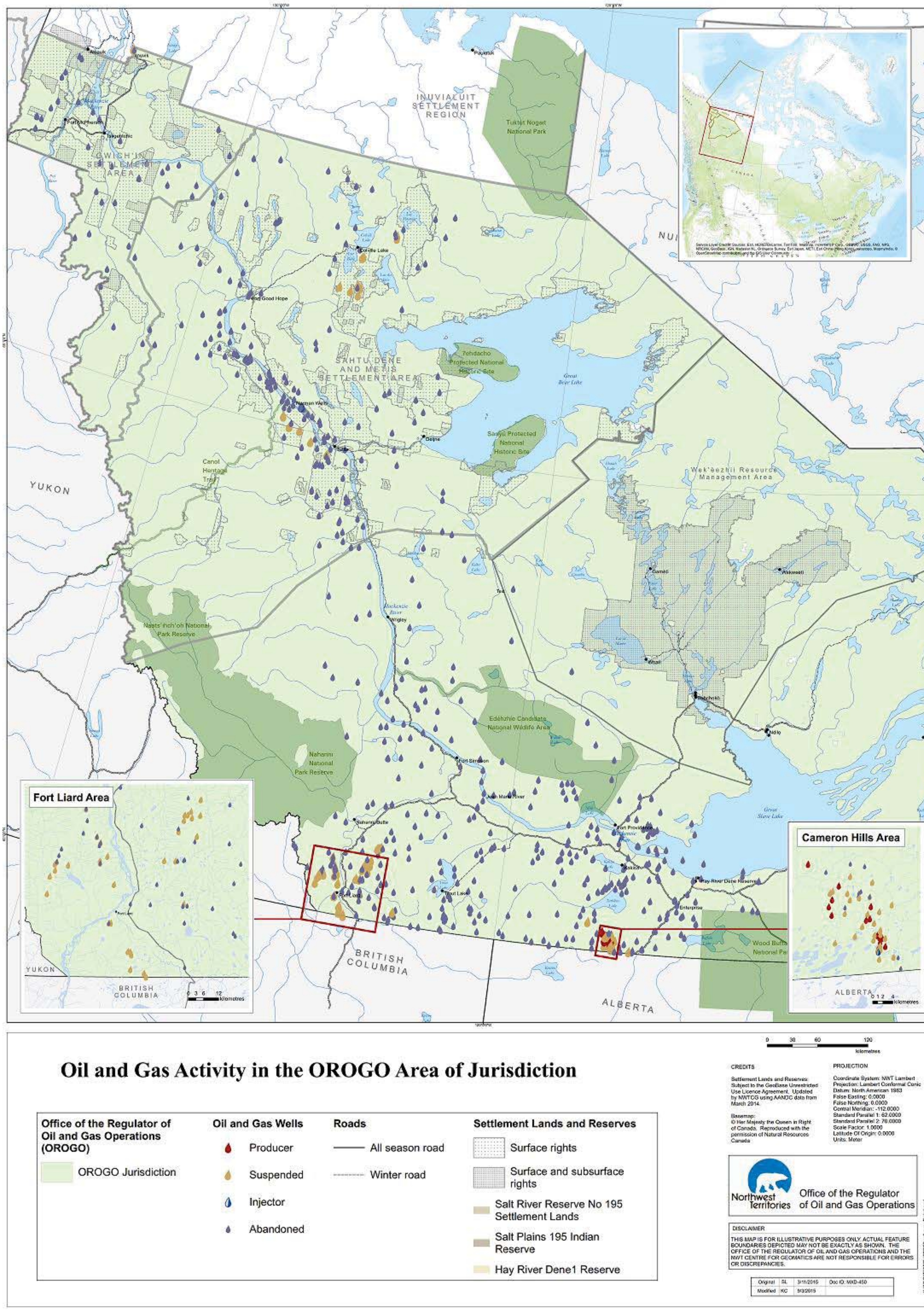


Figure 9. Map of oil and gas wells in the Northwest Territories as of March 2014. With the recent decrease in the price of oil, nearly all petroleum exploration and production in the Northwest Territories has been put on hold (Office of the Regulator of Oil and Gas Operations, 2015).

3.2 Alberta

Most of Alberta's surface water resources are found in northern Alberta, while most of the population and agricultural/industrial demand occurs in the south. Groundwater is present in practically every part of the province, but aquifer depths, yields and potability vary widely (Alberta Environment and Parks, 2016e).

Preliminary interpretations for provincial-wide groundwater use in Alberta was compiled by Lemay & Guha (2009), and which was estimated by AMEC (2007) including a number of scenarios for community, agricultural, petroleum, commercial, industrial and other uses for each of the 13 major river basins in Alberta (Figure 10). Of these river basins, five are within the Mackenzie River Basin, including:

- Athabasca sub-basin;
- Buffalo River sub-sub-basin (Great Slave sub-basin);
- Hay River sub-sub-basin (Great Slave sub-basin);
- Liard sub-basin; and
- Peace sub-basin.

The Buffalo River and Hay River sub-sub-basins are considered part of the Great Slave sub-basin. The Alberta Geological Survey (AGS) holds geographical information systems (GIS) files of the major river basins and water-well locations for the Province of Alberta. To exclude any wells that may be abandoned, only wells that were 20 years old or less were selected for consideration in Lemay & Guha (2009).

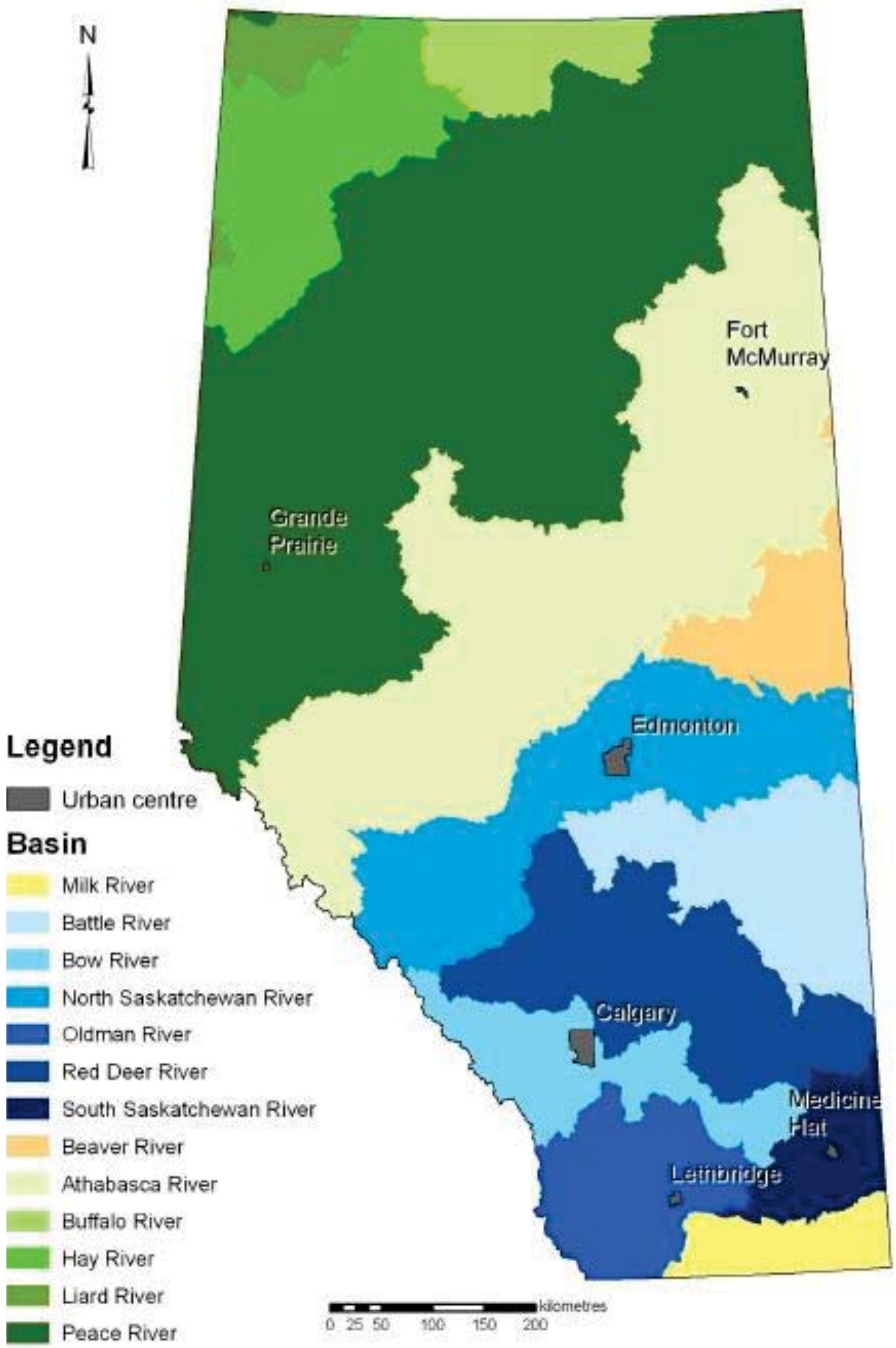


Figure 10. Map of major river basins in Alberta (Lemay & Guha, 2009).

It should be noted that both Lemay & Guha (2009) and AMEC (2007) used the Alberta Water Well Information Database (Alberta Environment and Parks, 2016a), which contains a database of approximately 500,000 records with nearly 5,000 new drilling reports added annually. The database contains information about individual water well drilling reports, chemical analysis reports up to the end of 1986, springs, flowing shot holes, test holes, and pump tests conducted on the wells.

Table 4 shows the distribution of water wells from Lemay & Guha (2009) in each sub-basin within the Transboundary Area, which provides an insight into groundwater use in the Alberta portion of the Mackenzie River Basin.

Table 4. Summary of water-well information by major river basin in the Transboundary Area of Alberta (Lemay & Guha, 2009).

Major River Basin in Transboundary Area	Number of Water Wells (Estimated)
Athabasca	11,123
Great Slave [a]	198
Liard River	25
Peace	4,996

Notes:
[a] Includes Buffalo River and Hay River

The AMEC (2007) water use estimates were forecasted for low, medium, and high water-use scenarios provided for the years 2005, 2010, 2015, 2020 and 2025. The medium water use estimate was considered for this report because it represented a reasonable starting point for examining water-use data, and the year 2015 was chosen since it is the closest estimate to the present. Table 5 below gives a summary of the water use forecasts for 2015 for the Transboundary Area in Alberta.

For the AMEC (2007) water use estimates, Lemay & Guha (2009) provided estimates of water usage by townships in Alberta, presented geographically. For those estimates, the groundwater-use value for each well (each has an associated description of its legal land location) can be calculated by township from the number of wells in each township. Similarly, the number of wells in each proposed use category and the groundwater use for each category can be summarized for each township. Lemay & Guha (2009) defines groundwater use qualitatively using categories from least to most use, rather than being defined numerically. As a very general estimate, Lemay & Guha (2009) states that each classification of groundwater use would be ten times greater than the previous classification. The maps are shown in Figure 11 through Figure 16 and discussed in the subsequent sections.

Table 5. Forecast of medium scenario groundwater use for 2015 by type of use for the sub-basins in the Transboundary Area of Alberta, summarized from AMEC (2007).

Sub-basin	Medium forecast water use, for 2015 (m^3 per year)						
	Community	Agricultural	Commercial	Petroleum	Industrial	Other	Total
Athabasca	1,860,000	5,131,000	1,125,000	54,020,000	1,729,000	169,000	64,034,000
Great Slave [a]	11,000	94,000	5,000	158,000	0	0	268,000
Liard	0	0	0	50,000	0	0	50,000
Peace	1,079,000	1,236,000	419,000	6,324,000	163,000	0	9,221,000

Notes:
Volumes rounded to nearest 1,000.
[a] Includes Buffalo River and Hay River

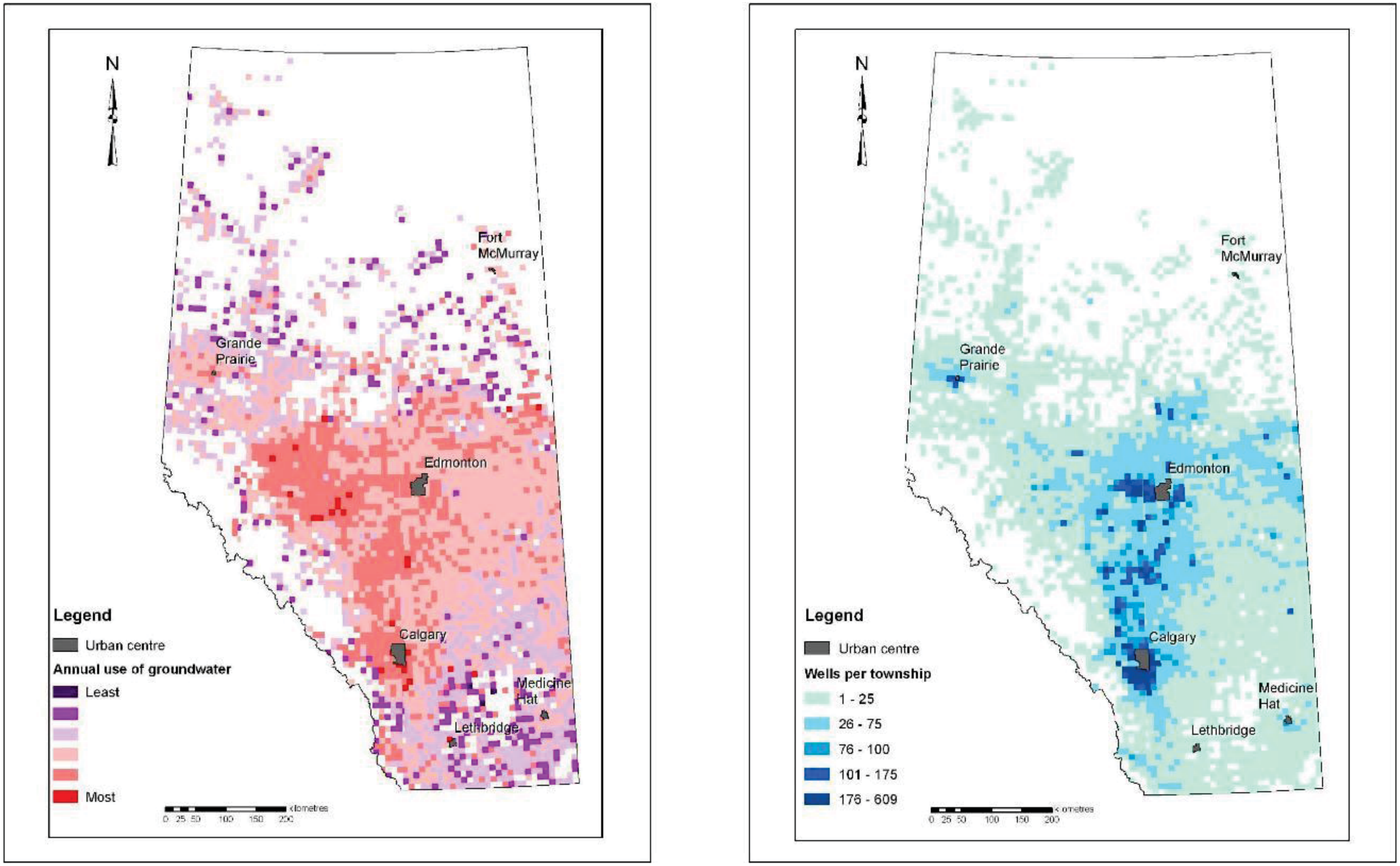


Figure 11. All groundwater use and total number of water wells, by township (Lemay & Guha, 2009).

3.2.1 Community and Domestic

AMEC (2007) and Lemay & Guha (2009) combine community groundwater use and private domestic groundwater use in to a single use category “community”. The groundwater use for this category is presented in Table 5 for the various sub-basins in the Transboundary Area, and also shown in Figure 12 and Figure 13 for community and domestic use, respectively.

3.2.3 Oil, Gas and Mining

AMEC (2007) and Lemay & Guha (2009) combine groundwater use for oil, gas and mining into the use category of “Petroleum”, and notes that the petroleum sector includes water allocations for oil sands mining, thermal and gas and petrochemical plants. The groundwater use for this category is presented in Table 5 for the various sub-basins in the Transboundary Area. AMEC (2007) further describes the particular makeup of the petroleum use category by water licence and usage for each of the Transboundary Area river basins. It notes that the major groundwater use for the petroleum use category in the Athabasca River basin includes the six major oil sands projects including:

- Suncor, including the Voyageur projects;
- Syncrude;
- Albian Sands Project;
- Fort Hills Project (Petro-Canada/UTS Energy/Teck Cominco);
- Horizon Project (Canadian Natural Resources Limited (CNRL)); and
- Jackpine Project (Shell Canada).

AMEC (2007) also describes that 99% of allocations for the petroleum sector in the Hay River Basin (Great Slave Basin) are for injection purposes for enhanced oil and gas recovery, and that two active surface water licences have been issued for injection purposes in the Liard River Basin.

3.2.4 Commercial

AMEC (2007) and Lemay & Guha (2009) provide groundwater use for commercial uses (Table 5), which includes golf courses, gardening, bottling, water hauling, parks and recreation, dust control, food processing, and aggregate washing.

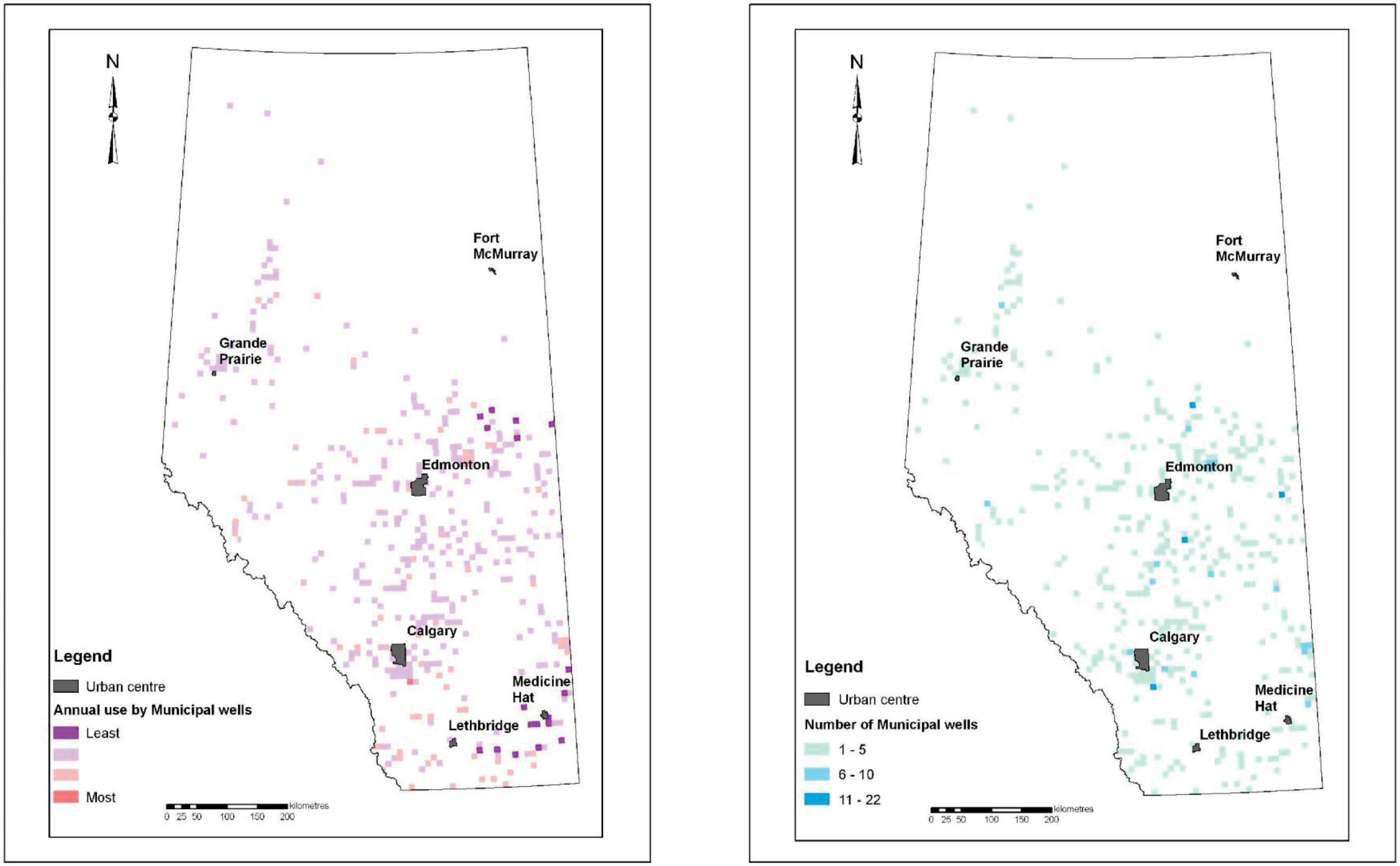


Figure 12. Groundwater use by community wells and number of community wells, by township (Lemay & Guha, 2009).

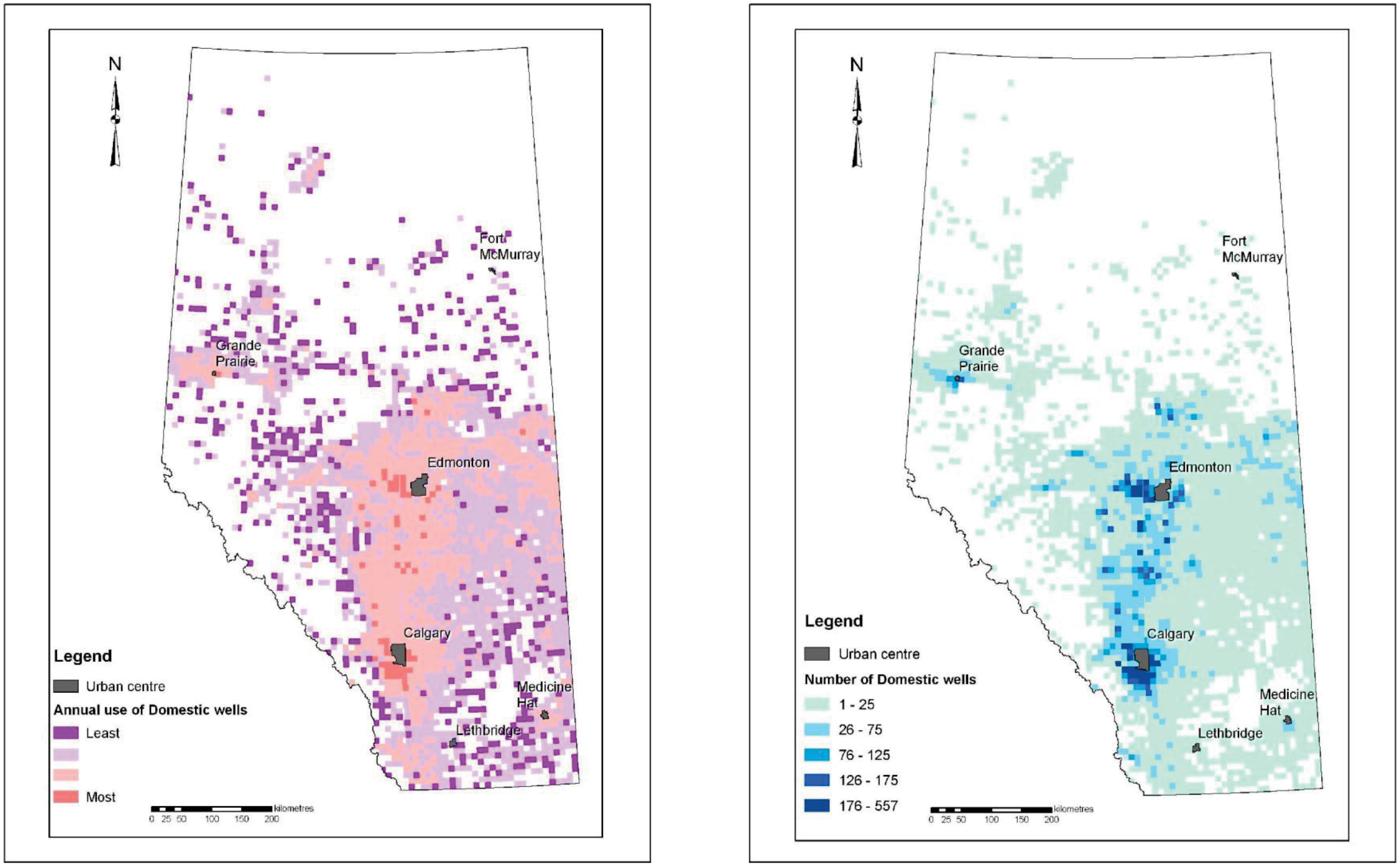


Figure 13. Groundwater use by domestic wells and number of domestic wells, by township (Lemay & Guha, 2009).

3.2.5 Industrial

AMEC (2007) and Lemay & Guha (2009) provide groundwater use estimates for the industrial use category, which is shown in Table 5 and Figure 14. AMEC (2007) describes the industrial use category as water allocations for cooling (thermal power generation or cooling such as air conditioning), forestry, coal mining, and other industrial activities.

3.2.6 Agricultural

AMEC (2007) and Lemay & Guha (2009) combine groundwater use for livestock and irrigation purposes into a single category of "agricultural". Groundwater use estimates for the agricultural use category is shown in Table 5, with Figure 15 and Figure 16 showing groundwater use for livestock and irrigation, respectively.

3.2.7 Other

AMEC (2007) and Lemay & Guha (2009) provide groundwater use under the "other" category, which is described to include water used for habitat enhancement and water management (flood control and lake stabilization). This use is shown in Table 5 for the Mackenzie River sub-basins in the Alberta.

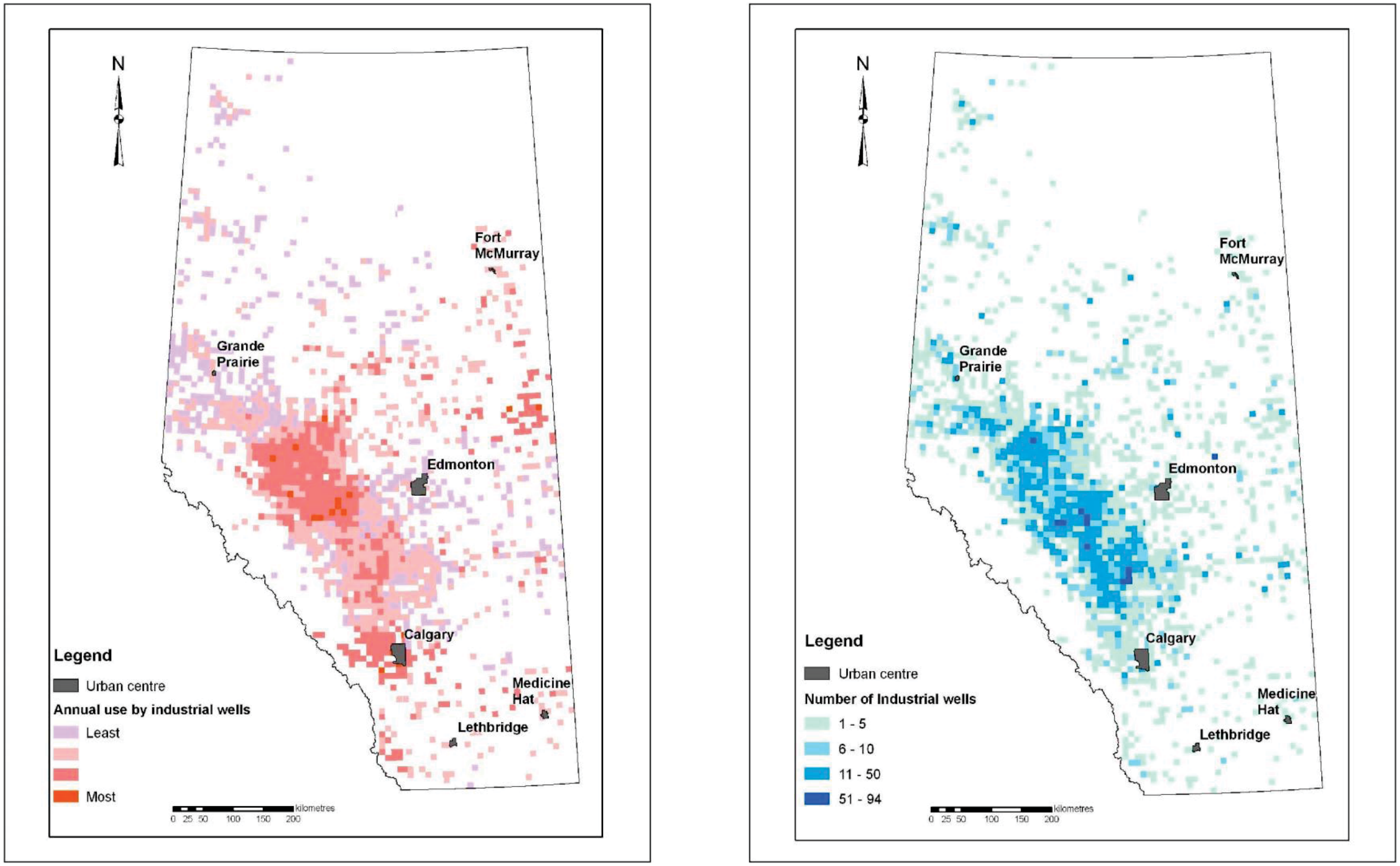


Figure 14. Groundwater use by industrial wells and number of industrial wells, by township (Lemay & Guha, 2009).

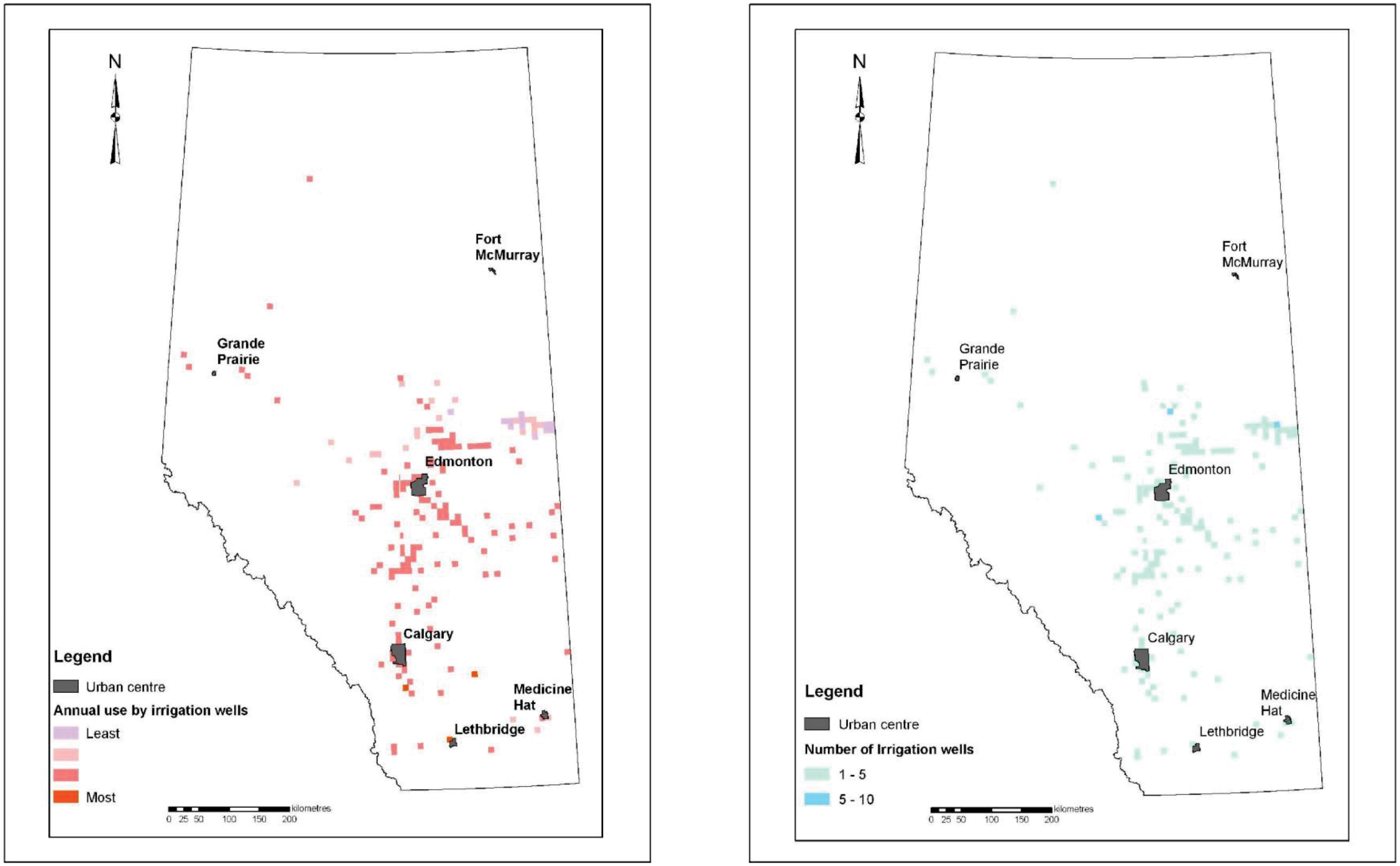


Figure 15. Groundwater use by irrigation wells and number of irrigation wells, by township (Lemay & Guha, 2009).

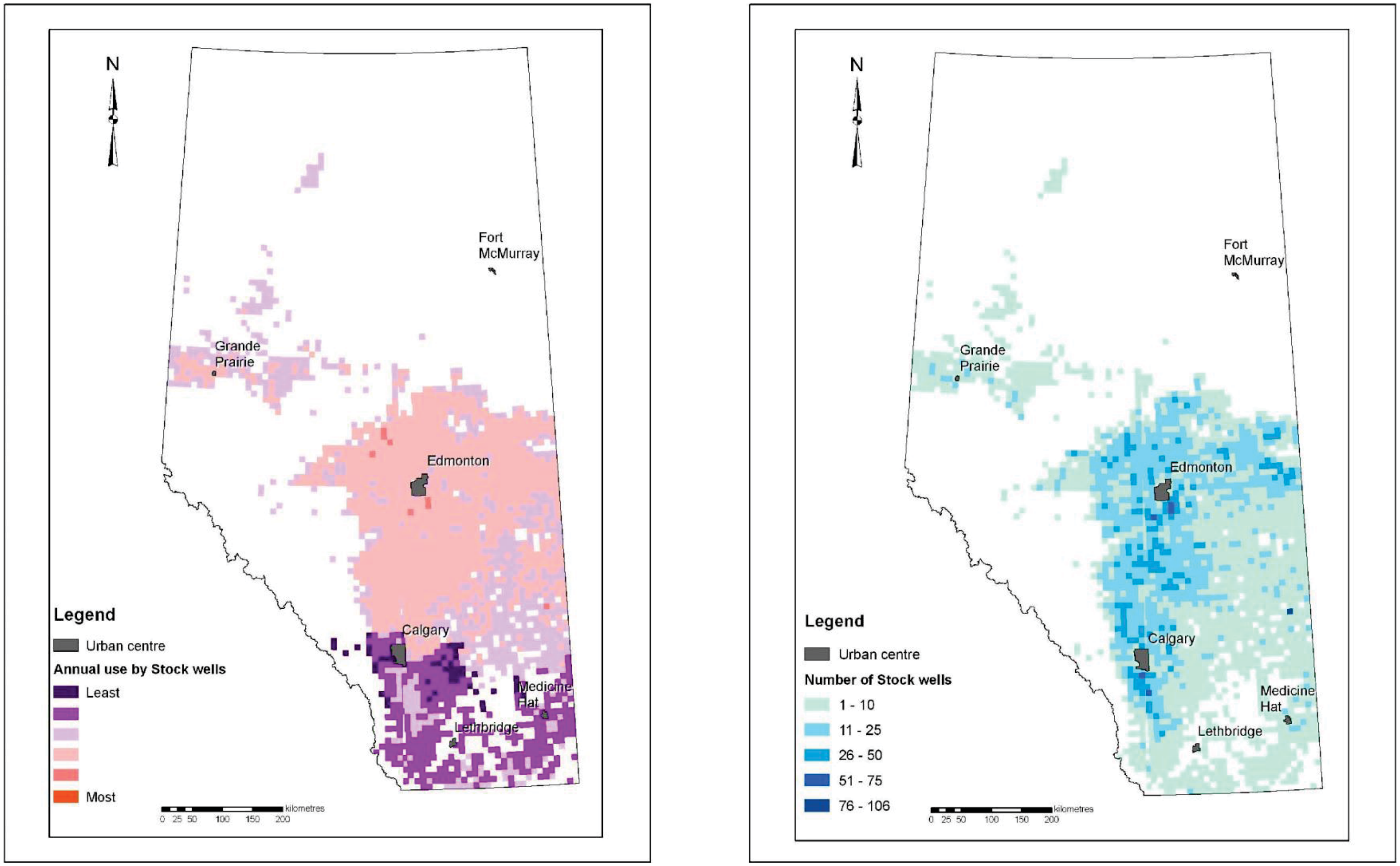


Figure 16. Groundwater use by livestock wells and number of livestock wells, by township (Lemay & Guha, 2009)

3.3 British Columbia

Groundwater use in British Columbia is currently unregulated, and users are not required to pay and subsequently report quantities of groundwater used. Therefore no groundwater use records exist for the Peace and Liard River Basins in British Columbia. British Columbia's Water Sustainability Act received Royal Assent in May 2014, and is expected to come into force in 2016 (Government of British Columbia, 2015). According to the Water Sustainability Act, irrigators, industries, waterworks and others who use groundwater for non-domestic purposes will need to obtain a water licence and to start paying water fees and rentals. They will also have defined water rights, and greater clarity regarding their priority of use for the first time. Stream water and groundwater rights will be integrated, to enable management of water as one resource. The Water Sustainability Act will allow people and businesses to drill a new well without a groundwater licence. It requires them, however, to obtain a licence before using water from that well for a non-domestic purpose.

According to Government of British Columbia (2015), approximately 80,000 existing wells in British Columbia provide water for domestic uses only, and are not expected to pay water fees and rentals. The Water Sustainability Act enables the owners of domestic wells to have a water right of up to 2,000 litres per day. The Water Sustainability Act also makes it possible in the future to licence domestic use in areas of the province where there are water shortages or conflicts. However, both domestic and non-domestic users, will have to comply with regulations regarding groundwater protection (Government of British Columbia, 2015). Approximately 20,000 existing wells in British Columbia supply groundwater for non-domestic uses (Government of British Columbia, 2015). The owners of these wells will have three years from the date the Water Sustainability Act comes into force in which to apply for a water licence. While their licence application is under review they will be able to continue to divert, use, and store groundwater (Government of British Columbia, 2015).

A database of water wells in British Columbia is available at Government of British Columbia (2016) and Groundwater Information Network (2014). The Government of British Columbia (2016) database will let public viewers examine locations and construction details of wells drilled across the province, and is broken up into the following use categories:

- Drinking water supply system wells (community);
- Domestic well use (private wells);
- Commercial and Industrial well use;
- Irrigation well use (agricultural);
- Other well use; and
- Unknown well use.

However, the Government of British Columbia (2016) database does not let viewers reproduce maps at a large scale, nor give any further descriptions for the above uses. As such Figure 17 was produced from Groundwater Information Network (2014) to show groundwater wells across northern sections of British Columbia, however they do not show the various types of uses outlined above.

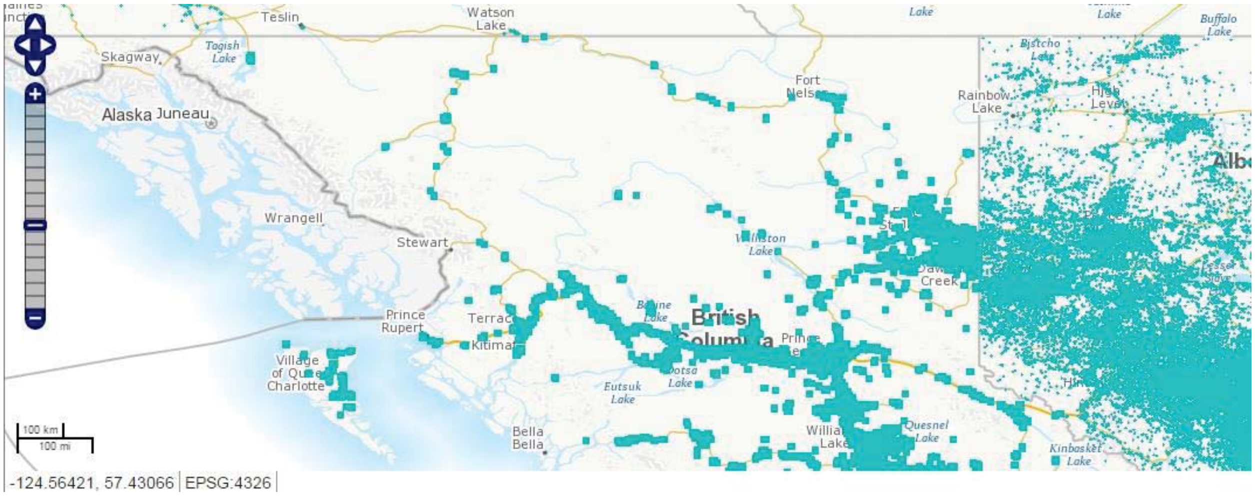


Figure 17. Locations of groundwater wells in Northern British Columbia (Groundwater Information Network, 2014).

3.4 Saskatchewan

There are currently no groundwater users in the Transboundary Area of Saskatchewan, which includes the Athabasca and Great Slave sub-basins. As shown in Figure 1, water in the Athabasca sub-basin flows from the Northwest Territories, into Saskatchewan and through Alberta, before re-entering the Northwest Territories; the Northwest Territories portion of the Athabasca sub-basin has had no development. Only the Tazin sub-sub basin, within the Great Slave basin, flows directly from Saskatchewan into the Northwest Territories, however, there has been little development in this region other than diversion of water for hydroelectric generation (Freeman, 2008). Northern Saskatchewan is scarcely populated and due to the abundant surface water, no communities are using groundwater. Historically, gold and uranium mines operated in the Mackenzie River Basin, but at the present time all active mines are located outside of the Mackenzie River Basin to the south and east. The southwest area of the Athabasca sub-basin, Saskatchewan, has had very minor oil and gas exploration. It is likely that future users of groundwater in this region will be related to mining, or potentially oil and gas.

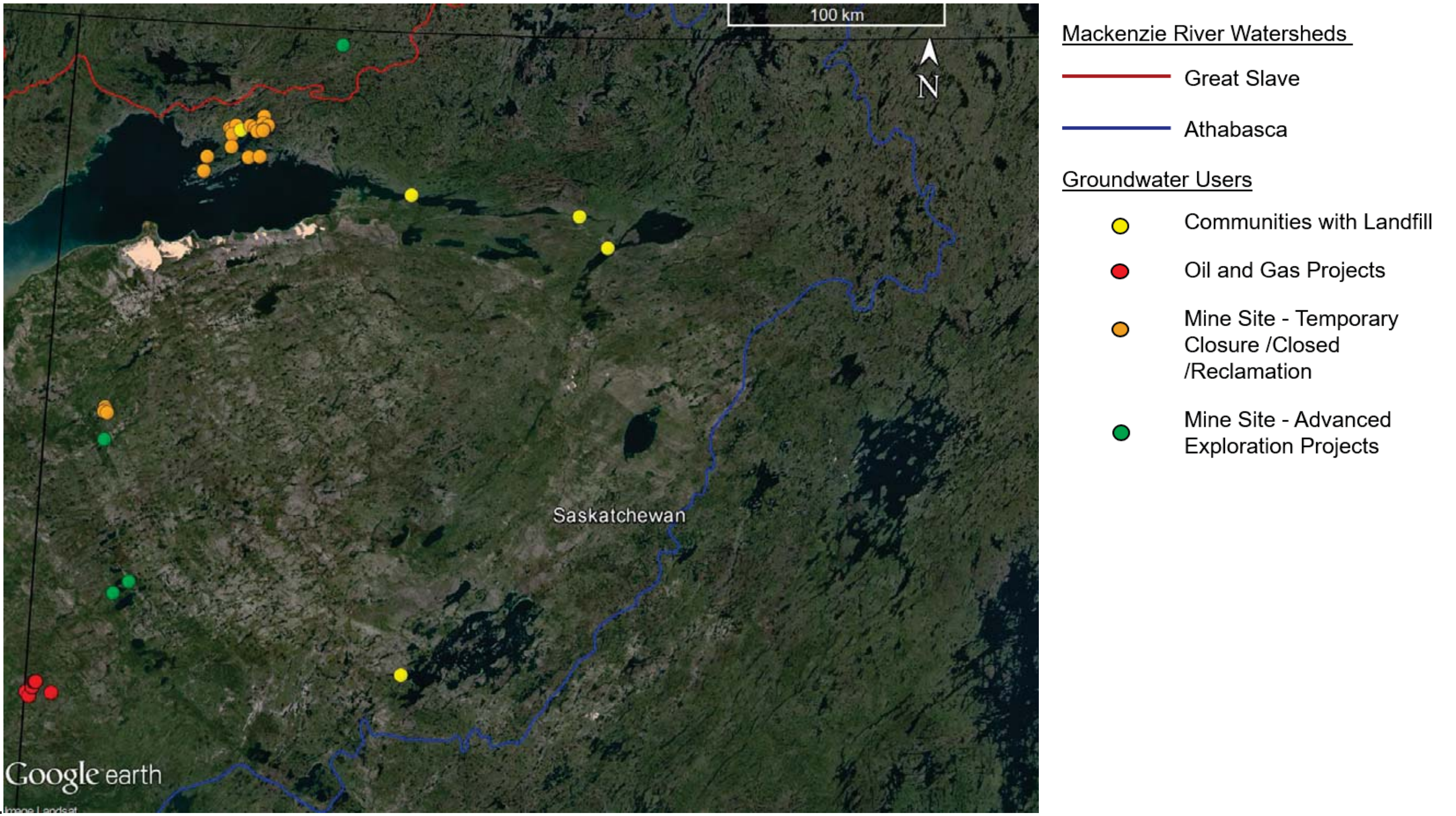


Figure 18. Groundwater users in the Mackenzie River Basin, Saskatchewan.

3.5 Yukon

Groundwater use in the Transboundary Area of the Yukon (Liard, Great Bear and Peel River Basins) is from communities, domestic uses, mining developments, and oil and gas production.

3.5.1 Community and Domestic

Community and domestic wells were located using data from the Groundwater Information Network's (GIN) Basic Map Viewer (Groundwater Information Network, 2014) and supplemented with additional unpublished well locations provided by the Yukon's Department of Environment Water Resource Branch (Figure 19) (Williams, 2016). The Water Resource Branch indicated that the provided list was incomplete and did not account for all wells in the Yukon. All 219 listed wells in the Yukon portions of Mackenzie River Basin were located in the Liard sub-basin, mostly around Watson Lake; no wells were recorded in the sparsely populated Peel sub-basin. Water quality and quantity for these domestic wells are not recorded.

3.5.2 Mining

Mine sites and advanced exploration projects with active water licences were located using data from the Government of Yukon's GeoYukon (The Government of Yukon, 2014). Three active water licences were identified in the Liard sub-basin in southeastern Yukon (Figure 19): the Sa Dena Hes Mine (Yukon Water Board, 2015), the Wolverine Mine (Yukon Water Board, 2007), and the Kudz Ze Kayah Project (Yukon Water Board, 1999). No active water licences associated with mining were identified in the Peel sub-basin.

Table 6. Groundwater use at mine sites and advanced exploration projects in the Liard sub-basin, Yukon.

Mine/Project	Quantity of Water Used	Source
Sa Dena Hes Mine	Maximum of 1056 m^3 per day and 44 m^3 per hour from all wells	Upper False Canyon Creek drainage area and North Creek Impoundment
Wolverine Mine	None	Wells for dewatering mine
Kudz Ze Kayah Project	1,100 m^3 per day from all wells	Wells located between two South Lakes

3.5.3 Oil and Gas

Historic oil and gas wells were located using data from the Government of Yukon's GeoYukon (The Government of Yukon, 2014) (Figure 19). Oil and gas in the Yukon, within the Mackenzie River Basin, is located in three areas: the Liard Basin (geological) in the Liard sub-basin (watershed), southeastern Yukon; the Peel Plateau in the Peel sub-basin, northwestern Yukon; and the southern tip of Eagle Plains, in the Peel sub-basin, north-central Yukon. Although there are presently no producing oil or gas wells in the Yukon, future operations may occur in these same areas.

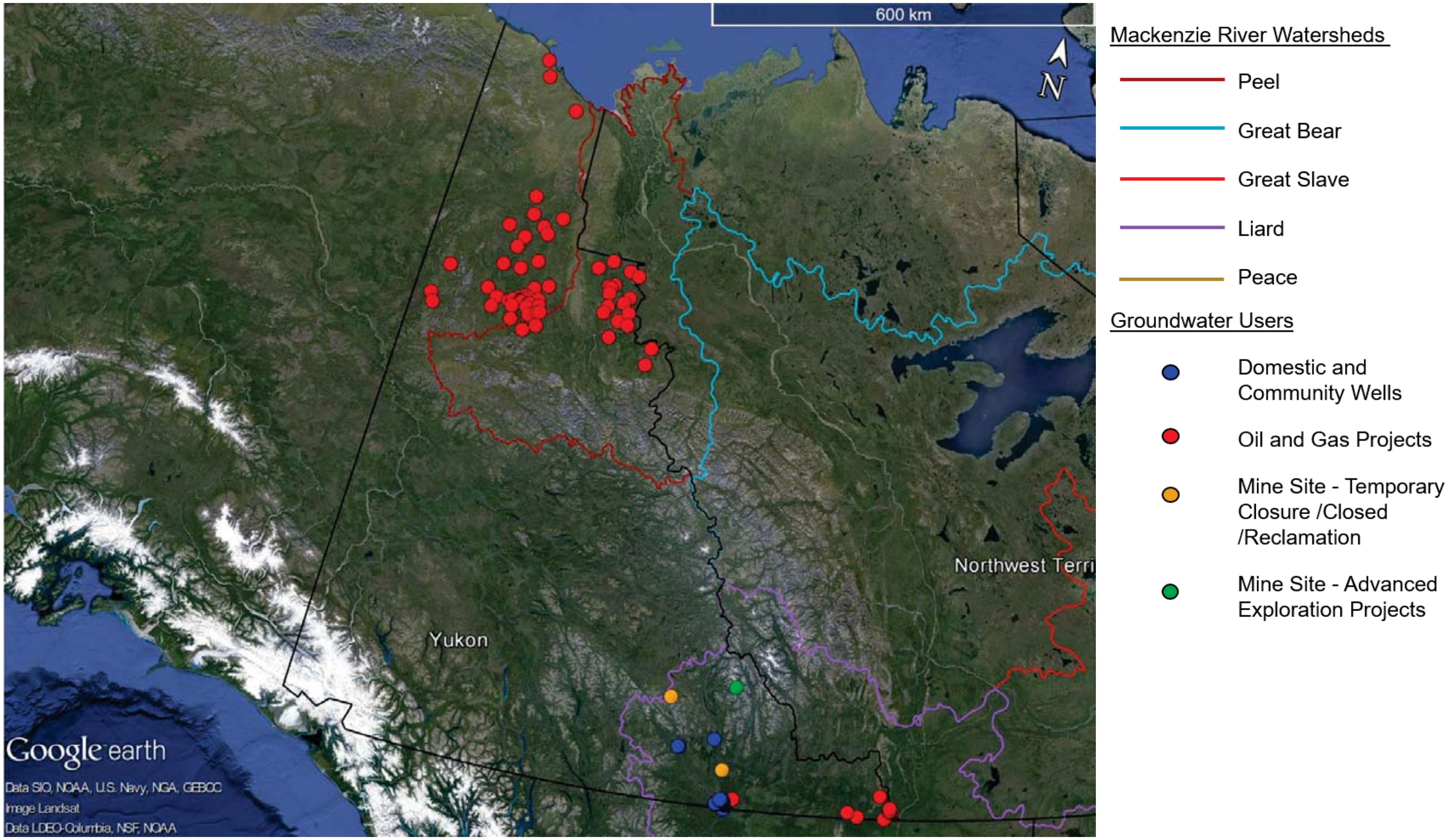


Figure 19. Groundwater users in the Mackenzie River Basin, Yukon.

3.6 Summary

Table 7. Summary of the state of knowledge groundwater uses by stakeholder jurisdiction.

Groundwater Use	Summary of the State of Knowledge for Groundwater Uses by Stakeholder Jurisdiction				
	Northwest Territories	**Alberta**	**British Columbia**	**Saskatchewan**	**Yukon**
Community and Domestic	Limited number of users. Some communities record quantity of groundwater used as required by Water Licence.	Large number of wells and high use. Estimates of total groundwater use by area, and database of groundwater users.	Large number of wells and high use. No estimate of total groundwater use. Water use to be regulated, but no reporting on quantities removed. Database of water wells locations.	No known users. Surface water is the primary water source.	Limited number of users. Environment Yukon has water well registry but does not track volume of water used in domestic wells.
Mining	Prairie Creek is the only known mine using groundwater as a water source, and are required to record the volume of water used. Most mines extract large volumes of water through dewatering. Water licences may require this volume of water to be recorded.	Alberta combines water use for mining, and oil and gas. Largest user of groundwater for the entire Mackenzie River basin, in particular oil sands mining in the Athabasca and Peace sub-basins. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. No active mines. Surface water has historically been the primary water source.	Two of three mines are using groundwater. Water licences limit the volume used, and require the volume used to be reported annually.
Oil and Gas	Oil and gas exploration and production is limited by current oil prices. Oil and gas production is a major user of groundwater in the NT during production. Some water licences limit volume of water used, and require annual reporting of quantities.		Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Limited exploration has been completed.	No known users. Oil and gas exploration and production is limited by current oil prices and regulatory framework. A potential major user of groundwater in the YK.
Commercial	No known users. Region has low population and limited infrastructure.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region has low population and limited infrastructure.	No known users. Region has low population and limited infrastructure.

Groundwater Use	Summary of the State of Knowledge for Groundwater Uses by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Industrial	No known users. Region has low population and limited infrastructure.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region has low population and limited infrastructure.	No known users. Region has low population and limited infrastructure.
Agricultural	There is limited agriculture in the Hay River sub-sub-basin. No known groundwater users due to abundant surface water.	Large number of wells and very high use relative to other jurisdictions. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users. Region is not ideal for agricultural practices	No known users. Region is not ideal for agricultural practices
Local Community Information	Information from local communities on groundwater is available for some locations. Not all communities had responded at the time of writing.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.	Local community information on groundwater was not investigated.
Other	No known users.	Alberta uses groundwater for water management and habitat enhancement. Estimates of groundwater use by area, and database of groundwater users.	Groundwater use is not regulated until 2016. Database of water wells locations.	No known users.	No known users.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;
Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
Red = Data is unavailable or not recorded and will result in gaps within Learning Plans.
Tan = Not applicable.

4.0 POTENTIAL IMPACTS TO GROUNDWATER

Groundwater can be impacted by several means. Each jurisdictional stakeholder in the Transboundary Area have their own unique developments that may impact groundwater. These may include identified or potential environmental remediation sites, landfills (community and industrial), mining undertakings, and/or oil and gas production undertakings. Identified aspects that have the potential for groundwater impacts are discussed below for each Transboundary Area stakeholder. Possible sources of groundwater impact include:

- Environmental remediation sites are properties that are either known to be, or are potentially contaminated. A site is considered contaminated if its land, water and/or sediment are unsuitable for particular uses from waste that exceeds environmental quality standards.
- Landfills in most jurisdictions are engineered facilities that accept waste. Modern facilities are typically lined to reduce or prevent seepage of leachate and or waste in the ground, and are constructed either on or in the ground. There is potential for leaks from the landfill which may impact groundwater. Older landfills, or dump sites, are not engineered, have no liner, and could directly impact groundwater quality; these dump sites are sometimes typical of rural and/or remote areas.
- Mining operations have the potential to reduce the quantity of groundwater in an adjacent aquifer or alter groundwater flow during dewatering operations, as well as contaminate groundwater during post-closure flooding.
- Oil and gas production may use wells to inject fluids, which may be a source of contamination to groundwater if done incorrectly. Two types of injection wells are associated with oil and gas production: Disposal wells and Enhanced recovery wells. Disposal wells inject fluids into underground formations or reservoirs that are confined and isolated from groundwater sources. These fluids are primarily brines separated from hydrocarbons at the surface after extraction. Enhanced recovery wells inject fluids into oil-bearing formations to recover residual oil or in less-common scenarios, natural gas. Enhanced recovery wells may also include those used for hydraulic fracturing; hydraulic fracturing requires injection of a viscous fluid to fracture the host rock, followed by injection of a propping agent (e.g., sand) to hold the fractures open. Additionally, enhanced recovery wells may also use acid fracturing, which increases conductivity by dissolution by injecting an acidic solution. There are often disposal wells and enhanced recovery wells associated with oil and gas production fields. It should be noted that there has only been one confirmed case of groundwater contamination as a result of hydraulic fracturing to date in Canada (Government of the Northwest Territories, 2015).

4.1 Northwest Territories

The Northwest Territories is located downstream of the other jurisdictions in the Mackenzie River Basin, therefore contamination to groundwater in the Northwest Territories is unlikely to impact groundwater use of other stakeholders. The potential sources of groundwater contamination in the Northwest Territories are primarily related to landfills, petroleum exploration and production, and mining. Extensive permafrost (Figure 4) across the region greatly reduces the potential of contamination to groundwater from surface activities.

4.1.1 Environmental Remediation Sites

Prior to devolution, there were 60 federal contaminated sites in the Northwest Territories that were considered high priority for remediation (Treasury Board of Canada Secretariat, n.d.). Most of these locations are located within the Great Slave (29) and Great Bear (24) sub-basins, with two located in the Peel sub-basin (Figure 20). The majority of these high priority contaminated sites correspond to the sites listed by Indigenous and Northern Affairs Canada's (INAC) Contaminants and Remediation Directorate (CARD). CARD has listed 25 sites that are currently undergoing assessment or remediation, and eight sites where reclamation is complete, but monitoring is ongoing (Indigenous and Northern Affairs Canada, 2013). The responsibility for these sites at this time would be subject to the Northwest Territories devolution agreement.

4.1.2 Landfills

Most communities in the Northwest Territories have an associated landfill for solid waste disposal (Figure 21) (ARKTIS, 2012). As shown in Table 8, all sub-basins include at least one landfill; the majority of the landfills are located in the Great Slave sub-basin. The presence of permafrost (Figure 4) across most of the territory reduces the potential for contamination to aquifers at depth, but shallow aquifers may still be vulnerable to contamination from landfills, particularly in the southern sections of the territory, where discontinuous permafrost is more prevalent.

Table 8. Number of community landfills by estimated annual waste generation in the Mackenzie River Basin, Northwest Territories (ARKTIS, 2012).

Sub-basin	<350 tonnes/year	350-700 tonnes/year	700-1400 tonnes/year	1400-2800 tonnes/year	>2800 tonnes/year
Athabasca	0	0	1	0	0
Liard	2	0	0	0	0
Great Slave	9	1	1	1	1
Great Bear	4	3	0	0	0
Peel	2	1	0	1	0

4.1.3 Mining

Mining in the Northwest Territories has the potential to impact both groundwater quantity and quality. There are currently several advanced exploration projects within the Mackenzie River Basin (Figure 8). The majority of historic, operating and prospective mines are located in either the Cordilleran Orogeny or the Canadian Shield; the exception being the closed Pine Point Mine, which is currently under care and maintenance and is located in the Interior Platform. All operating mines and prospective mines in the Northwest Territories portion of the Mackenzie River Basin lie within the Liard and Great Slave basins (Figure 8).

4.1.4 Oil and Gas

There are often disposal wells and enhanced recovery wells associated with oil and gas production fields. Imperial Oil re-injected brine produced during extraction into the Norman Wells oil field reservoir; and were also permitted to inject freshwater into the reservoir to enhance production. Paramount Resources Ltd. had also drilled an injection well for disposal of brines in the Cameron Hills oil and gas field (Government of the Northwest Territories, 2015).

Hydraulic fracturing has been completed by Conoco Phillips (30,000 m^3 per well for two wells) (Government of the Northwest Territories, 2015; Sahtu Land and Water Board, 2014), by Husky Oil (1000 m^3 per well for four wells) (Sahtu Land and Water Board, 2013), and by Imperial Oil near Norman Wells, which is located in the Great Bear sub-basin. Hydraulic fracturing has also been completed by Lone Pine Resources Ltd. around Fort Liard, Northwest Territories, located in the Liard sub-basin near the British Columbia and Yukon borders. Hydraulic fracturing has also been completed by Paramount Resources Ltd. in the Cameron Hills oil and gas field adjacent to the Alberta border, and located along the Liard-Great Slave sub-basin boundary (Government of the Northwest Territories, 2015). Paramount Resources Ltd. also conducted acid fracturing in the Cameron Hills oil and gas field (Government of the Northwest Territories, 2015).

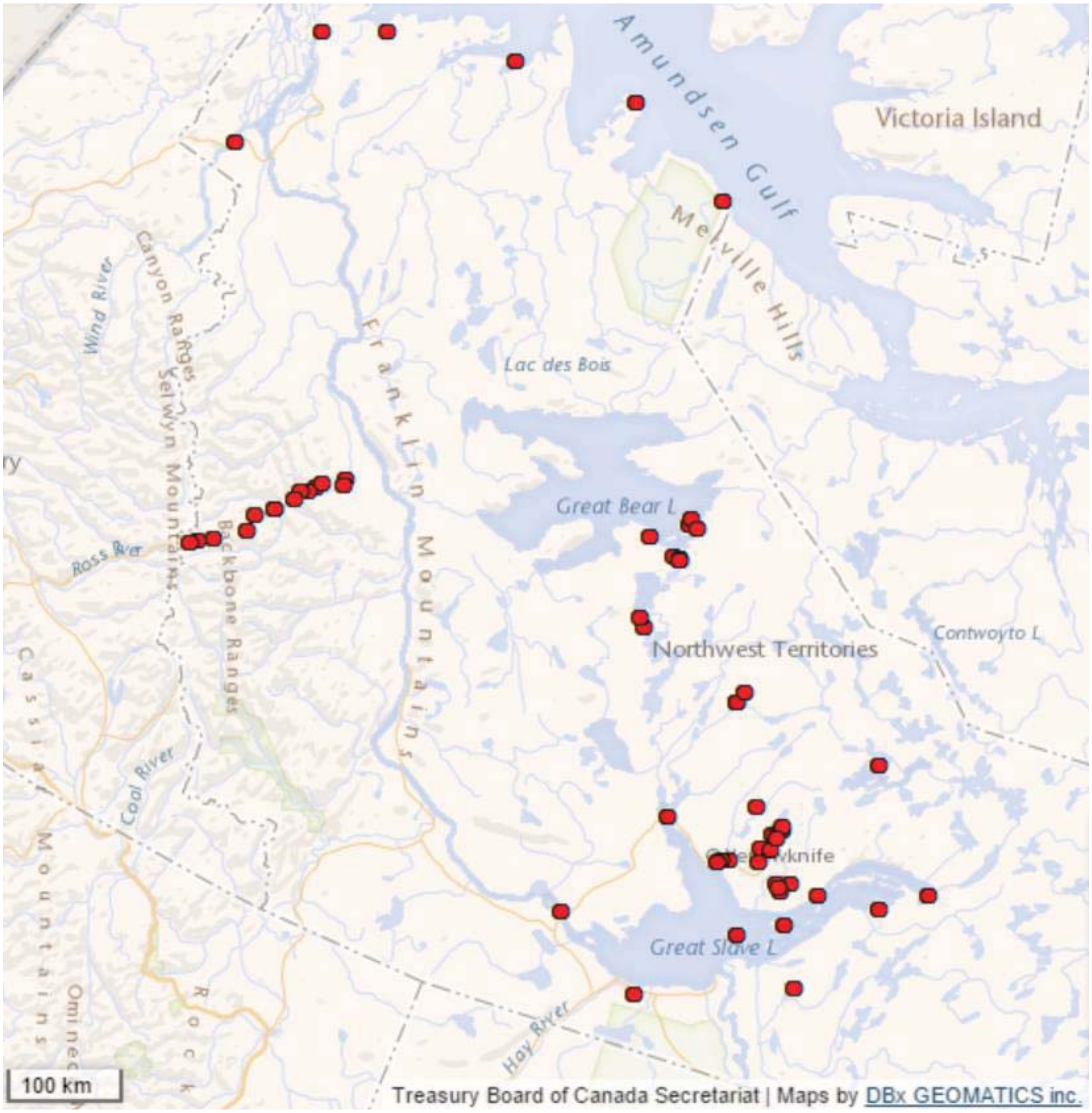


Figure 20. High priority federal contaminated sites in the Northwest Territories (Treasury Board of Canada Secretariat, n.d.).

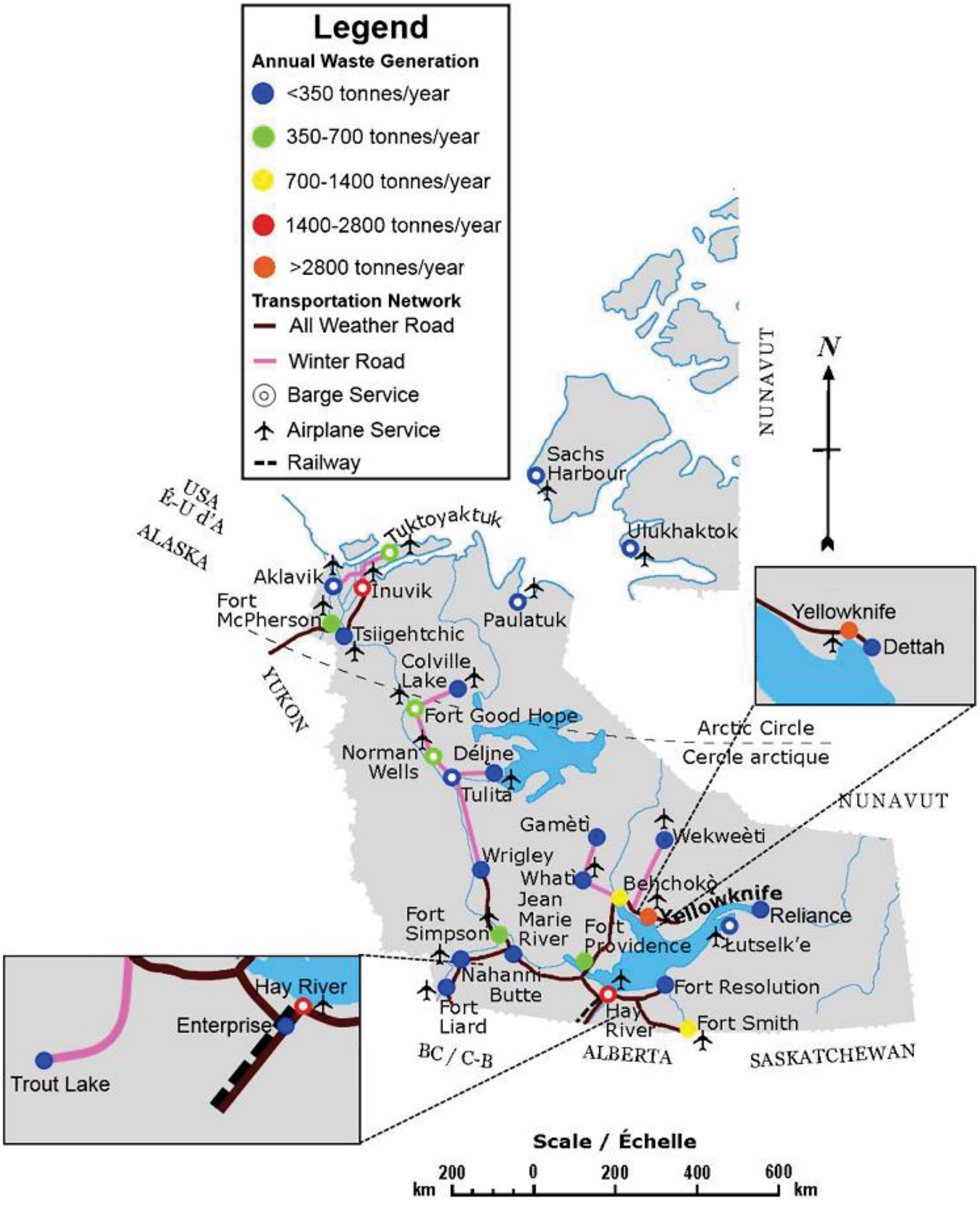


Figure 21. Location of community landfills and estimated annual waste generation in the Northwest Territories (ARKTIS, 2012).

4.2 Alberta

4.2.1 Environmental Remediation Sites

Alberta Environment and Parks maintains an online database, called the Environmental Site Assessment Repository (ESAR). The ESAR provides scientific and technical information about assessed and/or remediated and/or reclaimed sites throughout Alberta (Alberta Environment and Parks, 2016b), and further states that environmental site assessments determine the quality of soil and groundwater of a site. However, it should be noted that a site assessment does not necessarily mean a site is, or ever was, contaminated.

Reclamation certificates issued for oil and gas well sites, gravel pits and other specified sites on private land are also available on ESAR, along with the associated file information for the certificates (applications, reports, etc.). Information relating to reclamation certificates issued for sites on public lands may be obtained through Alberta Energy for a fee (Alberta Environment and Parks, 2016b).

Data at Alberta Environment and Parks (2016b) is searchable and can be used to access data regarding contaminated sites within the Transboundary Area, which may affect groundwater quality. The potential impacts to groundwater from these sites was not reviewed as part of this report.

4.2.2 Landfills

Per Alberta Environment and Parks (2016c), Alberta began regionalizing its community landfill system in the 1970s so that, instead of small community "dumps" throughout the countryside, regional landfills with a network of transfer stations would consolidate waste. This allowed for the cost effective development of engineered landfill sites. Modern landfills have become sophisticated waste management facilities that are typically integrated with other activities such as organics management, and collection sites for household hazardous waste, tires, white goods and other recyclable materials (Alberta Environment and Parks, 2016d). Landfills in Alberta are classified by the waste streams they can accept; and are classified as: Class I, or hazardous waste landfill; Class II, or non-hazardous waste landfill; and Class III, or inert waste landfill.

Figure 22 was provided by Alberta Environment and Parks (Guha, 2016), and shows the distribution of both active and inactive landfills across the province of Alberta. Data regarding landfill class and location is currently unavailable on a public database, however this data can be provided by Alberta Environment and Parks to determine the number, location, status, and class of landfills within the Transboundary Area of Alberta.

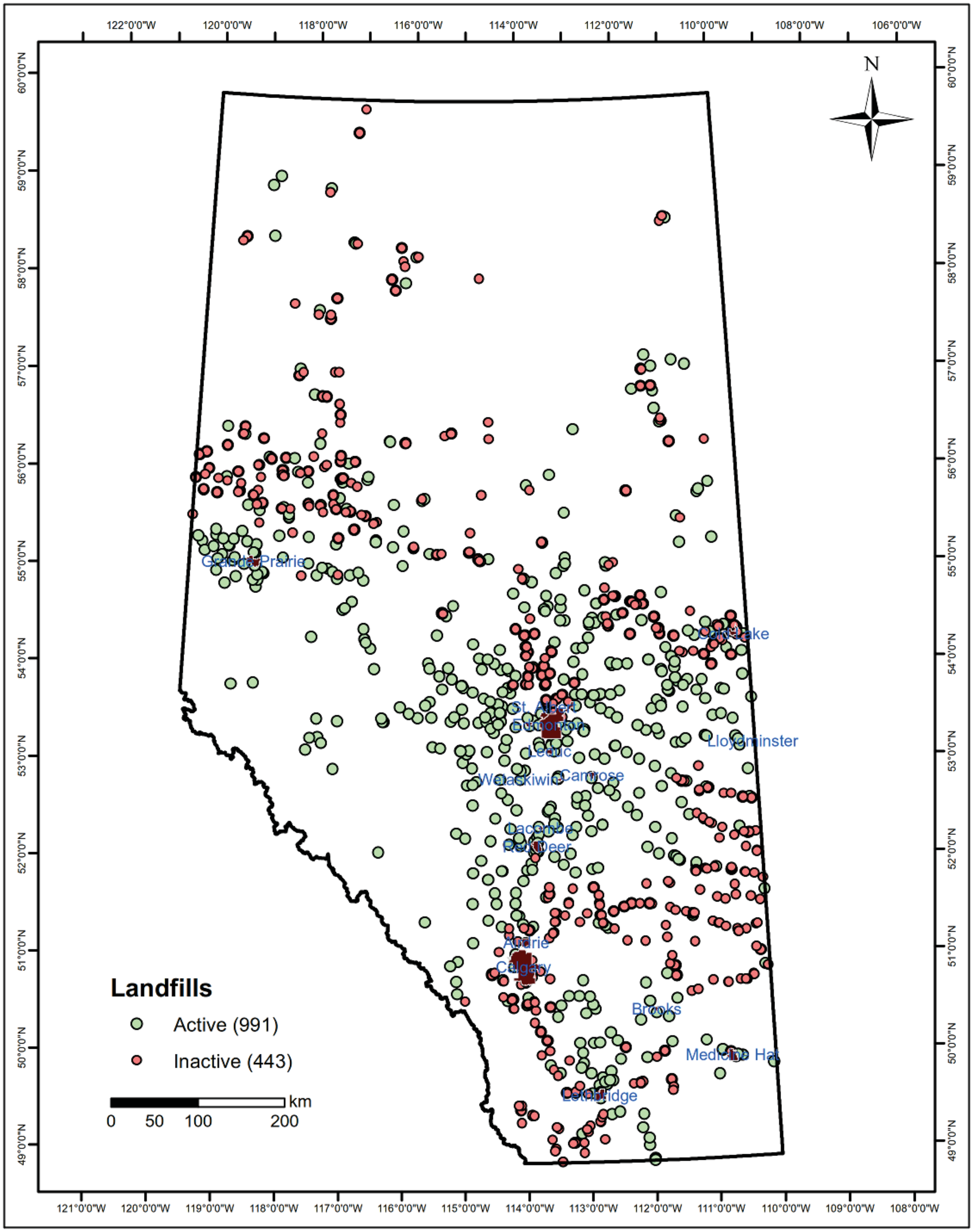


Figure 22. Map of Alberta showing active (green) and inactive (pink) landfill locations, provided by Alberta Environment and Parks (Guha, 2016).

4.2.2 Mining

Mining in Alberta may have potential negative impacts on groundwater quality within the Transboundary Area. Notable mining operations in Alberta includes:

- Coal Mining: Alberta Energy Regulator (AER) notes that there are extensive coal deposits within the province of Alberta. Alberta's coal contains more than twice the energy of all of the province's other non-renewable energy resources, including conventional oil and pentanes, natural gas, natural gas liquids, and bitumen and synthetic crude, and is generally low in sulphur and therefore burns relatively clean compared to many coals mined around the world. Alberta Energy Regulator (2015) provides detailed information on number of mines, coal reserves, production and disposition, by coal type and by destination. Currently, there are 10 permitted coal mines in the province within the Athabasca sub-basin, and 5 within the Peace River sub-basin. Of those permitted mines, in 2015, two were in operation in the Athabasca sub-basin, as well as two in the Peace sub-basin. The remaining coal mines are no longer being operated or have not begun production (Alberta Energy Regulator, 2015). Historic coal mines are also located in the database.
- Oil Sands Mining: Alberta Environment states that Alberta's oil sands are the third-largest proven crude oil reserve in the world, with oil sands production is expected to increase from 2.3 million barrels per day in 2014 to 4 million barrels per day in 2024 (Alberta Energy, 2014d). The oil sands mining activities are predominantly located within the Athabasca and Peace sub-basins in Alberta, as shown in Figure 23.
- Mineral Mining: According to Alberta Energy (2016), non-energy minerals excavated and mined in Alberta today include sand and gravel, sandstone and other building stone, iron and magnetite, and gold. Salt and limestone continue to be the leading non-fuel minerals produced in Alberta. Other minerals produced or potentially available in Alberta include metallic minerals, diamonds, ammonite, and other precious stones, industrial minerals and stone. Presently, there are no metal mines active in Alberta. There are five limestone quarries, and two in-situ leaching salt mines active in the Athabasca sub-basin of Alberta (Alberta Energy, 2015). There is one active silica sand quarry in the Peace sub-basin (Alberta Energy, 2015). Additionally, Alberta has hundreds of sand and gravel pits of various sizes. A map of non-energy mining operations in Alberta is shown in Figure 24.

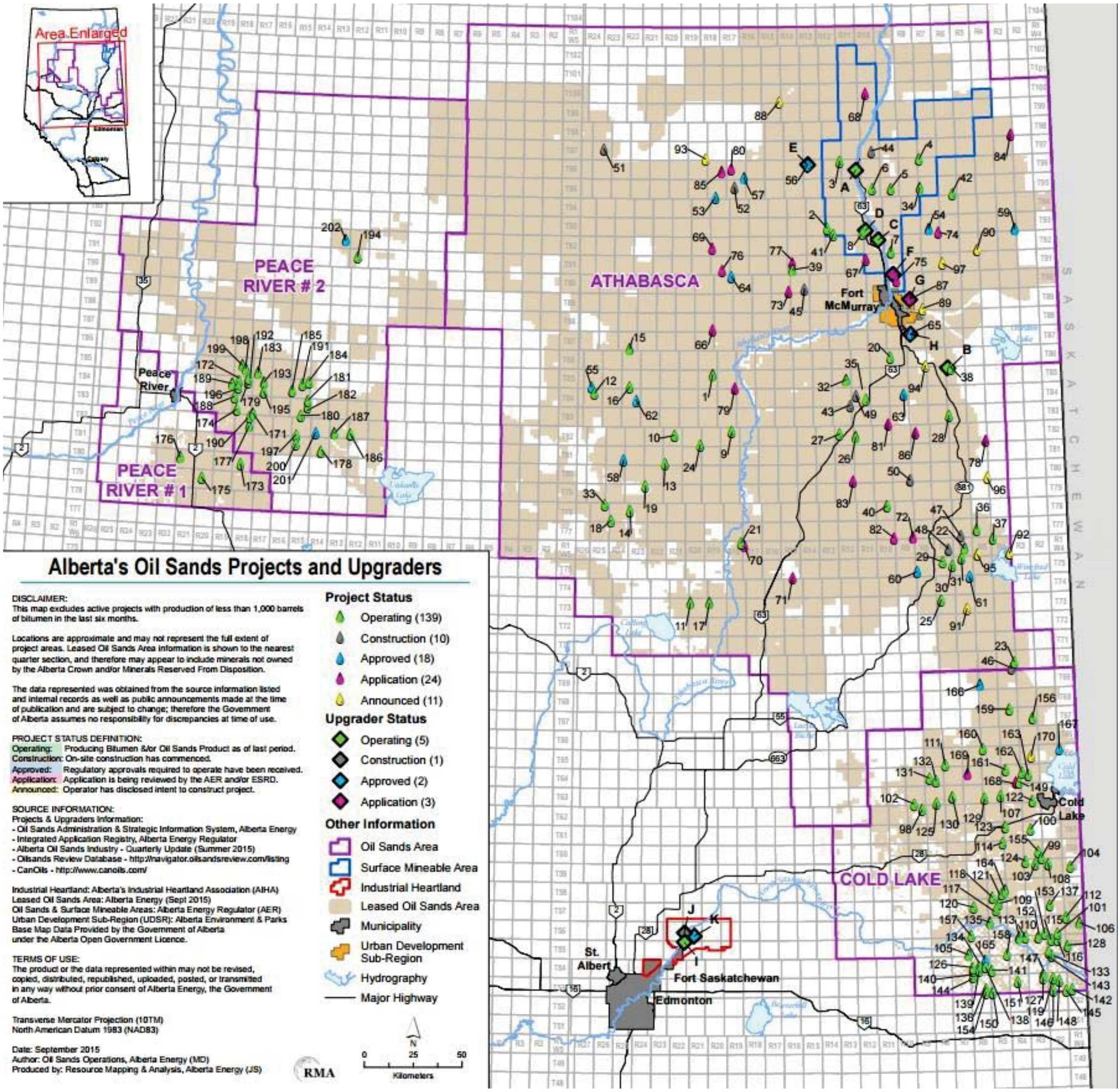


Figure 23. Map of Alberta's Oil Sands Projects and Upgraders (Alberta Energy, 2014d).

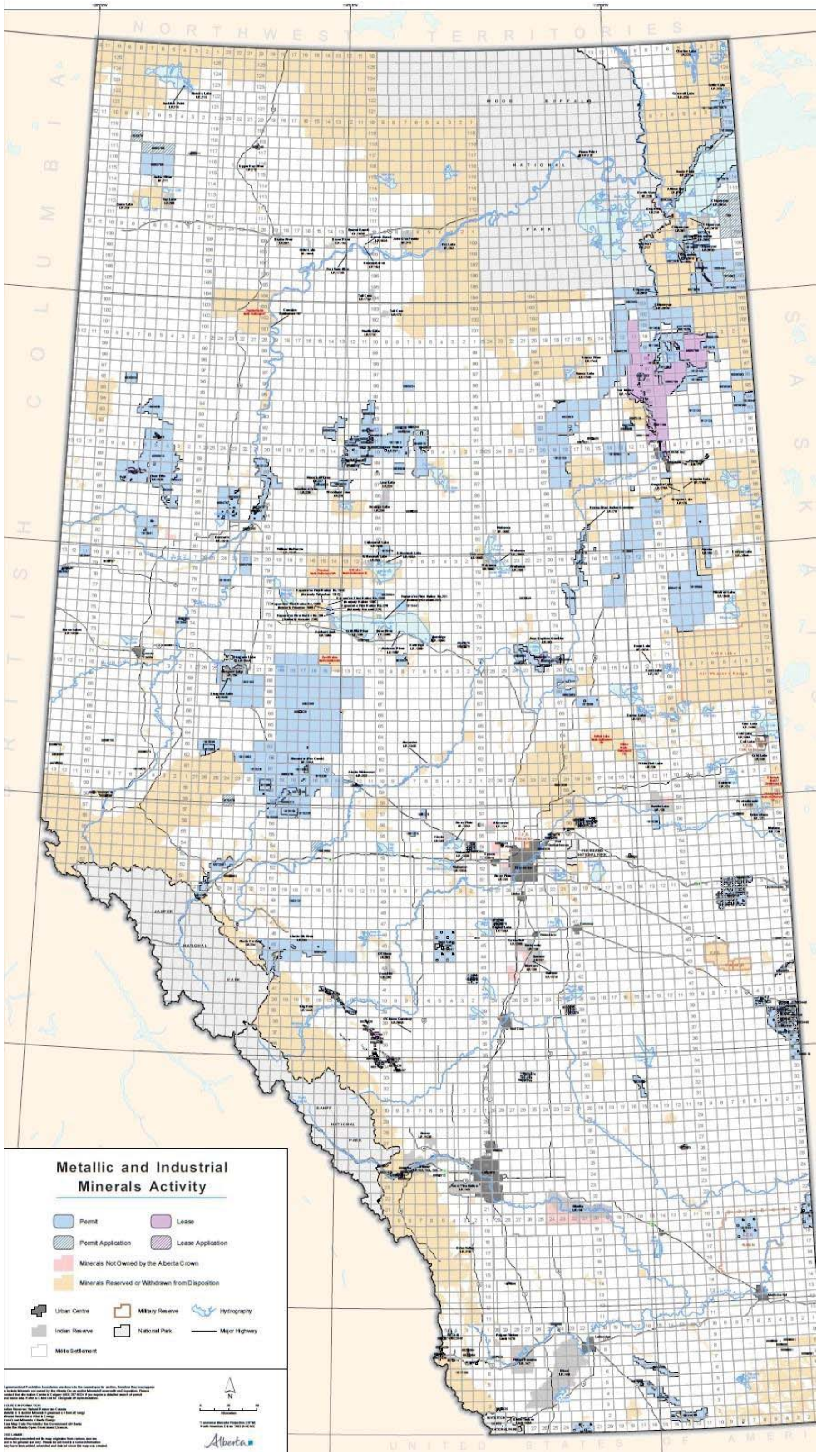


Figure 24. Map of Alberta's metallic and industrial minerals activity (Alberta Energy, 2016).

4.2.3 Oil and Gas

Oil and natural gas production in Alberta is broken down into conventional and unconventional, and described herein. Unconventional oil production in Alberta is produced from oil sands deposits, and is described in Section 4.2.2 Mining above. Details of oil and gas production include:

- Conventional Gas: Alberta accounts for 67% of the natural gas produced in Canada. It is estimated that 32.4 trillion cubic feet of recoverable, conventional natural gas can still be extracted (Alberta Energy, 2014a). As of 2014, there are 1,824 conventional natural gas wells drilled in Alberta (Figure 25). Wells are in the Transboundary Areas are predominantly located in the Athabasca and Peace sub-basins, but are also found further north in the Liard and Great Slave sub-basins. Wood Buffalo National Park in northeastern Alberta is more or less the only part of the Transboundary Areas in Alberta without natural gas wells. Injection wells associated with recovery (noted in Section 3.2 above) are an added source of groundwater contamination.
- Conventional Oil: Conventional crude oil is produced by drilling wells. It is differentiated from non-conventional crude oil by the method used for extraction, and by geography (Alberta Energy, 2014b). As of 2014 for conventional oil, 2,808 successful oil wells were drilled, out of a total of 4,668 oil well drilled (Figure 25). Wells are in the Transboundary Areas are predominantly located in the Athabasca and Peace sub-basins, but are also found further north in the Liard and Great Slave sub-basins. Wood Buffalo National Park in northeastern Alberta is more or less the only part of the Transboundary Areas in Alberta without oil wells. Injection wells associated with recovery (noted in Section 3.2 above) are an added source of groundwater contamination.
- Unconventional Oil and Gas: Unconventional drilling methods are used to develop coalbed methane and shale gas in Alberta. Per Alberta Energy (2014c), the same techniques used for conventional shallow gas development may also be used with shale gas drilling. Shale gas can be produced from vertical and directional wells. However, due to the low permeability that is characteristic of shale formations, horizontal drilling and stimulation techniques such as multi-stage hydraulic fracturing are often required to achieve economic production. Vertical and directional shale wells are commonly commingled with other production zones to yield economic production. According to Alberta Energy Regulator (2014), 179,000 wells have been fractured up to 2014, and more than 9,000 horizontal wells have used multistage fracturing. Figure 26 shows the potential for unconventional gas production in Alberta, which includes areas within the southern reaches of the Athabasca and Peace sub-basins of Alberta.

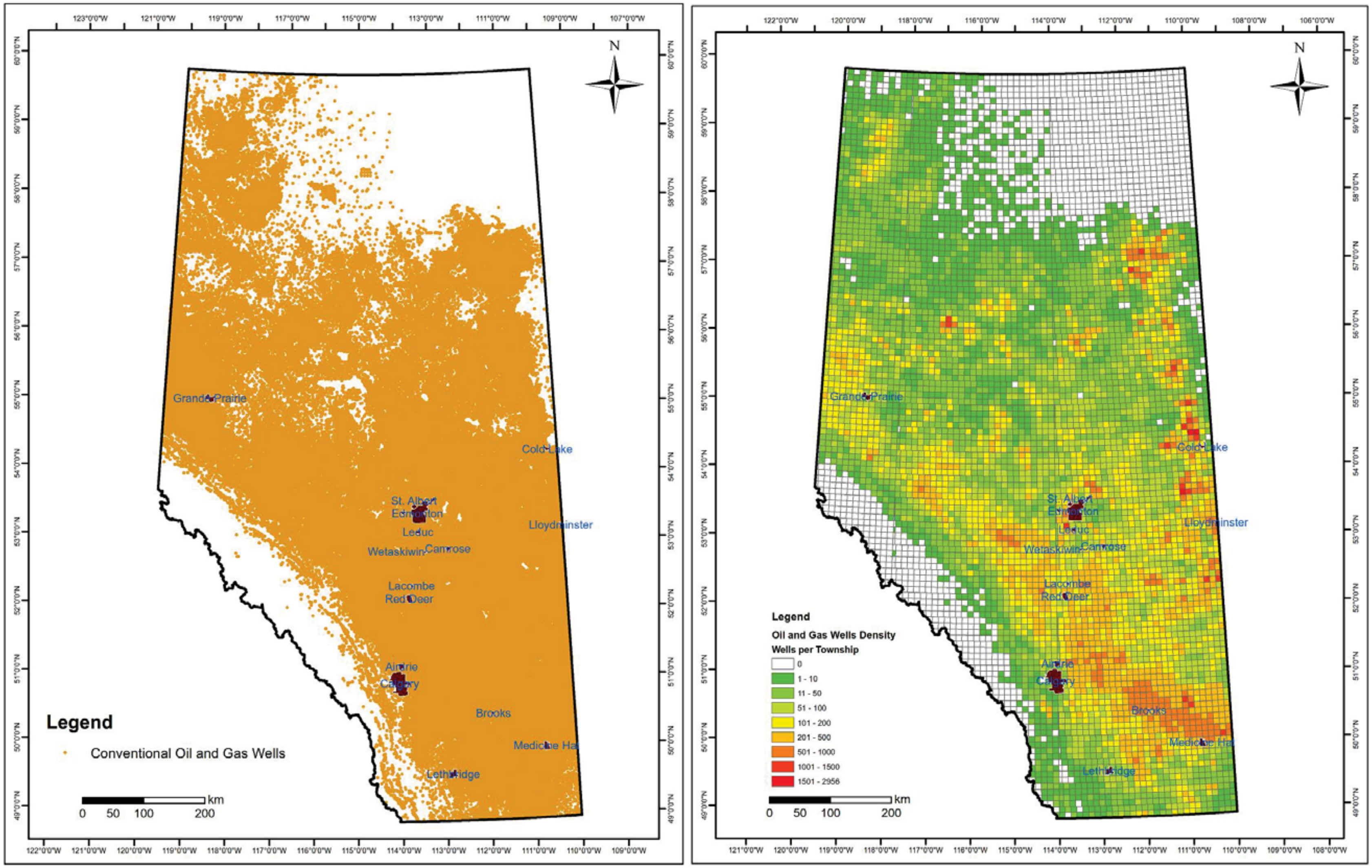


Figure 25. Map of Alberta showing conventional oil and gas well locations provided by Alberta Environment and Parks (Guha, 2016).

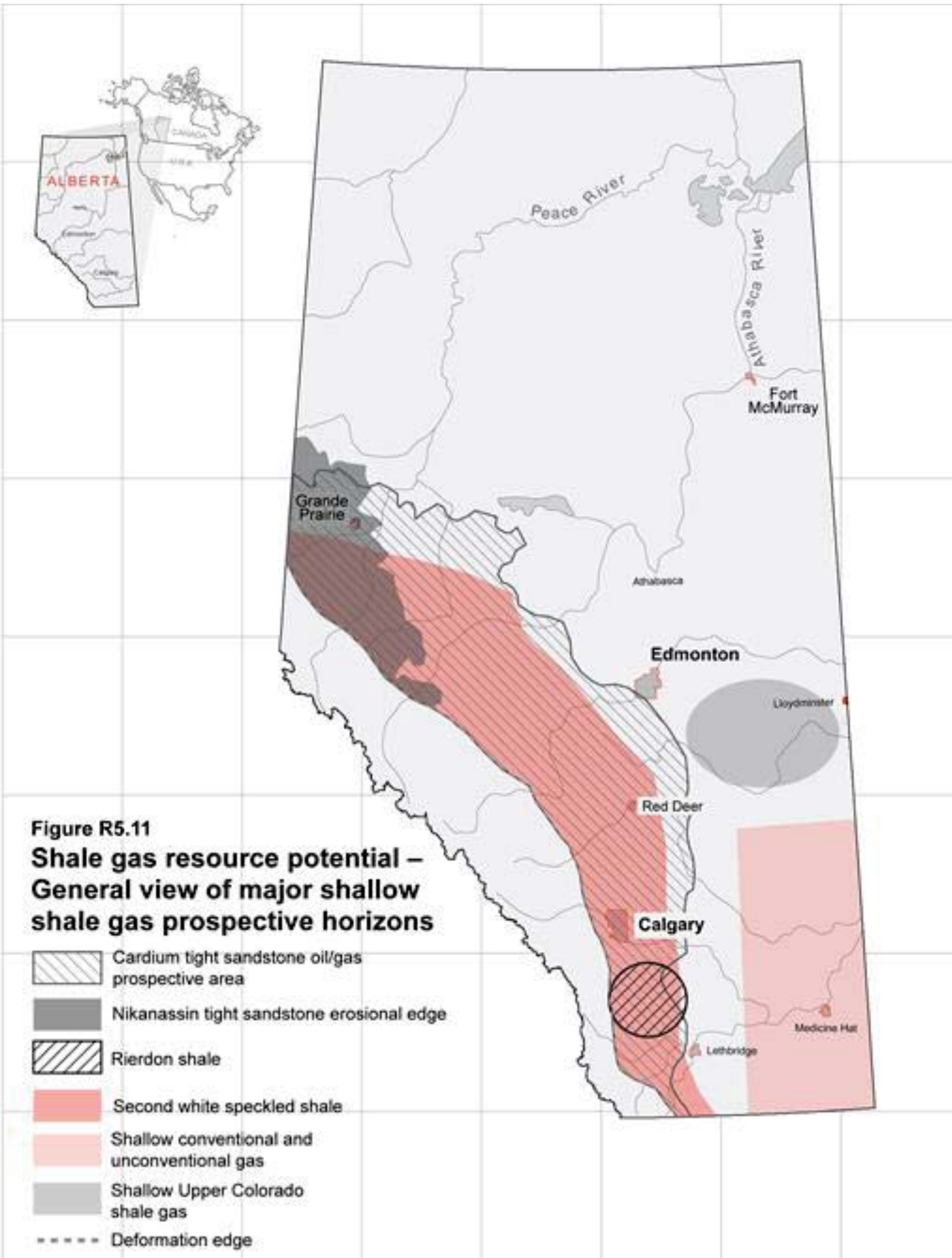


Figure 26. Map of Alberta showing shale gas resource potential .

4.3 British Columbia

4.3.1 Environmental Remediation Sites

The British Columbia Data Catalogue (Government of British Columbia, 2016b) maintains an online dataset (Government of British Columbia, 2016c) that contains known and potentially contaminated proprieties in British Columbia, and states that “a site is contaminated if its land, water and/or sediment are unsuitable for particular uses from waste that exceeds environmental quality standards.” The Ministry of Environment is currently modernizing this dataset, and as such states that the data will be unavailable to the public while the dataset is being modernized. Normal service is expected to resume by the end of March 2016.

4.3.2 Landfills

A catalogue of community landfills in the Transboundary Area of British Columbia was unavailable on the British Columbia Data Catalogue (Government of British Columbia, 2016b), however the Transboundary Area of British Columbia consists of a geographic region that predominantly includes the Peace River Regional District (PRRD), roughly the Peace sub-basin, and the Northern Rockies Regional Municipality (NRRM), which includes both the Liard and Great Slave sub-basins.

The PRRD operates three landfills throughout the region that accept a variety of items including household waste, bulky waste, wood waste, metal waste, tires, concrete and numerous others (Peace River Regional District, 2016). These landfills do not accept liquid waste, hazardous waste, smoldering ashes, and oil, gas and industrial waste. The PRRD also operates a series of transfer stations in rural locations to increase the level of service to residents, which include two types of transfer stations (Tier 1 and Tier 2):

- Tier 1 Transfer Station – Accepts items such as household recycling, household waste, bulky waste, wood waste, metal waste, and stewardship items such as tires and lead acid batteries.
- Tier 2 Transfer Stations – Accepts household recycling and household garbage.

The PRRD solid waste network is shown in Figure 27.

The NRRM operates one community solid waste landfill in Fort Nelson. Due to the sparse population of the NRRM, there is no network of transfer stations, rather routine pick waste pick up is maintained along the Alaska Highway along its entirety within the NRRM weekly in summer months, and bi-weekly in winter months (Northern Rockies Regional Municipality, 2015).

Several industrial waste facilities (Tervita, 2016) are operated within the Transboundary Area (Figure 28) including:

- Bioremediation facilities;
- Engineered landfills;
- Salt water disposal facilities; and
- Treatment recovery and disposal facilities.

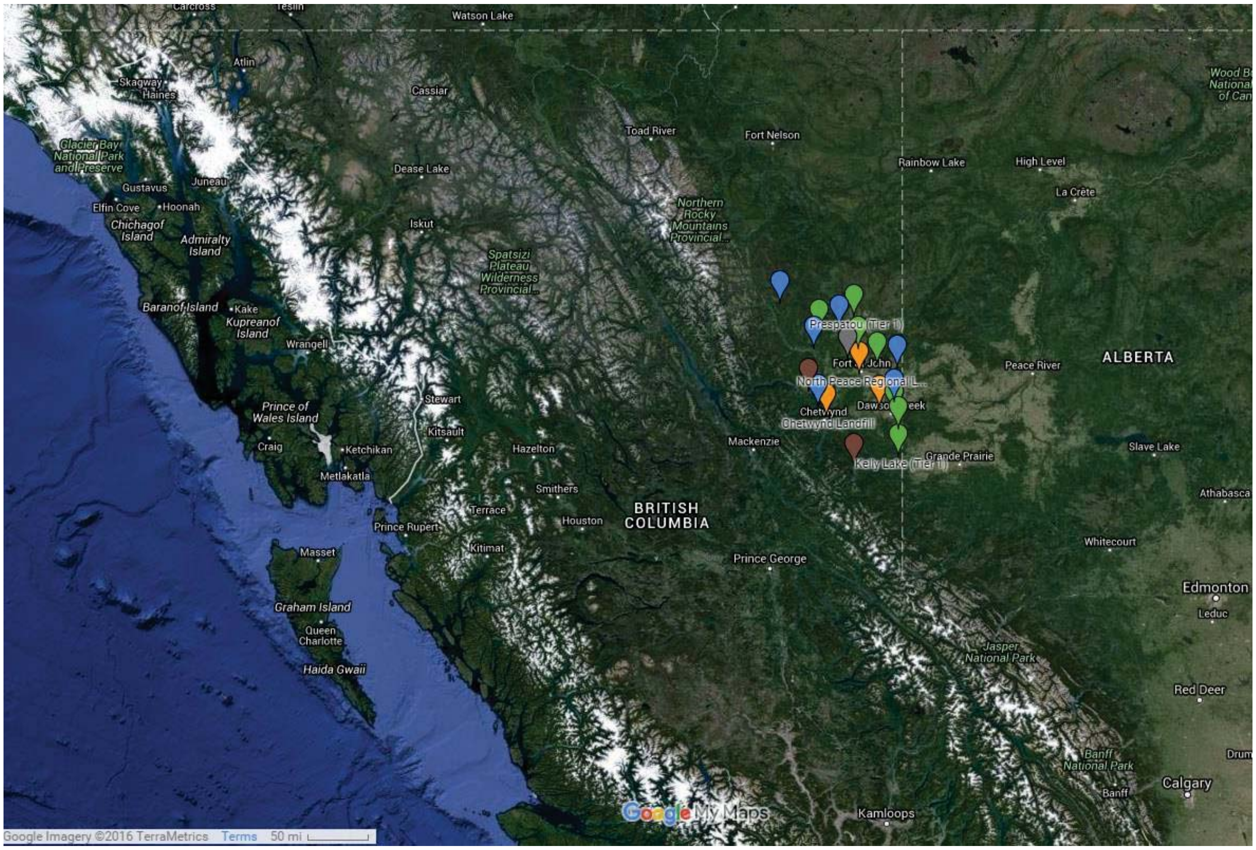


Figure 27. Map of Northern British Columbia showing PRRD landfills and transfer stations (Peace River Regional District, 2016).

Figure 28. Map of Northern British Columbia showing industrial waste facilities: light orange = bioremediation facilities, green = engineered landfills, light blue = salt water disposal facilities, dark blue = treatment recovery and disposal facilities, dark orange = field offices (Tervita, 2016).

4.3.3 Mining

The predominant type of mines operated in the Transboundary Area of British Columbia includes coal mines, and more recent exploration projects for copper. Figure 29 shows the location and status of major exploration projects and producing metal, coal, and industrial mineral mines in 2015 across British Columbia. There are three industrial mineral mines operating in the Liard sub-basin, as well as, one metal mine under development, and two advanced exploration projects. The Peace sub-basin has one operating industrial mineral mine, one operating metal mines, one mine in care and maintenance, and four operating coal mines, as well as 24 advanced exploration projects. Mount Milligan is the only operating metal mine in the Mackenzie River Basin.

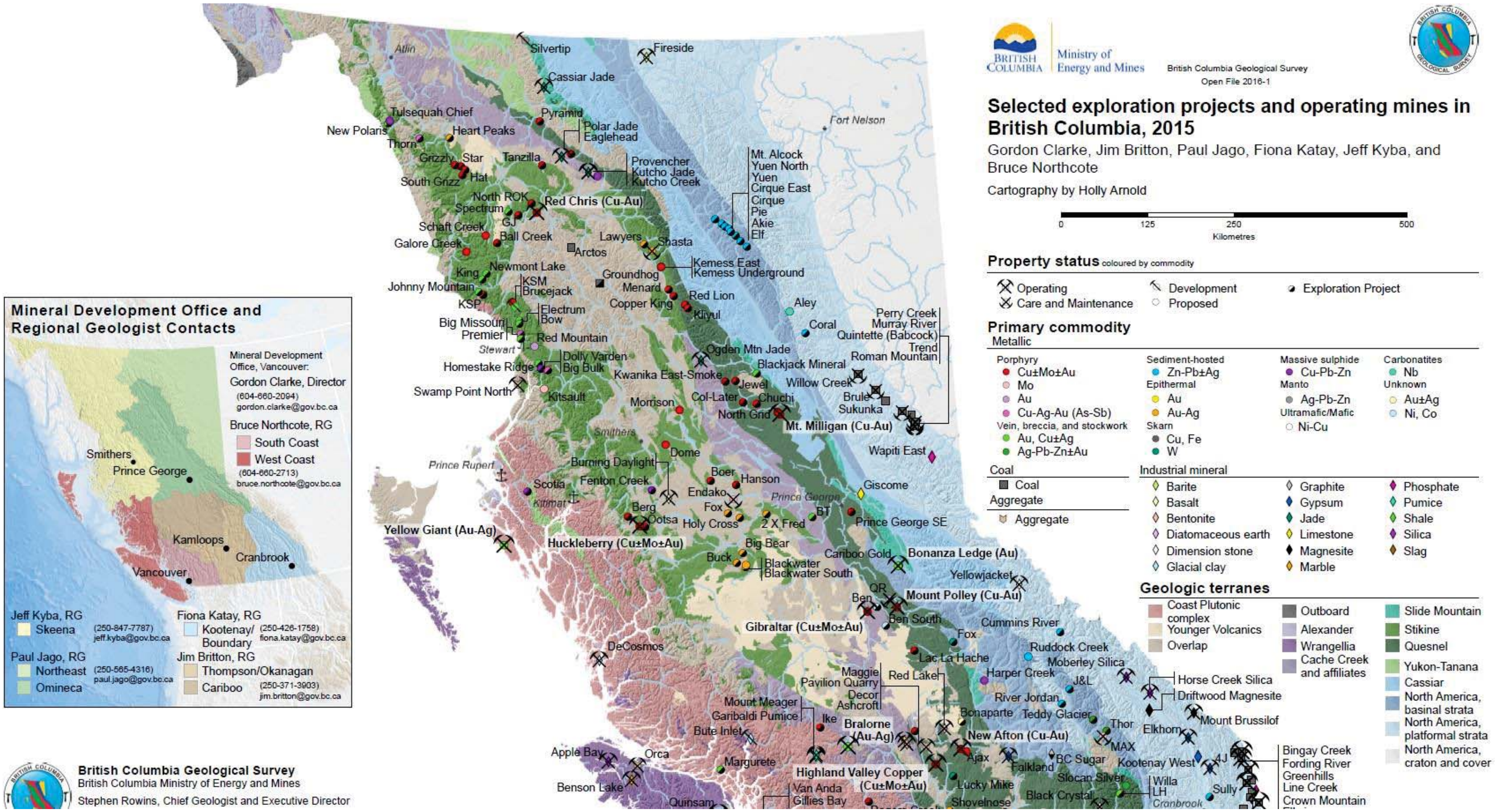


Figure 29. Map of British Columbia showing locations of operating mines and exploration projects in 2015 (British Columbia Ministry of Energy and Mines, 2015b).

4.3.4 Oil and Gas

Oil and gas development in British Columbia is referred to as either conventional or unconventional. According to British Columbia Oil and Gas Commission (2013), conventional oil and gas exploration is the exploration and development of porous and permeable rock formations in the subsurface. These types of reservoirs are typically less than 20 metres in thickness and have well defined and limited areal extent. By comparison, unconventional reservoirs such as fine grained sandstones, siltstones and shales occur over large areas and individual formations can reach thicknesses in excess of 300 metres. There are a number of surface requirements for development. During both conventional and unconventional drilling operations, sumps or tanks are used to contain drilling and waste fluids; pipelines connect all producing gas and oil wells to markets and wellpads are accessed by a combination of all-season and/or winter access roads, and occasionally by air.

The northeast area of British Columbia is within the Transboundary Area, including parts of Liard, Great Slave, and Peace sub-basins, and is a part of the Western Canada Sedimentary Basin (WCSB). This is the only area of British Columbia currently producing commercial quantities of oil and gas (British Columbia Ministry of Energy and Mines, 2007). Figure 30 shows the areas of conventional oil and gas potential in British Columbia.

British Columbia has substantial tight gas and shale gas resource potential. New shale gas discoveries and advancements in shale and tight gas extraction technology have expanded British Columbia's unconventional gas opportunities. Conservative estimates indicate a gas-in-place of 1,200 trillion cubic feet (Tcf) of shale gas and 300 Tcf of tight gas in northeast British Columbia (British Columbia Ministry of Energy and Mines, 2015a).

British Columbia Oil and Gas Commission (2013) states that of the 17.5 million hectares (ha) of land in northeastern British Columbia, approximately 375,600 ha is used for both conventional and unconventional oil and gas activities, or roughly 2.14% of the overall reporting area. The surface footprint includes wells, roads, facilities, pipelines, seismic lines (from geophysical activities) and other oil and gas infrastructure (such as camps).

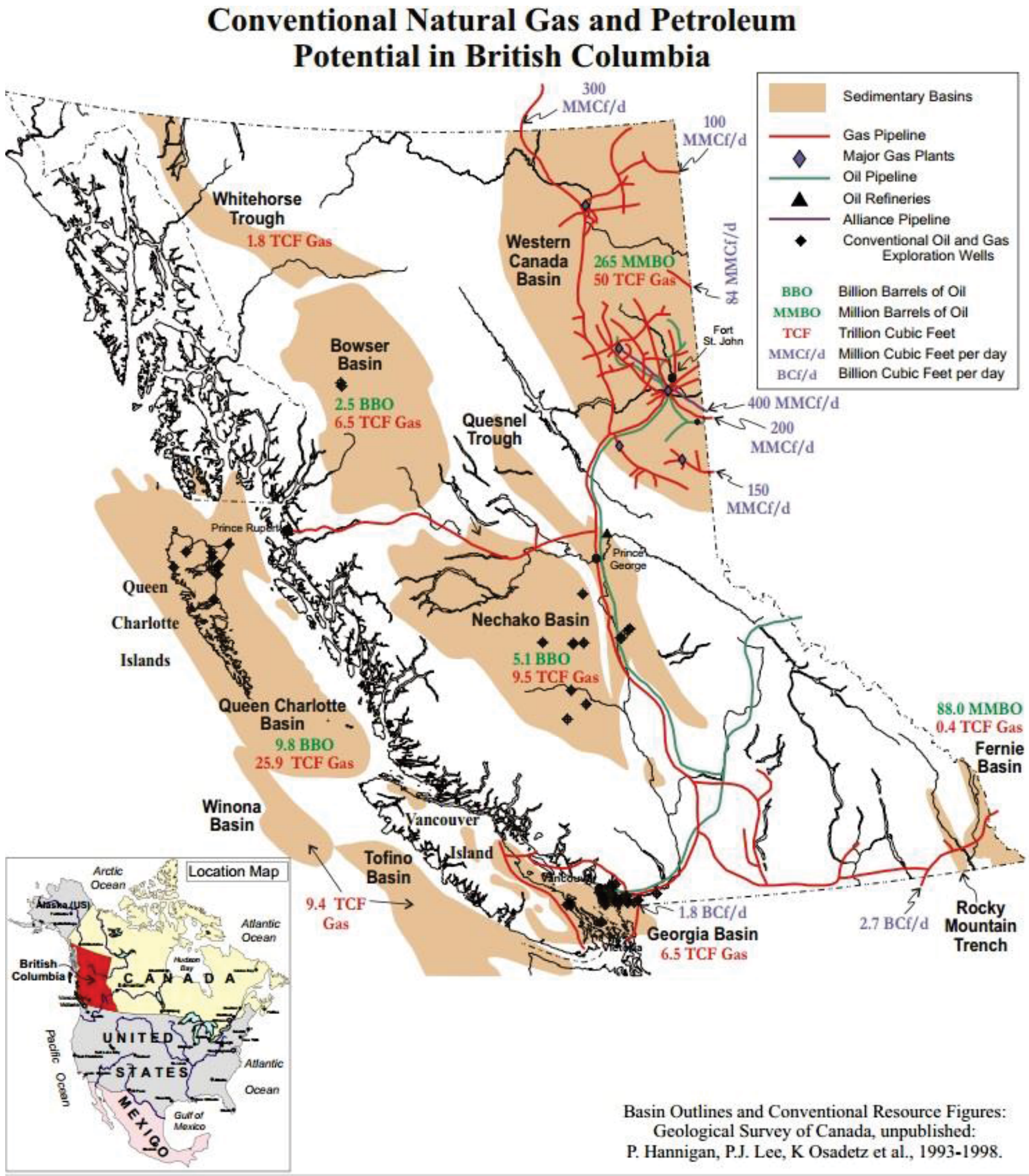


Figure 30. Map of British Columbia showing locations conventional oil and gas potential (British Columbia Ministry of Energy and Mines, 2007).

4.4 Saskatchewan

4.4.1 Environmental Remediation Sites

There are 1,580 federal contaminated sites in Saskatchewan (Treasury Board of Canada Secretariat, n.d.). Only three of these locations are considered high priority for remediation, and only one is located in the Mackenzie River Basin (Athabasca sub-basin) (Figure 31). There is approximately 15,000 m^3 of petroleum hydrocarbon contamination near the First Nation's community of Fond-du-Lac, which has the potential to contaminate local groundwater sources. The Saskatchewan Research Council is currently in the process of remediating two uranium mill and mine sites, as well as 35 satellite uranium mines near Uranium City in the Athabasca sub-basin (Figure 18) (Saskatchewan Research Council, n.d.).

4.4.2 Landfills

Four communities were identified in northern Saskatchewan as potentially having landfill sites (Figure 18). All were located within the Athabasca sub-basin.

4.4.3 Mining

As discussed above, there are a large number of abandoned uranium mines being remediated in the region that have the potential to impact water quality. Future mineral exploration and production will be the most likely source of contamination to groundwater.

4.4.4 Oil and Gas

A limited number of oil and gas exploration wells have drilled in the southwest region of the Athabasca sub-basin, Saskatchewan (Figure 18).

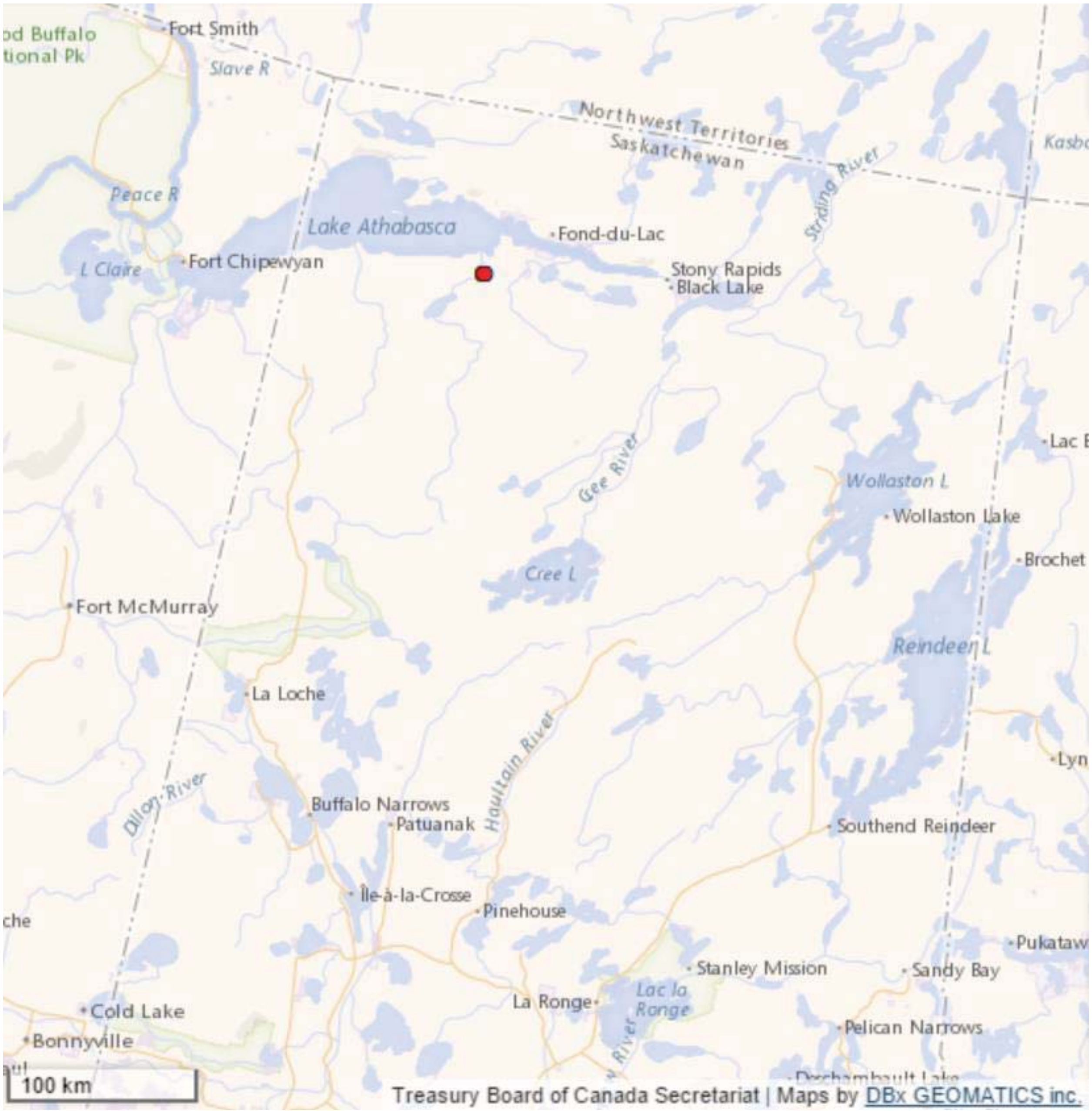


Figure 31. High priority federal contaminated sites in Saskatchewan (Treasury Board of Canada Secretariat, n.d.).

4.5 Yukon

4.5.1 Environmental Remediation Sites

There are 21 federal contaminated sites in the Yukon that are considered high priority for remediation (Figure 32) (Treasury Board of Canada Secretariat, n.d.); two of these are located in the Liard sub-basin near Watson Lake, while no high priority sites are located in the Peel sub-basin.

4.5.2 Landfills

Watson Lake and the adjacent community of Upper Liard were the only communities in the Yukon with a landfill inside the Mackenzie River Basin (ARKTIS, 2012); both are located in the Liard sub-basin. The Watson Lake landfill acts as a regional waste disposal facility for all communities located in the Liard sub-basin, Yukon (Figure 33). Historic landfills and dump sites were not located as part of this report.

4.5.3 Mining

Three active water licences associated with mine sites and advanced exploration projects were identified in the Liard sub-basin in southeastern Yukon (Figure 19); the Sa Dena Hes Mine is permanently closed and is undergoing active reclamation; the Wolverine Mine is currently in a state of temporary closure due to low commodity prices; the Kudz Ze Kayah Project is an advanced exploration project. These lead-zinc mining operations have the potential to reduce the quantity of groundwater in an adjacent aquifer or alter groundwater flow during dewatering operations, and also have the potential to contaminate groundwater during post-closure flooding.

4.5.4 Oil and Gas

Oil and gas wells in the Yukon are shown in Figure 19 (The Government of Yukon, 2014). The oil gas wells are located in the following parts of the Mackenzie River Basin: the Liard Basin (geological) in the Liard sub-basin (watershed), southeastern Yukon; the Peel Plateau in the Peel sub-basin, northwestern Yukon; and the southern tip of Eagle Plains, in the Peel sub-basin, north-central Yukon. Although there are presently no producing oil or gas wells in the Yukon, future operations may occur in these same areas.

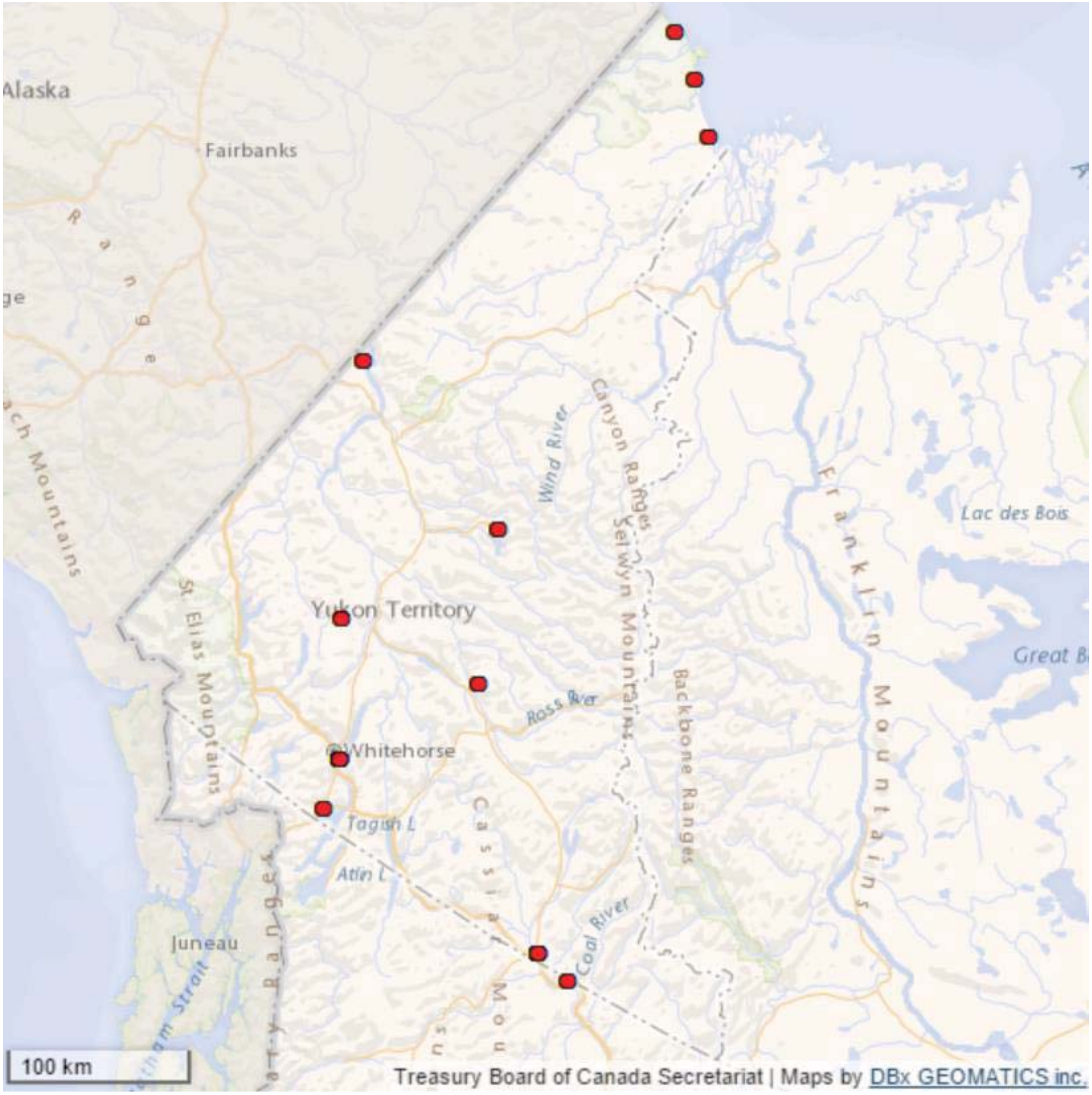


Figure 32. High priority federal contaminated sites in the Yukon (Treasury Board of Canada Secretariat, n.d.).

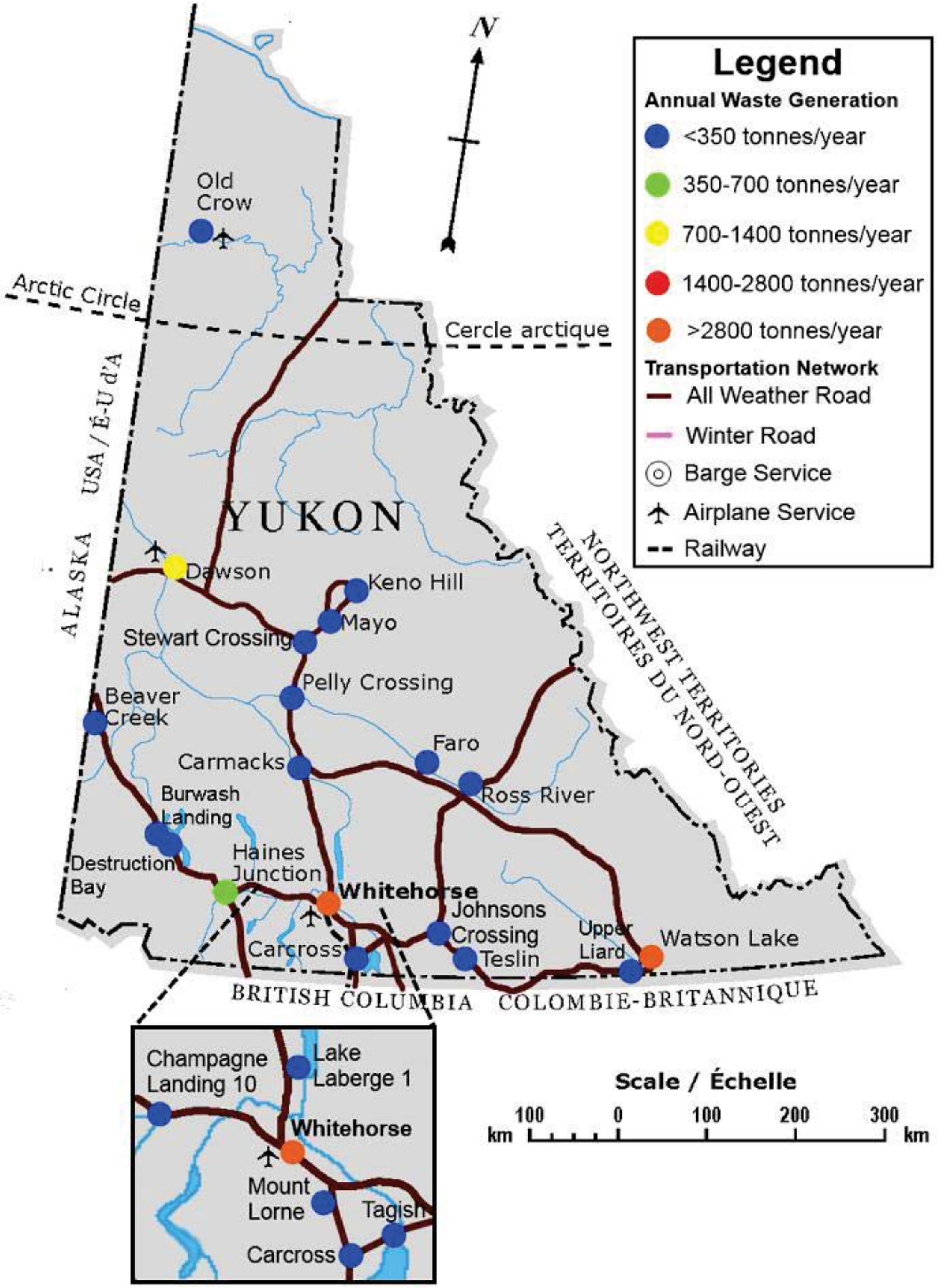


Figure 33. Location of community landfills and estimated annual waste generation in the Yukon (ARKTIS, 2012).

4.6 Summary

Table 9. Summary of the state of knowledge for potential impacts to groundwater by stakeholder jurisdiction.

Source of Impact	Summary of the State of Knowledge for Potential Impacts to Groundwater by Stakeholder Jurisdiction				
	Northwest Territories	**Alberta**	**British Columbia**	**Saskatchewan**	**Yukon**
Environmental Remediation Sites	Database of federal contaminated sites. Does not include private or territorial contaminated sites. Potential impact to groundwater not assessed in this report.	Provincial database of contaminated sites. Database of federal contaminated sites. Potential impact to groundwater not assessed in this report.	Provincial database of contaminated sites. Database of federal contaminated sites. Potential impact to groundwater not assessed in this report.	Database of federal contaminated sites. Does not include private or provincial contaminated sites. Potential impact to groundwater not assessed in this report.	Database of federal contaminated sites. Does not include private or territorial contaminated sites. Potential impact to groundwater not assessed in this report.
Landfills	This report has assumed landfills to be associated with communities in the NT. Impacts would likely be restricted to shallow aquifers due to the prevalence of permafrost. Potential impact to groundwater not assessed in this report.	Database of active landfills and historic dump sites. Potential impact to groundwater not assessed in this report.	Database of active landfills and waste disposal facilities. Potential impact to groundwater not assessed in this report.	This report has assumed landfills to be associated with communities in northern SK. Impacts may be reduced due to permafrost. Potential impact to groundwater not assessed in this report.	One landfill was identified in YK portion of the basin. Historic landfills and dump sites may be located elsewhere. Impacts may be reduced due to permafrost. Potential impact to groundwater not assessed in this report.
Mining	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	No licensed mines in region. The locations of advanced exploration projects were not identified in this report. Impacts to groundwater would be predicted during environmental assessment and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.	Database of licensed mines, and advanced exploration projects. Impacts to groundwater are predicted during environmental assessment, and assessed over the mine life. Abandoned mines have been considered under environmental remediation sites.
Oil and Gas	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment	Database of historic, and exploration oil and gas wells. No production has occurred in the region. . Impacts to groundwater would be predicted during	Database of historic, producing and exploration oil and gas wells. Impacts to groundwater are predicted during environmental assessment

Source of Impact	Summary of the State of Knowledge for Potential Impacts to Groundwater by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
	and assessed during production phase.	and assessed during production phase.	and assessed during production phase.	environmental assessment and assessed during production phase.	and assessed during production phase.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;
Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
Red = Data is unavailable or not recorded and will result in gaps within Learning Plans.

5.0 GROUNDWATER MONITORING

A network of observation wells is critical to understanding groundwater use on aquifer levels and to the quality of groundwater. Identified monitoring in each of the Transboundary Area stakeholder jurisdictions is provided below.

5.1 Northwest Territories

The communities of Fort Liard (Mackenzie Valley Land and Water Board, 2010), in the Liard sub-basin, and Whatì (Mackenzie Valley Land and Water Board, 2007), in the Great Slave sub-basin, are both required by their respective water licences to record the monthly and annual quantity of groundwater withdrawn.

Mine sites in the Northwest Territories (Figure 8), whether active, in temporary closure, or in reclamation, are required to monitor the quality and quantity of mine water and groundwater for contamination from mine operations. Currently these mine sites include Cantung (Mackenzie Valley Land and Water Board, 2016) and Prairie Creek (Mackenzie Valley Land and Water Board, 2013a) mines in the Liard sub-basin, southwestern Northwest Territories, Snap Lake (Mackenzie Valley Land and Water Board, 2014b) and Gahcho Kué (Mackenzie Valley Land and Water Board, 2014a) mines in the Great Slave sub-basin, southeastern Northwest Territories, which are required by their respective water licences to monitor groundwater quality and/or mine water discharge. Some abandoned mine sites in the Northwest Territories have ongoing long term groundwater monitoring programs, such as Con Mine (Mackenzie Valley Land and Water Board, 2008) and Giant Mine (Indigenous and Northern Affairs Canada, 2015). These groundwater monitoring programs are on a local scale, and therefore have not been reviewed in detail at this time. Groundwater monitoring may occur in the future at advanced exploration projects, such as the NICO deposit, and the Nechalacho deposit in addition to groundwater baseline studies that may have already been completed.

5.1.1 Liard Basin

There are few companies with active water licences in the Liard Basin (geological) area of the Northwest Territories, near the British Columbia and Yukon borders. The following sites are located within 100 km of the Northwest Territories boarder.

- Apache Canada Ltd. (Apache): Apache's water licence (Mackenzie Valley Land and Water Board, 2014c) is for testing of a single injection well, approximately 30 km northwest of Fort Liard. The water licence does not require Apache undertake any groundwater monitoring. The water licence expired on August 27, 2015.
- Paramount Resources Ltd. (Paramount): Paramount has two active water licences near Fort Liard. Type 'B' Water Licences MV2013L1-0002 and MV2013L1-0003 are for care and maintenance of Natural Gas Facilities (Mackenzie Valley Land and Water Board, 2013c, 2013d); no groundwater monitoring is required for either water licence. Type 'B' Water Licence MV2009L1-0006 for the suspended Liard Project also does not require groundwater monitoring (Mackenzie Valley Land and Water Board, 2009). The limited scope of the water licences may be attributed to the current state of the project (i.e., no production, maintenance, reclamation).

5.1.2 Cameron Hills

There is one company with an active water licence in the Cameron Hills area of the Northwest Territories near the Alberta border:

- Strategic Oil and Gas Ltd. (Strategic): Strategic has an active Type ‘A’ water licence, MV2010L1-0001, for exploration, development, and production of oil and gas in the Cameron Hills area (Mackenzie Valley Land and Water Board, 2013b). The water licence permits 60 planned and constructed wells. No groundwater monitoring has been completed at Cameron Hills by Strategic since acquiring the project from Paramount in 2013 (Strategic Oil and Gas Ltd., 2015). Operations at the Cameron Hills oil and gas field are currently suspended.

5.2 Alberta

Groundwater monitoring in Alberta is performed via the Groundwater Observation Well Network (GOWN), which is an Alberta Government-owned network of groundwater monitoring wells located in various aquifers throughout the province. Most wells are fitted with data loggers and sensors that continually record groundwater levels. In addition, many of these well are periodically pumped and sampled for water quality analysis. Currently, there are over 250 active observation wells across the province. Regional technologists maintain the wells, collect the data, sample the wells and archive the data into departmental databases. Current and historical groundwater level for the active and inactive wells in the GOWN can be accessed from Alberta Environment and Parks (2016b). The locations of the GOWN wells for water levels, and the wells used to examine groundwater chemistry are shown in Figure 34. Observation wells in the Transboundary Area of Alberta are relatively sparse, compared to other areas of the Province.

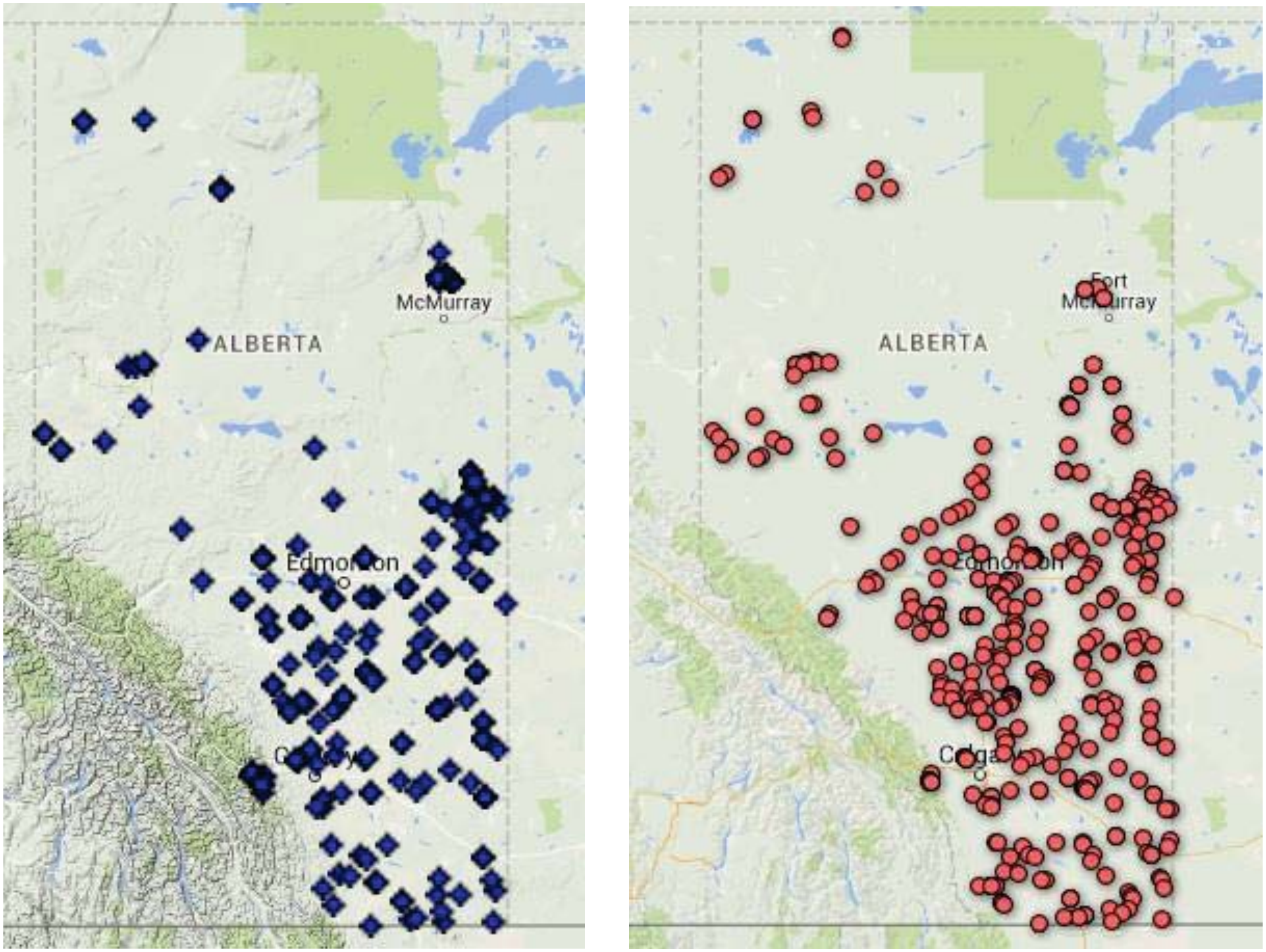


Figure 34. Map of Alberta showing GOWN well locations for water levels (blue) and water quality (red) (Alberta Environment and Parks, 2016b).

5.3 British Columbia

Groundwater monitoring in British Columbia is performed using the British Columbia Observation Well Network (BCOWN). As of July 2009, there were 145 active observation wells in the network covering major groundwater areas of the province (Government of British Columbia, 2015). The primary purpose of the Observation Well Network is to collect, analyze and interpret groundwater hydrographs and groundwater quality data from various developed aquifers in British Columbia. Observation wells are equipped with automatic water level recorders or data loggers that monitor on a continuous basis. Some sites are monitored manually with a wetted tape by local observers. Each year about 25 observation wells are sampled for complete inorganic chemical analysis. Criteria for selecting sampling frequency of observation wells are based on physical characteristics of aquifer development, well construction and water quality trends (Government of British Columbia, 2015). Many of the wells are monitored in cooperation with irrigation districts, and communities utilizing groundwater supplies. Information on the BCOWN is available to the public. Figure 35 shows the locations of observation wells across British Columbia. There are approximately 10 monitoring wells located within the Transboundary Area of British Columbia.

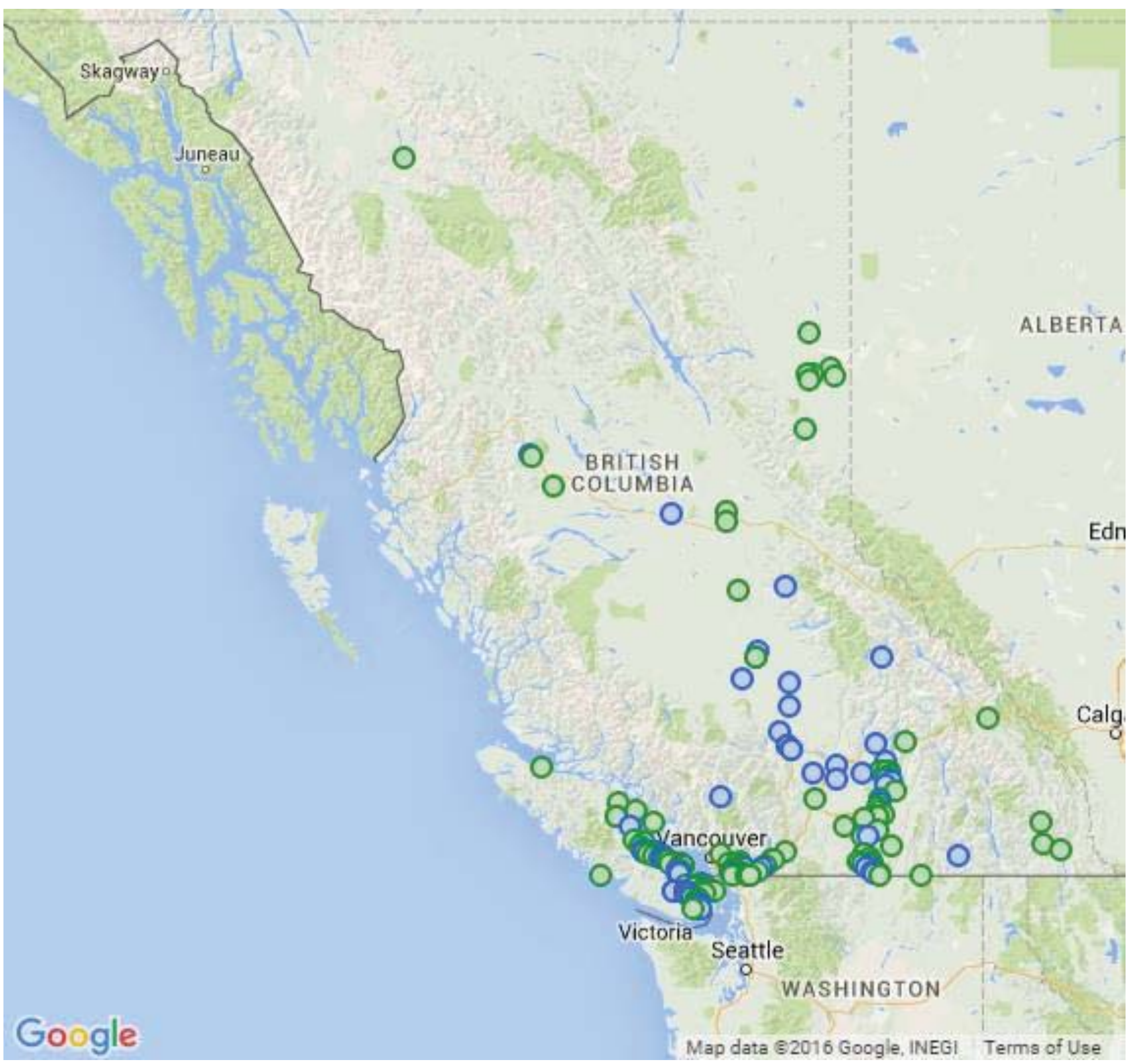


Figure 35. Map of British Columbia showing BCOWN well locations; green denotes wells with real time data; blue denotes wells without real time data (Government of British Columbia, 2015).

5.4 Saskatchewan

No groundwater monitoring programs were identified occurring at a regular interval in the northern Saskatchewan area of the Mackenzie River Basin. Although most of the mine sites in the region have already undergone reclamation, there is a possibility that environmental monitoring agencies will return to these sites to collect long-term monitoring data. The Saskatchewan Observation Well Network monitors groundwater level and quality, but has no wells located in the northern half of the province or Mackenzie River Basin (Saskatchewan Water Security Agency, n.d.).

5.5 Yukon

The Yukon Observation Well Network (YOWN) collects information on long-term trends in groundwater, but is focused on areas where there is infrastructure (Environment Yukon, 2015b). YOWN collects data on groundwater levels and quality. Currently there are 24 different active sites, however, none of these are located in the Mackenzie River Basin. The Yukon Government is also collaborating with the University of Calgary to develop baseline monitoring techniques that will aid in assessing potential impacts to groundwater from oil and gas projects, including hydraulic fracturing (Environment Yukon, 2015a).

Watson Lake, located in the Liard sub-basin, is the only community in the Yukon part of the Mackenzie River Basin with a landfill (The Government of Yukon, 2014). The Yukon requires groundwater monitoring wells be analyzed twice yearly for the parameters listed in Table 10 (Environment Yukon, 2012b).

The three mine sites and advanced exploration projects in the Liard sub-basin, southeastern Yukon (Figure 19) are required by their respective water licences to monitor groundwater quality and/or mine water discharge (Table 10).

Table 10. Groundwater monitoring locations in the Mackenzie River Basin, Yukon.

Mine/Project	Number of Monitoring Stations	Sampling Frequency	Parameters
Watson Lake (landfill)	NA	Biannually	Major ions (calcium, magnesium, sodium, potassium, chloride, sulphate, nitrate, nitrogen, nitrite, and phosphate), dissolved metals, mercury, pH, hardness, carbonate, bicarbonate, ammonia, dissolved organic carbon, volatile organic compounds, chemical oxygen demand, total Kjeldahl nitrogen, extractable petroleum hydrocarbons, volatile petroleum hydrocarbons, fecal coliforms, water level
Sa Dena Hes Mine (mine portals)	2	Monthly	Physical parameters, flow rate, alkalinity, ammonia, sulphate, hardness, total suspended solids, dissolved solids, total metals
Wolverine Mine (dewatering wells)	NA	NA	pH, total suspended solids, ammonia, sulphate, nitrate, dissolved metals
Wolverine Mine (monitoring wells)	24	Quarterly	Physical parameters, major anions (total alkalinity, total acidity, bromide, chloride, fluoride, sulphate), nutrients (ammonia,

Mine/Project	Number of Monitoring Stations	Sampling Frequency	Parameters
			nitrate, nitrite, phosphate), total metals, dissolved metals, water level
Kudz Ze Kayah Project	1 (multiple wells)	Quarterly	Physical parameters, dissolved metals, ammonia, nitrate, nitrite, CN (tot), CN (wad), cyanate, thiocyanate

Notes:
Physical parameters = temperature, conductivity, specific conductivity, pH

5.6 Summary

Table 11. Summary of the state of knowledge for groundwater monitoring by stakeholder jurisdiction.

Monitoring	Summary of Groundwater Monitoring by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Regulatory (Users)	Groundwater users are required by water licences to report the volume of groundwater used, but not necessarily the water level of the aquifer or water quality.	Regulatory monitoring requirements were not assessed as part of this report.	No regulations on groundwater use in province until 2016.	No known users.	Groundwater users are not required to monitor quantity or quality.
Regulatory (Impacts)	Active mining projects and mining projects under remediation are typically required by water licences to monitor groundwater quality if there is a potential for impact. Oil and gas facilities in care and maintenance are often not required to monitor groundwater.	Regulatory monitoring requirements were not assessed as part of this report.	Regulatory monitoring requirements were not assessed as part of this report.	Regulatory monitoring requirements were not assessed as part of this report.	Active mining projects and mining projects under remediation are typically required by water licences to monitor groundwater quality if there is a potential for impact. No oil and gas projects are active.
Provincial or Territorial Monitoring Network	No territorial groundwater monitoring network.	Provincial monitoring network, but limited number of wells in north. Continuously monitors groundwater level, and periodically water quality.	Provincial monitoring network, but limited number of wells in north. Continuously monitors groundwater level, and periodically water quality.	Provincial monitoring network, but no wells in basin. Continuously monitors groundwater level, and periodically water quality.	Territorial monitoring network, but no wells in basin. Continuously monitors groundwater level, and periodically water quality.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;
Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
Red = Data is unavailable or not recorded and will result in gaps within Learning Plans.
Tan = Not applicable.

6.0 GROUNDWATER – SURFACE WATER INTERACTION

Identified areas of groundwater and surface water interaction are discussed subsequently.

6.1 Northwest Territories

In the Northwest Territories groundwater-surface water interaction can occur at the bottom of surface waterbodies, in karst landscapes, and at groundwater springs. Groundwater-surface water interaction in the northern regions of the Northwest Territories is largely limited by the pervasive presence of permafrost; where continuous permafrost is present, interaction is most likely to occur in through-taliks associated with deep surface waterbodies, or seasonally in the active layer.

Karst topography in the Northwest Territories was identified by Ford (2009) using air photo interpretation. Seven areas of the territory were reported to have karst development.

1. *Southeastern Region* – roughly from the Alberta border west of the Slave River, northwards to the shore of Great Slave Lake, and westwards to Kakisa Falls.
2. *Horn Plateau and Gypsum Shorelines* – the Horn Plateau is an extensive upland region to the east of Great Slave Lake that is composed of insoluble shale and sandstone underlain by carbonates and gypsum. The gypsum formations outcrop along the Northshore of Great Slave Lake.
3. *Southern Mackenzie Mountains* – broadly from the Alberta border north to the Redstone River, encompassing the karstic landforms located in the Nahanni National Park Reserve.
4. *McConnell Range* – the southern half of the Franklin Mountains, which are located east of the Mackenzie River. The karst features extend from community of Wrigley in the south to community of Tulita in the north.
5. *Northern Mackenzie Mountains* – located to the west of the Mackenzie River, near Norman Wells and on either side of the Canol Trail.
6. *Northern Extremities: the Horton and Anderson River plateaus, the Campbell Uplift, and the Parry Peninsula* – these are northern most karst landscapes in the Northwest Territories, located within the continuous permafrost zone. This is the only karst region located outside of the Mackenzie River Basin.
7. *Northern Franklin Mountains, Low Plateaus, and Hydration Ranges* – this region covers a very large area between Great Bear Lake and the Mackenzie River.

There is no map of all groundwater springs for the Northwest Territories. However, several studies (Ford, 2009; Michel, 1986) have identified and compiled spring locations. Michel (1986) has additionally provided groundwater chemistry and isotope data for select springs along the Mackenzie River.

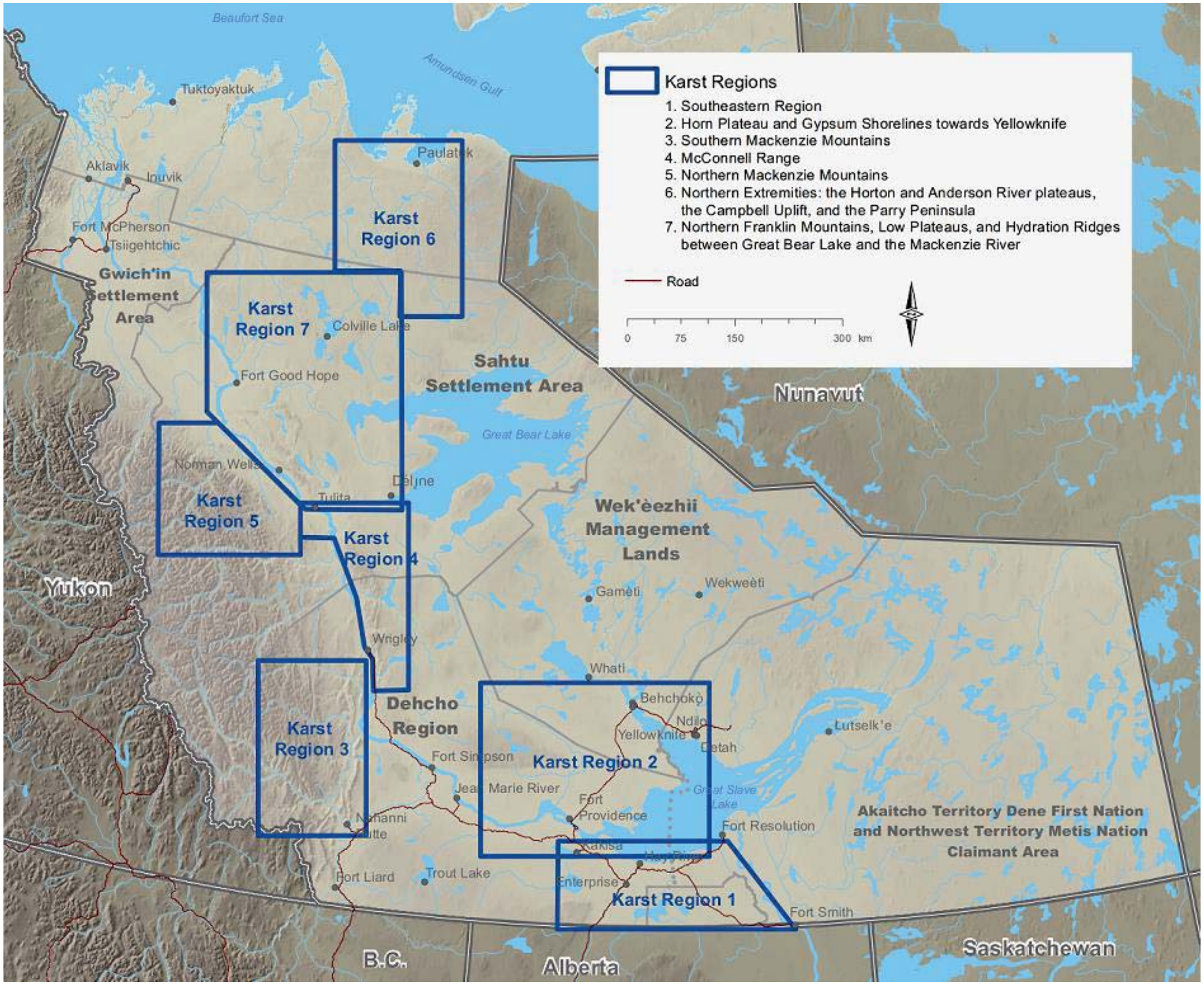


Figure 36. Karst regions in the Northwest Territories (Ford, 2009).

6.2 Alberta

Areas of groundwater-surface water interaction in Alberta occur in karst topography and at groundwater springs and at the bottom of surface waterbodies. Altosaar (2013) notes karstic features of the Middle Devonian Elk Point Group evaporites and carbonates within Wood Buffalo National Park (WBNP), located in the northeastern corner of Alberta, and extending northwards into the Northwest Territories. Due to the presence of at, or near-surface evaporites and fractured carbonates, hundreds of sinkholes of varying dimensions and ages can be found in the northeast corner of WBNP. There are also extensive networks of underground cavernous systems. These features are all attributed to solution of predominantly subsurface evaporites (and to a lesser extent, carbonates) coupled with collapse of overlying stratigraphic successions, and erosion (Altosaar, 2013).

The Bedrock Geology of Alberta map (Prior et al., 2013) shows the Elk Point Group in the northeastern corner of Alberta, which is known to have karstic features. Other Carbonate formations can be found in the Transboundary Area. Sinkholes have been noted in and around the Fort McMurray area, among other areas of Northern Alberta. Alberta Geological Survey (2015) shows carbonates and evaporites in Northern Alberta, and these sinkholes may be a result of dissolution.

An inventory of springs is maintained by Alberta Energy Regulator and Alberta Geological Survey (Alberta Energy Regulator & Alberta Geological Survey, 2016). Figure 37 shows the locations of known spring locations across Alberta. Alberta Energy Regulator & Alberta Geological Survey (2016) also presents a large database of known spring locations across Alberta, available on that website.

Figure 37. Map of Alberta showing location of popular springs (Alberta Energy Regulator & Alberta Geological Survey, 2016).

6.3 British Columbia

Groundwater-surface water interaction in British Columbia is likely to occur at the bottom of surface waterbodies, in karst landscapes, at groundwater springs, and abandoned mine adits. The Rocky Mountains of British Columbia contain the most extensive areas of soluble rock in the province, as well as Canada's longest and deepest documented caves (British Columbia Ministry of Forests and Range, 1997). Subsurface drainage systems, springs, and surface features, such as sinkholes, are common throughout the Rockies, with some of the most notable karst terrain occurring on plateaus as high as 2,000 metres.

The full extent and significance of karst in the Rocky Mountains and other parts of the interior are not well understood. Isolated locations, limited ground access, and extreme winter climates have made the exploration and documentation of interior karst lands difficult (British Columbia Ministry of Forests and Range, 1997).

A database of all groundwater springs and abandoned mine adit locations in British Columbia were not located. The Liard River Hot Springs, Grayling River Hot Springs, Toad River Hot Springs, and Prophet River Hot Springs are located in northeast British Columbia, all within the Liard sub-basin (Government of British Columbia, 2016a).

Figure 38. Map of British Columbia showing distribution of karst potential (British Columbia Ministry of Forests and Range, 1997).

6.4 Saskatchewan

Groundwater-surface water interaction in Saskatchewan is likely to occur at the bottom of surface waterbodies, in karst landscapes, at groundwater springs, and abandoned mine pits. The potential for karst in the Mackenzie River Basin in Saskatchewan is low. The University of Regina (2006) states that Saskatchewan is underlain throughout by crystalline Precambrian rocks of the stable North America Craton. In the northern portions of the province, these are exposed as part of the Canadian Shield. The oldest rocks in the province occur north of Lake Athabasca, in the northwestern portions of the province.

Unmetamorphosed sandstones and other sediments of the Athabasca basin overlie much of the north-central part of the Shield. Saskatchewan's uranium deposits are related to the weathered regolithic interface between the Athabasca Group and the underlying basement.

There are a number of abandoned uranium mines in Northern Saskatchewan currently under reclamation (Figure 18). There are four closed and decommissioned uranium mine sites in Northern Saskatchewan: Cluff Lake, Beaverlodge, Lorado and Gunnar (Canadian Nuclear Safety Commission, 2015). Tailings and mineralized waste rock have either been placed under water in mined-out open pits, or on surface facilities. The tailings and waste rock at uranium mines must be managed over the long term because they could contain significant concentrations of radioactive elements (primarily thorium-230 and radium-226, along with their associated decay products) (Canadian Nuclear Safety Commission, 2015).

An inventory of springs in Saskatchewan was unavailable.

6.5 Yukon

Groundwater-surface water interaction in the Yukon is likely to occur at the bottom of surface waterbodies, in karst landscapes, at groundwater springs, and abandoned mine adits. Groundwater-surface water interaction in the Yukon is limited by the pervasive presence of permafrost (Figure 4). Interaction is most likely to occur in through-taliks associated with deep surface waterbodies, or seasonally in the active layer.

A map of identifying karst landscapes in the Yukon was not located; conservatively, it can be assumed that karst topography may be present in all carbonate formations at surface. Known karst features, and groundwater springs, have been reported in Coal River Springs Territorial Park, in the Liard sub-basin, southeast Yukon (Environment Yukon, 2012a). A database of all groundwater springs and abandoned mine adit locations in the Yukon were not located.

6.6 Summary

Table 12. Summary of state of knowledge for groundwater-surface water interaction by stakeholder jurisdiction.

Type of interaction	Summary of State of Knowledge for Groundwater-Surface Water Interaction by Stakeholder Jurisdiction				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Surface water bodies	Interaction between surface water bodies and groundwater was not investigated. No database of talik locations.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.	Interaction between surface water bodies and groundwater was not investigated.
Karst landscapes	Regional study identifying known and potential karst landscapes. Karst landscapes have been identified locally.	Regional study identifying known and potential karst landscapes. Karst landscapes have been identified locally.	Regional study identifying potential karst landscapes. Karst landscapes have been identified locally.	No known karst landscapes.	Karst landscapes have been identified locally.
Springs	Local studies of spring locations and water quality.	Limited database of spring locations.	No provincial database of spring locations. Locations of protected hot springs identified.	No provincial database of spring locations.	No territorial database of spring locations. Locations of protected springs identified.
Abandoned mine adits (mountains)	Federal database of contaminated sites contains abandoned mines.	Federal and provincial database of contaminated sites contains abandoned mines.	Federal and provincial database of contaminated sites contains abandoned mines.	Not applicable.	Federal database of contaminated sites contains abandoned mines.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;
Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
Red = Data is unavailable or not recorded and will result in gaps within Learning Plans.
Tan = Not applicable.

7.0 SUMMARY

The state of groundwater knowledge required to develop Learning Plans is summarized in Table 13 for each of the jurisdictions of the Transboundary Area of the Mackenzie River Basin. A colour coding system has been developed to visually identify possible gaps in knowledge that exist, which may subsequently affect development of Learning Plans.

Table 13. Summary of groundwater knowledge and relevant notes required to develop learning plans.

Learning Plan Item	Data Gaps and Relevant Notes Per Stakeholder				
	Northwest Territories	Alberta	British Columbia	Saskatchewan	Yukon
Groundwater Resources	Limited number of hydrogeological studies available.	Limited number of hydrogeological studies available.	Limited number of hydrogeological studies available.	No hydrogeological studies were identified during writing of this report.	No hydrogeological studies were identified during writing of this report; however, one study occurred south of the border in British Columbia.
Groundwater Uses	Limited users due to sparse population of the area. Groundwater uses well defined and groundwater quantity reporting regulated.	Groundwater uses well defined and studies performed to examine groundwater quantity per water use category. Data available to public.	Groundwater use has not been regulated in past, and quantities have not been reported. New legislation is expected to be instituted in 2016 requiring water licences for non-domestic use. This will also require water use quantities to be reported.	Limited users due to sparse population of the area.	Limited users due to sparse population of the area. Incomplete list of users and associated quantities
Groundwater Impacts	List of federal contaminated sites is available. A complete list of landfills is available.	Risks to groundwater are well defined and available to public.	At the time of this report, limited data was available about environmental remediation sites. Other risks including landfills, mining and oil and gas production are well known.	List of federal contaminated sites is available. A complete inventory/ list of landfills and their status is unavailable,	List of federal contaminated sites is available. A complete list of landfills is available.
Groundwater Monitoring	Groundwater quality monitoring is required by the water license(s) issued to communities and mine sites. No network of monitoring points is maintained.	Groundwater levels and chemistry routinely monitored and data available to public. Relatively few wells are located in Transboundary Area despite significant oil and gas, mining, and other undertakings in the area.	Groundwater levels and chemistry routinely monitored and data available to public. Relatively few wells are located in Transboundary Area despite significant oil and gas, mining, and other undertakings in the area.	No network of monitoring points is maintained.	Groundwater quality monitoring is required by the water license(s) issued to mine sites. No network of monitoring points is maintained.
Groundwater – Surface Water Interaction	Karst locations are well documented. No territorial database for springs available.	Limited data available about karstic features across Alberta. A limited database of springs is available and updated routinely.	Limited data available about karstic features across Transboundary Area of British Columbia. No provincial database for springs available.	Limited data available about karstic features across Saskatchewan. No provincial database for springs available.	Limited data available about karstic features across Yukon. No territorial database for springs available.

Notes:
Green = Data is publically or readily available and can be used to develop Learning Plans;

Yellow = Data is available, but more studies or data is required to better develop Leaning Plans; and
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7.1 Gaps and Recommendations

Table 14 provides a summary of the gaps in the assessment, which are largely a result of not being able to find and/or extract the necessary data within the timeframe of this report. Table 14 also provides recommendations for further assessment of these gaps.

Table 14. Data gaps and recommendations.

Gap in Assessment	Recommendation
The scope of the current review specified the use of watershed boundaries at the sub-basin level as surrogates for delineating transboundary groundwater.	Further analysis of the identified gaps and limitations in the analysis is recommended only for high priority areas where there are known/potential risks and a reasonable likely hood of transboundary interaction (e.g., sub-sub-basin scale).
The current assessment identified a limited number of aquifers in the transboundary region.	Further delineation of aquifers should incorporate the abundant oil and gas well logs, and surficial and bedrock geology maps available through the federal, provincial and territorial geological surveys, which may identify groundwater resources in the region.
Groundwater users were identified in the report, however, the users could not be connected to specific aquifers.	With further delineation of aquifers, it is recommended that groundwater users be grouped by their respective aquifer sources.
An exhaustive review of local community information was not completed in this report, although early correspondence with Aboriginal Steering Committee members suggests that information could be available.	Further analysis of local community information may be achieved through further correspondence with the Aboriginal Steering Committee members.
The report identified the locations of potential impact sources, but did not assess the contaminants that may be released from each source.	Further analysis of the contaminants that may be released from the potential impact sources identified in the report.
The regulatory monitoring requirements of projects in Alberta, British Columbia, and Saskatchewan were not reviewed.	It is recommended that the regulatory monitoring requirements of projects in Alberta, British Columbia, and Saskatchewan be reviewed.
The current assessment provided limited data on groundwater-surface water interaction.	Further analysis on groundwater-surface water interaction should be informed by the surface water Learning Plans, which were not available at time of report preparation.
The information compiled in this report, along with any future data collected, may be presented in a more accessible format; for example as a geographical information systems (GIS) based webpage similar to the Groundwater Information Network, or Alberta's Water Well database.	It is recommended that future data collection be compiled into a spatial database to aid in locating relevant information for Learning Plans.

8.0 CLOSURE

This report has been prepared exclusively for the use of the GNWT ENR for the specific application described within this report. The details provided in this report are for general information purposes only. The information and recommendations contained in this report should not be used for any other purpose, at another location, or by any other parties. Any use of, or reliance on this report by any third party is at that party's sole risk. ARKTIS assumes no responsibly for inappropriate use of the contents of this report, and disclaims all liability arising from negligence or otherwise. General terms and conditions are provided in Appendix B.

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APPENDIX A – GEOLOGICAL MAPS

APPENDIX B – GENERAL TERMS AND CONDITIONS

USE OF REPORT

This report pertains to a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment.

This report and the assessments and recommendations contained in it are intended for the sole use of ARKTIS Solutions Inc.'s (ARKTIS) client. ARKTIS does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than ARKTIS' client unless otherwise authorized in writing by ARKTIS. Any unauthorized use of the report is at the sole risk of the user.

LIMITATIONS OF REPORT

This report is based solely on the conditions which existed on site at the time of ARKTIS' investigation. The client, and any other parties using this report with the express written consent of the clients and ARKTIS, acknowledge that conditions affecting the environmental assessment of the site can vary with time and that the conclusions and recommendations set out in this report are time sensitive.

The client, and any other party using this report with the express written consent of the client and ARKTIS, also acknowledge that the conclusions and recommendations set out in this report are based on limited observations and testing on the subject site and that conditions may vary across the site which, in turn, could affect the conclusions and recommendations made.

The client acknowledges that ARKTIS is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the client.

During the performance of the work and the preparation of this report, ARKTIS may have relied on the information provided by persons other than the client. While ARKTIS endeavors to verify the accuracy of such information when instructed to do so by the client, ARKTIS accepts no responsibility for the accuracy or the reliability of such information which may affect the report.

STANDARD OF CARE

Services performed by ARKTIS for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided, subject to the time limits and financial and physical constraints applicable to the services. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of this report.

ALTERNATE REPORT FORMAT

Where ARKTIS submits both electronic file and hard copy versions of reports, drawings and other project related documents and deliverables (collectively termed instruments of professional service), the Client agrees that only the signed and sealed hard copy versions shall be considered final and legally binding. The hard copy versions submitted by ARKTIS shall be the original documents for record and working purposes, and, in the event of a dispute or discrepancies, the hard copy versions shall govern over the electronic versions. Furthermore, the Client agrees and waives all future right of dispute that the original hard copy signed version archived by ARKTIS shall be deemed to be the overall original for the Project.

The Client agrees that both electronic file and hard copy versions of instruments of professional services shall not, under any circumstances, no matter who owns or uses them, be altered by any party except ARKTIS. The Client warrants that instruments of professional services will be used only and exactly as submitted by ARKTIS.