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AURORA GEOSCIENCES

Liard River Basin Transboundary Aquifer Assessment

FINAL REPORT

Palmer Project #
1508907

Prepared For
Government of the Northwest Territories and Government of Yukon

June 22, 2020

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Dear Isabelle,

Re: Liard River Basin Transboundary Aquifer Assessment (Final Report)
Project #: 1508907

Palmer, in association with Aurora Geosciences, is pleased to provide the governments of the Northwest Territories and Yukon with the final results of our transboundary assessment of potential aquifers in the portions of the Liard River basin in Yukon and Northwest Territories.

Through this desktop-based assessment, we have compiled and reviewed a large amount of groundwater-related information and, in doing so, identified significant data gaps. Within the limitations of available data, we have identified, delineated and characterized areas of aquifer potential and preliminarily assessed their vulnerability to existing land use activities. Recommendations for future groundwater-related research are based on a sub-basin-scale prioritization that reflects aquifer vulnerabilities and optimal opportunities for knowledge gain.

Should you have any questions, please do not hesitate to contact Robin McKillop at 604-355-8788 or robin.mckillop@pecg.ca.

Yours truly,
Palmer

Robin McKillop, M.Sc., P.Geo.
Principal, Surficial Geologist

Executive Summary

The protection and management of groundwater resources within the northern half of the Liard River basin is a priority established through the *Yukon-Northwest Territories Transboundary Water Management Agreement* (2002) under the *Mackenzie River Basin Transboundary Waters Master Agreement* (1997), yet little information exists on the types, distribution and characteristics of aquifers within this region. This report, completed by Palmer in association with Aurora Geosciences on behalf of the governments of Yukon and the Northwest Territories (NWT), presents the results of a desktop-based transboundary assessment of potential aquifers in the portions of the Liard River basin in Yukon and the NWT. Our work broadly aligns with a similar assessment by Levson et al. (2018) for the portion of the Liard River basin in British Columbia.

Systematic compilation and review of mapping of bedrock geology, surficial geology, permafrost, topography and land cover, as well as site-specific subsurface information available in well records, seismic shothole drillers' logs and hydrogeological studies, revealed incomplete and/or low-resolution groundwater-related data coverage. Areas of surficial aquifer potential were primarily delineated based on available regional-scale (≥1:250,000) surficial geology mapping, with refinements made possible through a topographic analysis in a ~34,000 km^2 portion of the study area only covered by nationwide (1:5,000,000) surficial geology mapping. Potential aquifers were classified according to Wei et al. (2009) and necessarily based on limited available subsurface information and knowledge of Quaternary history and stratigraphy.

A preliminary basin-wide water budget was completed based on the spatial partitioning of surplus precipitation into runoff and infiltration to better understand contributions to groundwater recharge within and beyond the delineated limits of potential aquifers. Most groundwater recharge occurs in the southern half of the study area, where permeable materials are more extensive, slopes are gentler and permafrost is only sporadic. Potential recharge within the study area is about 28.8 mm/yr, on average, or approximately 3.6×10^{10} m^3/yr annually. Baseflow estimated from groundwater recharge within the relatively large Frances River and South Nahanni River (above Virginia Falls) watersheds compared well with average baseflow estimated from long-term hydrometric data (within +/-5%). Greater contrast between estimates for the Scotty Creek watershed discourages application to small catchments in discontinuous permafrost.

An assessment of the vulnerability of groundwater to various land use activities was completed through an adaptation of the approach used by Levson et al. (2018). The vulnerability of groundwater quality was assessed for each of the 13 sub-basins in the study area through spatial association of the distribution of land use activities, categorized and weighted according to three levels of disturbance, with the entire sub-basin, areas of aquifer potential and average recharge potential. The vulnerability of groundwater quantity within each sub-basin was assessed simply based on its well density. Normalized indices used to rank each sub-basin identified groundwater resources in the *Headwaters Liard – 2*, *Francis* and *Lower Liard – Mouth* sub-basins as most vulnerable to impact from surface disturbance. The *Upper South Nahanni* sub-basin was consistently ranked lowest according to its groundwater vulnerability, irrespective of the index used.

Recommendations for future groundwater-related research are provided based on the basin-wide (geographic) results of this aquifer assessment, appreciation for the implications of gaps in the coverage or resolution of input data and the benefits of incorporating traditional knowledge, and uncertainty in anticipated changes in permafrost hydrogeology in response to climate change.

Table of Contents

List of Figures

List of Tables

List of Appendices

1. Introduction

Palmer, in association with Aurora Geosciences, is pleased to provide the governments of the Northwest Territories and Yukon with the results of our transboundary assessment of potential aquifers in the portions of the Liard River basin in Yukon and the Northwest Territories (NWT). This collaborative project follows from, and broadly aligns with, a similar assessment completed by Levson et al. (2018) for the portion of the Liard River basin in British Columbia. We present the results of our desktop-based assessment of potential aquifers and their vulnerabilities to different land use activities within the Yukon and NWT portions of the Liard River basin based on compilation, synthesis and analysis of existing geological, topographic, permafrost and limited hydrogeological information. Our key findings will ultimately help inform bilateral decision-making pertaining to the protection and management of groundwater resources in association with the *Yukon-Northwest Territories Transboundary Water Management Agreement* (2002) under the *Mackenzie River Basin Transboundary Waters Master Agreement* (1997).

Following provision of important introductory background information (Section 1), we outline the methods followed through all key phases of the project (Section 2). Results of the data compilation, review, analysis and interpretation are provided in Section 3. Key findings and recommendations for follow-up research are discussed in Section 4. Section 5 highlights overarching conclusions. Cited references are listed at the end of the report, and a more comprehensive bibliography of mapping, publications and datasets that inform understanding of aquifer potential in the Yukon and NWT portions of the Liard River basin is included in **Appendix A**. **Appendix B** includes a list of the land use activity mapping used in disturbance analyses. **Appendix C**, provided separately via web-link, includes the complete set of digital spatial data (GIS) files generated as part of this project.

1.1 Objectives

The governments of Yukon and the NWT identified three principal objectives of the project within the Yukon and NWT portions of the Liard River basin:

1. Infer and delineate potential aquifer areas;
2. Characterize aquifer conditions, groundwater flow directions and rates, groundwater recharge and discharge areas and surface water-groundwater interactions, where possible; and
3. Identify knowledge gaps as a basis for prioritizing future aquifer mapping and research.

Palmer additionally aimed to develop a preliminary water budget for the portions of the Liard River basin in Yukon and the NWT in order to better understand water movement and help quantify groundwater recharge potential using a simplified water partitioning methodology. This analysis will help quantify groundwater recharge in areas that may support groundwater-influenced natural features or have water supply potential.

1.2 Basic Premises and Limitations

This aquifer assessment is premised on the understanding that the general distribution and characterization of potential aquifers can be meaningfully inferred based on compilation and interpretation of available geological, topographic, permafrost and limited hydrogeological information. A comprehensive literature search and review completed following project commencement revealed incomplete regional-scale surficial geology mapping coverage and limited availability of subsurface and hydrogeological information, mostly restricted to the southeastern corner of the study area where oil and gas exploration and extraction are concentrated. Basin-wide mapping of permafrost is modelled and largely unverified through field investigations. As such, the accuracy and precision of analyses and associated interpretations must be considered in the context of the limitations of the source information. Where more than one spatial dataset of a particular type is available, preference was given to the higher-resolution (more detailed, larger scale) source. This avoided unnecessary information loss that would otherwise have occurred if a more spatially consistent product was produced through a simplification process. Characterization of potential aquifers was necessarily based on extrapolation and inference from limited well data and seismic shothole drillers' logs, as well as a few relevant publications on hydrogeological conditions predominantly from the Liard River basin in British Columbia.

The focus of the project is on baseline characterization of potential *surficial* aquifer areas and the potential vulnerability of groundwater to surface land use activities. Only brief mention is made of deep bedrock aquifers, for context, as their limited interaction with surface and inherent water quality (e.g. saline) give them a comparably low likelihood for impacts from surface activities. Aquifers utilized for potable water and that predominantly support stream baseflow and natural features are generally shallow and reflective of surficial geological conditions. No consideration is given to uncertain or speculative land use projections, or to the potential effects of climate change on surface water, groundwater and their interaction. The most up-to-date information on current land use activities (e.g. road networks) was used.

The relevance of traditional knowledge to the management and protection of groundwater resources is well appreciated. Although beyond the scope of this study, incorporation of traditional knowledge would valuably inform understanding of aquifer potential, traditional water uses and surface water and groundwater resources in particular need of protection.

1.3 Study Area

The study area includes the Yukon (62,192 km^2) and NWT (62,104 km^2) portions of the Liard River basin (watershed), which drains into the Mackenzie River and ultimately the Arctic Ocean (**Figure 1-1**). The study area encompasses the eastern slopes of the Pelly Mountains, the southern ridges and valleys of the Selwyn and Mackenzie Mountains, and the Liard River lowlands. It comprises portions of the Boreal and Taiga Cordillera ecozones, as well as a portion of the Taiga Plain ecozone within its eastern limits (Marshall et al., 1999). Elevations range from 120 m, at the mouth of Liard River, to 2,773 m, at the summit of Mount Nirvana (also known as Thunder Mountain). The Yukon and NWT portions of the Liard River basin include at least portions of 13 major sub-basins (drainage areas) (**Figure 1-1**). **Table 1-1** summarizes basic characteristics of each sub-basin.

The study area straddles the zones of sporadic, extensive discontinuous and continuous permafrost (Heginbottom et al., 1995; Bonnaventure et al., 2012; Carpino et al, in preparation). Permafrost is most common in peatlands, where surface drainage is poor and thick organic cover insulates the ground. Climate in the Liard River basin ranges from cold temperate to subarctic, with a notable vertical zonation in the mountainous areas. Mean annual temperature and precipitation in the Liard River basin, including the portions in British Columbia and Alberta, are approximately -3ºC and 490 mm, respectively (Burn et al., 2011). Air temperatures generally increase from the mountains in the west to the lowlands in the east. Precipitation decreases from the southwest, where coastal influence and orographic enhancement are more pronounced, to the northeast. Approximately 40% of annual precipitation falls as snow (Burn et al., 2011).

The study area largely comprises Boreal forest to tundra wilderness, with few communities and relatively isolated concentrations of resource industry activity. Surface disturbance is minimal at the basin scale. Nahanni National Park Reserve (Nahanni National Park) occupies portions of the Flat River and South Nahanni River watersheds in the north-central portion of the study area.

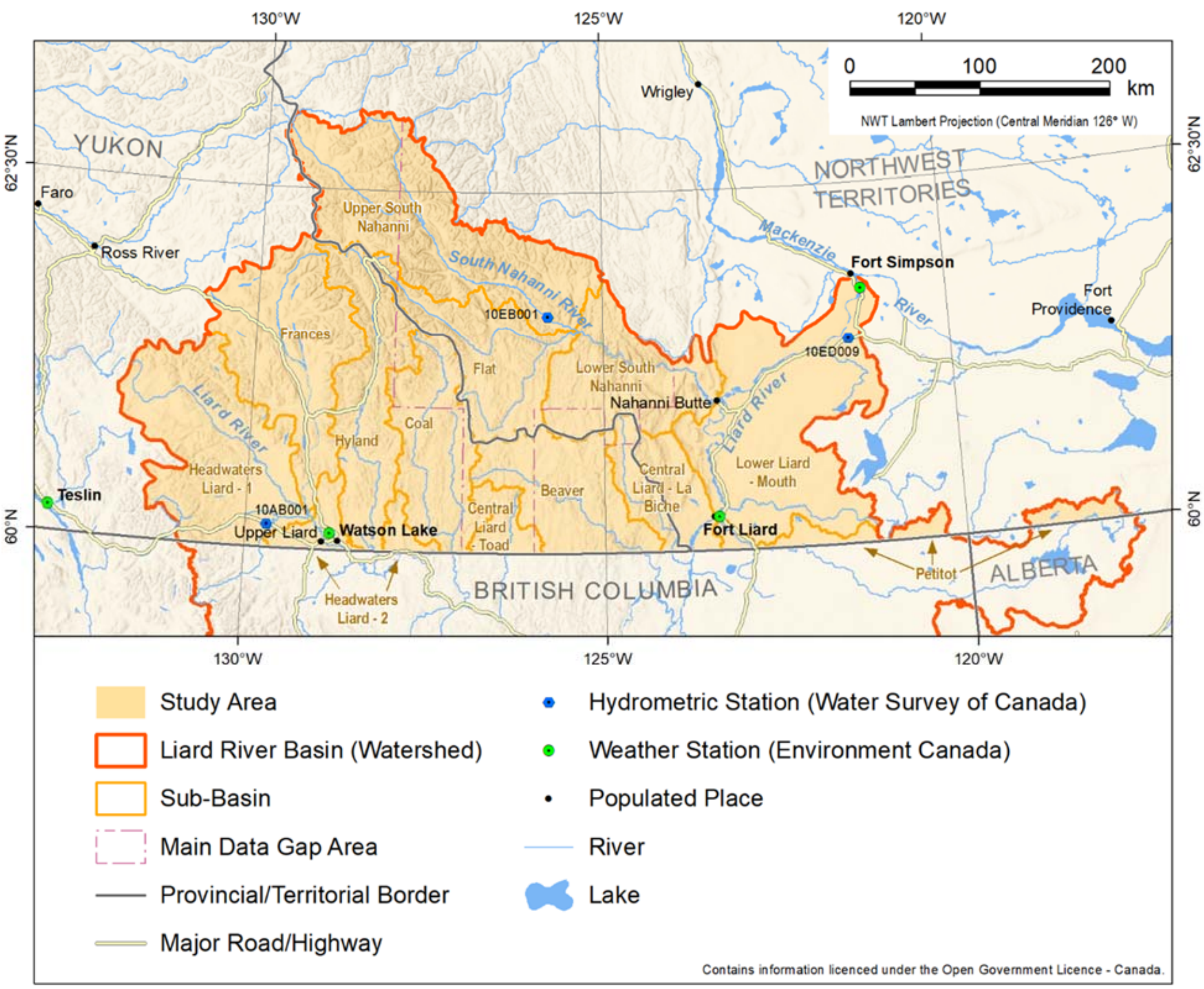

Figure 1-1. Location and sub-basins of the study area in Yukon and the NWT. Weather and hydrometric stations were used in development and validation of the water budget. Main data gap area in regional-scale (≥1:250,000) surficial geology mapping encompasses large portions of the Flat and South Nahanni River watersheds.

Table 1-1. Basic Characteristics of the 13 Sub-basins in the Study Area

Sub-basin	Area (km^2)	Lowest Elevation (m)	Highest Elevation (m)
Beaver	8,647	296	1,652
Central Liard - La Biche	5,501	210	1,953
Central Liard - Toad	2,052	586	1,616
Coal	8,648	579	2,471
Flat	8,543	420	2,615
Frances	13,231	640	2,358
Headwaters Liard - 1	14,953	640	2,320
Headwaters Liard - 2	2,844	558	1,801
Hyland	9,479	590	2,557
Lower Liard - Mouth	19,537	120	1,675
Lower South Nahanni	9,459	146	1,983
Petitot	3,271	210	735
Upper South Nahanni	18,128	396	2,773

2. Methods

Palmer achieved the objectives stated above (Section 1.1) through the completion of five main phases of desktop-based work, each of which is described in the following subsections. The project was approached in a way that broadly aligns with Levson et al.'s (2018) aquifer assessment in the portion of the Liard Basin in British Columbia, as per the original terms of reference, with improved representation and quantification of groundwater recharge through development of a preliminary basin-wide water budget.

2.1 Data Compilation and Review

A systematic and comprehensive search for information pertinent to understanding the distribution, types and characteristics of aquifers in the study area was completed following project commencement. Publications containing groundwater-related information, such as bedrock and surficial geology mapping, biophysical maps, water well records, seismic shothole drillers' logs (e.g. Smith, 2011), spring locations and characteristics, regional groundwater studies and information on current groundwater uses, were compiled and reviewed. Representatives from the governments of Yukon and the NWT, as well as the Geological Survey of Canada, reviewed the initial data compilation and shared additional information of direct or indirect relevance. A number of site-specific hydrogeological assessment reports provided by Government of Yukon, for context and completeness, are listed in the bibliography in **Appendix A**.

Digitization of surficial geology maps only available online in PDF format (e.g. 1:50,000-scale mapping within the Fort Liard area (95B) by Bednarski, 2002, 2003a, b, c, d, e, f, g, h, i, j, k, l, m, n, o) was beyond the scope of this project, so Côté et al.'s (2013) pre-existing digital compilation of 1:125,000-scale mapping was used in their place. Only in association with final project reviews was it clarified that the Geological Survey of Canada would be able to provide access to the Fort Liard area mapping in GIS (vector) formats for future research. Unpublished surficial geology mapping by the Geological Survey of Canada's D. Huntley (Trout Lake area, 95A) and A. Duk-Rodkin (Fort Simpson, 95H) was also inaccessible. Attempts to access an unpublished report on the geomorphology of Nahanni National Park (Ford, 1974), which may contain more refined surficial geology information than is available in the nationwide coverage that is otherwise all that is available in this area ("Main Data Gap Area" in **Figure 1-1**), were unsuccessful. Mapping of permafrost probability in southern Yukon (Bonnaventure et al., 2012) and southwestern NWT (Carpino et al., in preparation) was compared with nationwide mapping of permafrost zones by Heginbottom et al. (1995) and Brown et al. (2002). Reports by Petrel Robertson Consulting Ltd. (2013), ARKTIS Solutions Inc. (2016) and Golder Associates (2017) on the state of groundwater and related knowledge in portions of the study area summarized useful background information.

Key information on land use activities, such as oil and gas, agricultural, mining and forestry activities (e.g. cut lines, wells, pipelines, facilities); transportation facilities and networks (e.g. roads, highways, airstrips); and community infrastructure (e.g. townsites, transmission lines), was compiled in a GIS format. Systematic interpretation of aerial photography or satellite imagery as a means of identifying any additional activities not already represented by existing spatial data layers or specific sites highlighted by the governments of Yukon and the NWT was beyond the scope of this study.

2.2 Mapping of Surficial Aquifer Potential

2.2.1 Delineation

Areas with potential surficial aquifers[1] were delineated based primarily on the pre-existing compilations of 1:50,000- to 1:250,000-scale surficial geology mapping available within each territory (NWT, Côté et al., 2013; Yukon, Lipovsky and Bond (compilers), 2014). The compilation for each territory was combined into a single dataset (shapefile) for analysis purposes. Each of the numerous, unique surficial geology map units (polygons) in the Yukon and NWT datasets, which are at least attributed according to surficial material (e.g. fluvial) and surface expression (e.g. plain), was classified either with "Low Aquifer Potential" to represent a poor aquifer (or an aquitard) or according to one of the six main types of aquifers defined for the Canadian Cordillera Hydrogeologic Region by Wei et al. (2009) (**Table 2-1**). Classification of aquifer potential was primarily based on the type (e.g. glaciofluvial, till), thickness (surface expression) and texture (as defined, calibrated through review of subsurface logs, or inferred based on an understanding of material geneses) of surficial material. Only secondary consideration was given to the potential depth to the groundwater table (below which material is saturated), potential thickness and lateral extent of the water-bearing material, and ease with which groundwater could be withdrawn.

Table 2-1. Summary of Aquifer Classification from Wei et al. (2009)

Type	Hydrologic Connections with Surface Water
1. Unconfined aquifers of fluvial[a] origin along river valley bottoms	
a. Aquifers along higher-order rivers	Common
b. Aquifers along moderate-order rivers	Common
c. Aquifers along lower-order rivers	-
2. Unconfined deltaic aquifers	Common
3. Unconfined fluvial, colluvial fan aquifers	Common in aquifers adjacent to surface water
4. Aquifers of glacial or pre-glacial origin	
a. Unconfined glaciofluvial aquifers	Common in aquifers adjacent to surface water
b. Confined glacial or pre-glacial aquifers	-
c. Confined glaciomarine aquifers	Limited
5. Sedimentary rock aquifers	
a. Fractured sedimentary rock aquifers	Limited
b. Karstic aquifers	Unknown, but possible
6. Crystalline rock aquifers	
a. Flat-lying volcanic flow aquifers	Limited
b. Fractured igneous intrusive, metamorphic, volcanic or metavolcanics aquifers	Limited

[a] Type 1 aquifers excluded landforms of glaciofluvial origin, otherwise included by Wei et al. (2009), due to overlap with Type 4a aquifers at the scale of this study.

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[1] *For the purposes of this project, surficial aquifers are considered areas of near-surface (<100 m depth), water-bearing unconsolidated material (e.g. glaciofluvial deposits) and/or bedrock (e.g. karstic limestone) with the capacity to transmit groundwater.*

High-permeability surficial materials comprising sand or coarser sediment, such as fluvial[2] plains and glaciofluvial landforms, were assumed to have high aquifer potential. This may overestimate aquifer potential in some glaciofluvial landforms that form topographic highs (e.g. eskers), which are well-drained and may be unsaturated beyond their base. Glaciolacustrine deposits were interpreted as having low aquifer potential, at least in comparison to glaciofluvial deposits, based on field observations by McKillop (2012) and generalized descriptions on available surficial geology mapping (e.g. Dyke, 1990). Tills in the region have relatively low permeabilities and are generally considered to be aquitards (R. Smith, pers. comm.). Areas mapped as organic material were assumed to have low aquifer potential, despite having relatively high near-surface permeability based on their composition, for three main reasons: (i) organics are commonly underlain by low-permeability till or glaciolacustrine sediments (even if unmapped); (ii) organics are more likely to contain permafrost, making them an aquitard, even in the zone of sporadic permafrost; and (iii) organics were universally assumed by Levson et al. (2018) to be permafrost-controlled aquitards even in a more southern (warmer) study area. It is important to acknowledge that even unconsolidated material or bedrock with low aquifer potential can generally accept groundwater recharge and provide a groundwater discharge function. While these units would not be targets for water supply and would have a lower vulnerability to disturbance, they still provide an important function as part of the overall water balance within the study area.

Mapped veneers (i.e. thinner than about 1 or 2 m) were disregarded in the classification of surficial aquifer potential, because they are commonly discontinuous and weathered. Infiltration of surface water generally occurs readily through veneers, irrespective of material type, so aquifer potential within areas of mapped veneers was instead classified based on the underlying material (unconsolidated or bedrock). Aquifer potential in areas of exposed or veneered bedrock was classified based on inference from bedrock formations and lithologies, considering the type and typical properties of bedrock (e.g. Freeze and Cherry, 1979) and reference to limited water well records and publications from British Columbia (e.g. Petrel Robertson Consulting Ltd., 2013). Map units (polygons) with a stratigraphic relation used to represent a material with aquifer potential (e.g. glaciofluvial outwash) overlain by a material with little to no aquifer potential (e.g. till, fine-grained glaciolacustrine sediment) were classified as potential (confined) aquifers. For the purposes of this basin-wide study, consideration was only given to primary materials in the uncommon cases where the presence of a secondary material (~10-50% areal extent) was noted in the label of a map unit.

Potential aquifer areas could not be reasonably identified based on available 1:5,000,000-scale surficial geology mapping, in the large data gap encompassing much of the Flat and South Nahanni River sub-basins (**Figure 1-1**), because it provides no representation of fluvial deposits and only very approximate representation of a few glaciofluvial deposits. Therefore, an attempt was made to improve representation of potential aquifer areas through an analysis involving generation of a series of Topographic Position Indices (TPIs) (Jenness, 2006). The TPI is a scale-dependent index that compares the elevation of a cell in a digital elevation model (DEM) to the mean elevation of a specified neighbourhood around that cell. It provides a means of classifying areas of a landscape into one of ten topographic landform categories (i.e. streams, midslope drainages, upland drainages, U-shaped valleys, plains, open slopes, upper slopes, local ridges, midslope ridges, high ridges) based on relative relief. Potential fluvial aquifer areas, beyond those identified through association with mapped surficial geology, were inferred based on their association with

[2] *The term "fluvial," as opposed to "alluvial," is used throughout this report for simplicity and consistency with most mapping.*

ranges of TPI values and particular landform categories in a 24,000 km^2 'training area' of similar topography, immediately adjacent to the data gap (TPI analysis) area. TPI values within "U-shaped valleys" and "plains" landforms were determined to be the best predictors of Type 1 aquifers, and values within "midslope drainages" and "upland drainages" landforms were determined to the best predictors of Type 3 aquifers. Inference of the potential distribution of Type 4a (glaciofluvial) or Type 4b (buried glacial) aquifers based on TPI analysis was deemed inappropriate due to complexities in glacial and deglacial histories that correlate poorly with (topographic) landforms alone.

The distribution and extent (continuity) of permafrost affects surficial aquifer potential by acting as a local barrier to infiltration and groundwater flow. Materials considered to have aquifer potential in permafrost-free regions may function more like aquitards where frozen. Notwithstanding this, permafrost was conservatively disregarded in the basin-wide mapping of aquifer potential (except in the case of organic terrain) to avoid inconsistencies introduced by incomplete permafrost probability mapping across the study area and because there is reasonable potential for groundwater recharge in areas of discontinuous permafrost (the vast majority of the study area). An explanation of how permafrost was incorporated into the basin-wide estimation of groundwater recharge is provided in Section 2.3.

2.2.2 Characterization

Limited subsurface information was available in the study area, mainly in association with oil and gas activity in the southeastern corner. Water and oil and gas well records, seismic shothole drillers' logs (Smith, 2011), and regional groundwater-related studies (e.g. Petrel Robertson Consulting Ltd., 2013; ARKTIS Solutions Inc., 2016; Golder Associates, 2017), where available, were used to help characterize the main types of aquifers. Information from available well logs and site-specific hydrogeological assessments (as noted in **Appendix A**) informed understanding of typical ranges of groundwater table depths and well yields. Subsurface conditions were also necessarily inferred based on knowledge of Quaternary history and stratigraphy, correlated with available surficial geology mapping, given the sparsity of actual subsurface information.

2.3 Preliminary Water Budget

A meaningful understanding of where current or proposed land use activities are most likely to affect groundwater quantity and quality cannot be gained without consideration of the relative amount and distribution of groundwater recharge contributions across the landscape. Some areas without the properties of an aquifer (e.g. till plains) still provide important groundwater recharge and discharge functions, especially where driven by low-relief and depressed terrain, so they should not be screened out as was done by Levson et al. (2018). As such, a preliminary water budget was developed for the entire study area to improve representation and quantification of groundwater recharge areas within and beyond areas of mapped aquifer potential (Section 2.2.1).

2.3.1 Water Balance

In its most basic sense, a water budget is used to describe the movement of water in a basin. For the purposes of this assignment, it was assumed that the political boundaries of Yukon and the NWT are representative of a basin. It is acknowledged that this assumption is not correct for the Liard River basin and that surface water and, to a much lesser extent, groundwater enters the Yukon and NWT portions of the basin from British Columbia (as noted in Section 4.1). The purpose of this water balance was to characterize local groundwater recharge within the study area, however, so this assumption did not directly impact the results.

The total *precipitation* (P) accounts for the water that falls both as rainfall and as snow and constitutes the total amount of water available for hydrological processes such as stream flow or groundwater recharge. A water budget also considers the amount of water that is returned to the atmosphere by both *evaporation* and plant *transpiration* in the combined process called *evapotranspiration (ET)*. The amount of water held as soil moisture can vary seasonally, especially in areas that undergo freeze-thaw cycles, and should be accounted for in a water balance calculation. The surface water flow component of the water balance can be represented by the volume of runoff (RO), whereas the groundwater component can be represented by the volume of recharge (R). Over a large area and a large timescale, the change in storage components for groundwater, surface water, and soil moisture can be assumed to be zero.

With the above assumptions and limitations in mind, a simplified water budget equation can be expressed as follows:

$$P = RO + R + ET$$

where:

P = Precipitation (mm/yr)

RO = Surface Runoff (mm/yr)

R = Groundwater Recharge (mm/yr)

ET = Evapotranspiration (mm/yr)

Within a large drainage basin, precipitation rates can be spatially and temporally variable. Therefore, it is important to obtain precipitation estimates from multiple points within a basin that have been averaged over a long period of time. Long-term meteorological data from the 1981 – 2010 average was obtained from Environment Canada for the following four weather stations in Yukon and the NWT (**Figure 1-1**):

- Fort Liard (ID 2201575)
- Fort Simpson (ID 2202101)
- Teslin[3] (ID 2101100)
- Watson Lake (ID 2101200)

ET estimates have been made by others within the Liard River basin based on the difference between total annual precipitation and annual stream discharge. These estimates would therefore assume that deep groundwater recharge is limited, and that the vast majority of groundwater recharge supports the shallow groundwater flow system and ultimately discharges to surface water features. Estimates of ET using this

[3] *Teslin is slightly outside the study area, but aids representation of the higher elevation/mountainous areas in the west.*

method have been found to range from 237 mm/yr (St. Amour et al., 2005) to 297 mm/yr (Kane and Yang, 2004). In the Hydrological Atlas of Canada (den Hartog and Ferguson, 1978), nationwide estimates for ET were calculated using the Thornthwaite and Mather (1957) soil moisture balance method. For the Yukon and NWT portions of the Liard River basin, a value of approximately 240 mm/yr was estimated using this method. For the purposes of completing this preliminary water balance to estimate groundwater recharge within the Liard River basin of Yukon and NWT, an ET value of 240 mm/yr was used.

2.3.2 Liard River Basin Water Surplus

Assuming that changes in soil moisture storage (ΔS_s) are negligible and that there is no change in groundwater storage (ΔG_s) in the basin, the total *water surplus* that is available for *surface runoff* to the surface water system and *infiltration* as groundwater recharge can be determined. The water surplus (mm/yr) is expressed as follows:

$$Surplus = P - ET$$

The proportion of the water surplus that infiltrates or runs off depends primarily upon the characteristics of the surficial materials, topography, land use and vegetative cover. The premise of this concept is that water will infiltrate more easily though flat-lying, high permeability soils than it will on steep slopes or through low permeability soils. Water that infiltrates recharges the groundwater table and shallow aquifers. In permafrost terrain or within low permeability materials, infiltration of precipitation may recharge only a perched groundwater table. Groundwater is expected to flow laterally towards river valleys and contribute to baseflow, which supports flow during the winter months within the study area. The travel time though the soil may be slow, thus creating a long time lag (often ranging from weeks to years or even decades) between when the water infiltrated and when it is exposed again at surface.

Surface runoff, on the other hand, generally coincides with rainfall and snowmelt events. As the surficial soil layers become saturated by rainfall, water may run off to low-lying areas. This process is especially pronounced during the spring snowmelt where the melting snowpack is forced to run off because the upper soil layers are still frozen and prevent infiltration. Furthermore, the amount of runoff depends on a large number of factors such as surficial materials, slope gradients, vegetative cover and the soil moisture prior to the rainfall.

The overall water surplus was determined for each of the five meteorological stations by the difference between the mean annual precipitation (P) and the estimated ET (**Table 2-2**). An average water surplus during the ice-free period was therefore estimated to be 161 mm/yr. This volume of water is available to either runoff (RO) directly to surface water features or recharge (R) the water table.

Table 2-2. Water Surplus by Meteorological Station

Station	Latitude	Longitude	Elevation	Average Precipitation (mm/yr)	Evapo-transpiration (mm/yr)	Surplus (mm/yr)	Average Surplus (mm/yr)
Fort Liard (ID 2201575)	60°14'06"N	123°28'01"W	215.8 m	452	240	212	161
Fort Simpson (ID 2202101)	61°45'37"N	121°14'12"W	169.2 m	388		148	
Teslin (ID 2101100)	60°10'27"N	132°44'09"W	705.0 m	346		106	
Watson Lake (ID 2101200)	60°06'59"N	128°49'20"W	687.4 m	416		176	

Notes:
1. *Data obtained from the 1981 – 2010 average at each meteorological station.*
2. *Evapotranspiration (ET) estimated from Hydrological Atlas of Canada (den Hartog and Ferguson, 1978).*
3. *Station locations identified in **Figure 1-1**.*

2.3.3 Partitioning between Recharge and Runoff

Based on the annual water surplus calculated in **Table 2-2**, groundwater recharge and surface water runoff rates were quantitatively calculated for the study area using a GIS-based analytical model. The model integrates physical characteristics such as slope, aspect, elevation, surficial materials, land use, and land cover over a 30 x 30 m grid to estimate groundwater recharge rates and runoff volumes for the Liard River basin with Yukon and the NWT.

To partition between runoff and recharge, a distribution of weighted runoff/recharge factors was determined for each of the different surficial and exposed/veneered bedrock geological units, vegetative types (land cover) and topographies (i.e. slope classes) within the study area. The DEM and land cover mapping used to assign values for slope and vegetative (land) cover are presented in Section 3.1.1 and Section 3.1.5, respectively. **Table 2-3** specifies the infiltration factors assigned on the basis of land cover type and **Table 2-4** lists the infiltration factors assigned on the basis of slope class. The surficial geology map presented in Section 3.1.3 provided the data for weighting infiltration values in the model and summarizes the ranking of infiltration factors for the various types of surficial material (including landforms) and bedrock. Once weights were applied to all layers, they were combined within the GIS to create a layer of infiltration distribution. The runoff/recharge factors are based on hydrologic analysis designed for assessing peak runoff curves for storm water management purposes (e.g. US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) curves) and modified based on the specific conditions within the study area and Palmer's experience. This methodology provides a worst-case scenario with respect to runoff and is therefore conservative in estimating the amount of groundwater recharge.

Table 2-3. Infiltration Factors for Different Land Cover Types

Land Cover Type	Infiltration Factor
Temperate or sub-polar needleleaf forest	0.2
Sub-polar taiga needleleaf forest	0.2
Temperate or sub-polar broadleaf deciduous forest	0.2
Mixed forest	0.2
Temperate or sub-polar shrubland	0.15
Temperate or sub-polar grassland	0.15
Sub-polar or polar shrubland-lichen-moss	0.1
Sub-polar or polar grassland-lichen-moss	0.1
Wetland	0.05
Barren lands	0.3
Urban	0.05
Water	0
Snow and Ice	0

Table 2-4. Infiltration Factors for Different Slope Classes

Slope (%)	Infiltration Factor
>10	0.00
5 – 10	0.05
2.5 – 5	0.10
1 – 2.5	0.15
<1	0.20

Permafrost, where present, significantly reduces or nearly eliminates groundwater recharge. Even within the active layer, where precipitation can infiltrate during unfrozen (thawed) conditions, the volume of water recharging the groundwater table is expected to be minimal. To account for the groundwater recharge-limiting effects of permafrost, the following reduction factors were applied to the surficial geology and vegetation (land cover) parameters of each raster grid cell: 95% reduction in continuous permafrost, 70% in extensive discontinuous permafrost and 50% in sporadic permafrost. These reduction factors were selected based on Heginbottom et al.'s (1995) generalized proportions of ground underlain by permafrost within each zone: 90-100% extent in continuous permafrost (average 95%), 50-90% extent in extensive discontinuous permafrost (average 70%) and 10-50% in sporadic permafrost (average 30%). The reduction factor for sporadic permafrost of 50%, the upper end of the areal proportion of the range rather than the average (30%), was ultimately used as it yielded more realistic recharge results (Section 3.3). More complex partitioning of runoff/recharge in association with permafrost would require a more accurate understanding of the distribution of permafrost and active layer dynamics than is currently available.

The infiltration distribution, in combination with the distribution of water surpluses and permafrost effects, produced a model of the spatial variability of groundwater recharge across the study area, from which the estimated groundwater recharge could be evaluated spatially. The purpose of the recharge potential map is to highlight areas where there is a greater potential for groundwater recharge, which should correspond to more productive hydrostratigraphic units and higher, more sustained winter baseflows. The opposite is true for low recharge areas. Areas where there is a greater potential for surface runoff should correspond to areas with lower aquifer potential and proportionally higher peak flows with limited winter baseflows.

2.3.4 Baseflow Hydrograph Separation for Model Calibration

While many assumptions were made in the development of the preliminary water balance model, the overall results of the model can be tested against established datasets from hydrometric stations within the Liard River basin. At the watershed scale, it is reasonable to assume that the vast majority of groundwater recharge eventually discharges to surface as stream baseflow. Therefore, the baseflow component of the hydrograph provides a good approximation of groundwater recharge such that the assumptions made in the selection of precipitation, ET, infiltration factors, and permafrost reductions can be validated as a whole. Assuming that groundwater loss to deep aquifers and across watershed boundaries is negligible, the average annual recharge within a watershed should be equal to the average annual baseflow value of the surface water body draining the watershed. Therefore, baseflow separation was conducted to provide a comparison of the results of the GIS-derived water budget.

Baseflows were determined for three watercourses with long-term streamflow records at Water Survey of Canada (WSC) hydrometric stations: South Nahanni River above Virginia Falls, Scotty Creek and Frances River (**Figure 1-1 and Table 2-5**). These three watercourses were selected for water balance model calibration as they range in watershed area, climatic conditions and soil types and, overall, their watersheds are broadly representative of the different physical characteristics within the Liard River basin. The watershed areas for each are also fully contained within the Liard River basin.

Table 2-5. Hydrometric Stations Used in the Baseflow Separation Analysis

Watershed	Station No.	Watershed Area (km^2)
South Nahanni River above Virginia Falls	10EB001	14,500
Scotty Creek	10ED009	168
Frances River	10AB001	12,800

Note: Station locations shown on **Figure 1-1**.

Streamflow data for each of the three watersheds was accessed using the ‘tidyhydat’ R package (Albers, 2017). To be consistent with the evaluation of meteorological data, the baseflow analysis was conducted on streamflow data from 1981-2010, except for Scotty Creek, where data were only available since 1995. The baseflow separation was then conducted using the following two approaches:

1. **Winter Flow Method** – In northern watersheds, mid-winter streamflow is assumed to be completely sustained by groundwater inputs. During the winter period, contributions to streamflow from surficial inputs are generally considered to be negligible (St. Jacques and Sauchyn, 2009). Therefore, one approach to determine the baseflow component of the hydrograph was to assume that the total average streamflow from January 1 to March 31 is a reasonable approximation of the baseflow contributions over an annual cycle. This approach has been applied throughout the NWT in previous investigations of baseflow (e.g. St. Jacques and Sauchyn, 2009); however, this approach likely underestimates the total annual baseflow contributions, which likely are higher during summer months because of the effect of summer precipitation events on the groundwater table and subsequent groundwater fluxes (St. Jacques and Sauchyn, 2009).

2. **Recursive Filtering** – A common approach to separate the baseflow component of a hydrograph is through the application of a recursive filter, commonly referred to as an 'Eckhardt filter' (Gonzales et al., 2009; Eckhardt, 2012). This approach requires the specification of two input parameters: (1) a recession constant *(a)* and (2) a baseflow index to be modelled by the algorithm *(BFI)* (for further information regarding this technique refer to Eckhardt [2012]). The application of the Eckhardt filter to the streamflow data was conducted using the 'FlowScreen' R package (Dierauer and Whitfield, 2019). Following the guidance of Dierauer and Whitfield (2019), the *a* value was set at 0.925 for all three watersheds. The *BFI* input parameter was defined as 0.25 for South Nahanni River and Scotty Creek, and 0.5 for Frances River, based on the characteristics of the surficial materials that underlie these watersheds and the guidance of Eckhardt (2012). Initial visual evaluations of the baseflow separation using this recursive filter produced an unrealistically low baseflow component during winter months, when virtually all streamflow is sustained by baseflow contributions. Therefore, the Eckhardt filter was only applied to warm-season flows (April 16 – October 31) and it was assumed that total cold-season streamflow (November 1 – April 15) could be completely attributed to baseflow. The November 1 and April 15 boundaries between the 'cold' and 'warm' seasons were determined through visual interpretation of the inflection point in the long-term daily average hydrographs (**Figure 2-1**).

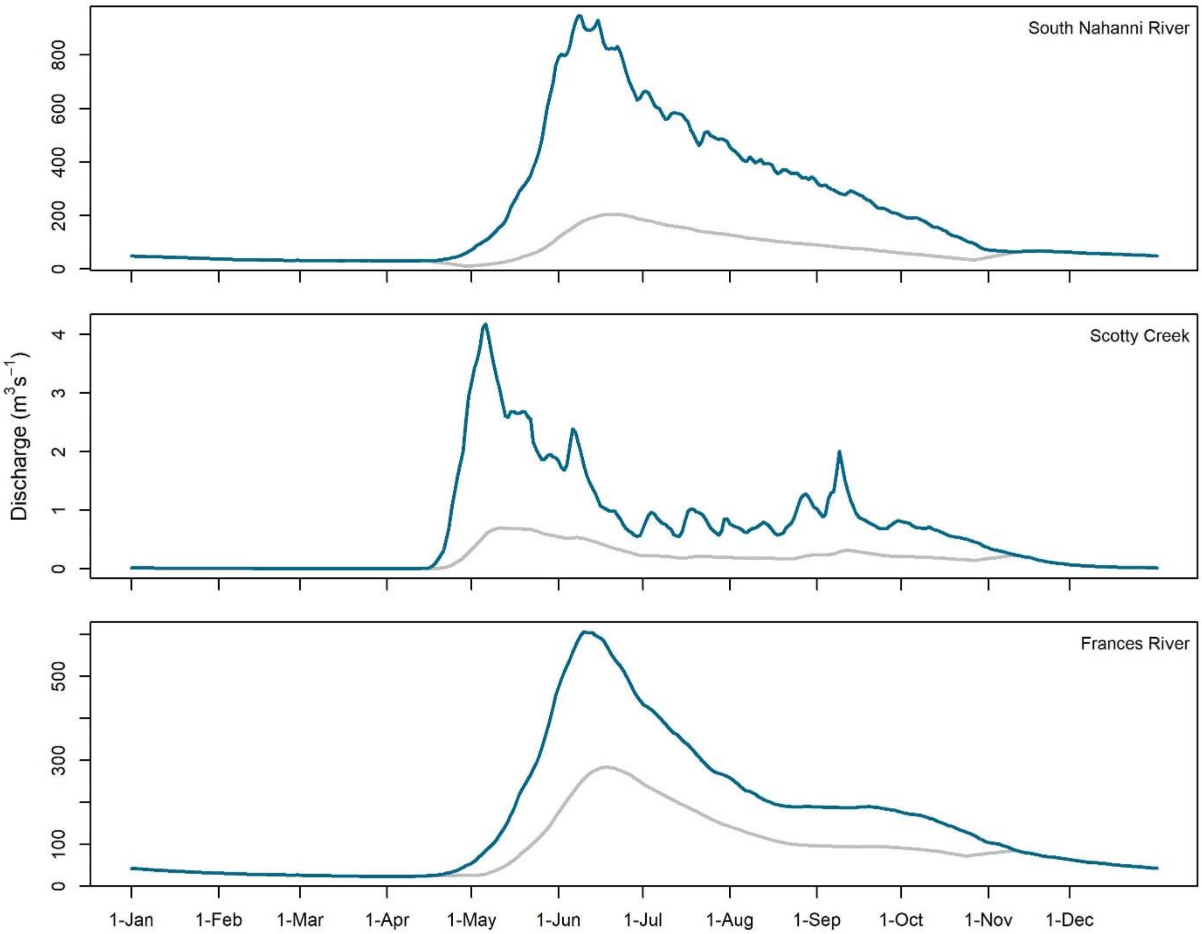


Figure 2-1. Average daily hydrographs of daily streamflow (blue) and the baseflow component derived using the seasonal flow recursive flow filter (grey) for the 1981-2010 period in South Nahanni River and Frances River and for the 1995-2010 period in Scotty Creek. The hydrological buffering effect of lakes explains the anomalous 'smoothness' of the Frances River hydrograph.

Long-term average annual baseflow rates are summarized in **Table 2-6**. The winter flow method provides baseflow estimates of <1% of mean annual discharge (MAD) in Scotty Creek where zero-flow conditions regularly exist throughout winter months, 16% of MAD in the South Nahanni River, and 19% of MAD in Frances River. As suggested by St. Jacques and Sauchyn (2009), these winter-flow estimates likely underrepresent actual baseflow conditions; therefore, they should only be used to project minimum potential baseflow values. In contrast, results using the seasonal recursive filter approach suggest that baseflow comprises 26% of MAD in Scotty Creek, 31% of MAD in South Nahanni River, and 55% of MAD in Frances River (**Figure 2-1**).

Table 2-6. Long-term Mean Annual Baseflow for Three Sub-basins in the Liard River Basin

Watershed	Mean Annual Discharge	Baseflow Contributions					
		Winter Baseflow Method			Recursive Filter		
	m^3/s	m^3/s	m^3/yr	mm/yr	m^3/s	m^3/yr	mm/yr
South Nahanni River	227.81	36.41	1.15×10^9	79	71.5	2.25×10^9	156
Scotty Creek	0.68	0.01	1.80×10^5	1	0.18	5.64×10^6	34
Frances River	157.54	29.81	9.38×10^8	73	87.4	2.76×10^9	215

2.4 Assessment of Potential Groundwater Vulnerability

Various land use activities have the potential to affect groundwater quality and/or quantity, especially where coincident with surficial (unconfined) aquifers or important recharge areas. An adaptation of Levson et al.'s (2018) approach for drawing attention to sub-basins most susceptible to contamination or unsustainable withdrawal of groundwater was followed, as described in the following subsections.

Mapping of all major land use activities[4] in the study area was compiled based on the highest-resolution, most up-to-date information available. All land use activities were evaluated and assigned to one of three broad categories based on their potential effect on groundwater quality and quantity in the study area (based on Levson et al., 2018) (**Table 2-7**). The relative degree of surface disturbance and potential for groundwater impact increase from Category 1 to Category 3. The highest disturbance category was used in areas where two or more disturbances overlapped.

Table 2-7. Categories of Disturbance Associated with Different Land Use Activities (Based on Levson et al., 2018)

Category	General Characterization	Example of land use activities
1	Land use activities involving minimal surface disturbance primarily to vegetation, with no or limited/short-term exposure of mineral soil, with relatively low potential for contamination of groundwater.	Cut-lines, powerlines, trails, seismic shotholes
2	Land use activities involving moderate surface disturbance, with removal of most or all vegetation and long-term exposure of mineral soils, with a low to moderate potential for contamination of groundwater.	Agriculture, water wells/drill holes, pipelines
3	Land use activities involving major surface disturbance, with removal of all vegetation, long-term exposure of mineral soils and reclamation unexpected, with the highest potential for contamination of groundwater.	Aggregate pits/quarries, cemeteries, residential areas, roads, runways, mining areas, oil & gas wells, waste facilities

[4] Only anthropogenic activities were included. Wildfires, which were included by Levson et al. (2018), were excluded due to their natural occurrence in northern Boreal and subarctic environments.

Areas (m^2) associated with each land use activity were adopted directly from polygon shapefiles of areal disturbances (e.g. agriculture, mining areas). For land use activities represented in available mapping as lines (e.g. pipelines, roads) and points (e.g. oil & gas wells, seismic shotholes), standardized buffers were applied to approximate the corresponding areal footprints (m^2) of disturbance. For example, a 5 m buffer was applied to cut-lines based on the average of modern and historical disturbance footprints. A 5 m-buffer disturbance footprint was assumed for seismic shotholes in accordance with permitted and typical footprints. A complete list of compiled land use activity mapping data and assumed areal footprints (buffers) is included in **Appendix B**.

2.4.1 Groundwater Quality

Land use activities can affect groundwater quality in surficial aquifers by introducing potential contaminants at rates and/or with concentrations that may trigger an exceedance of regulatory standards in the groundwater. Assessment of the potential impact of land use activities on groundwater quality within each of the 13 sub-basins was completed based on the distribution and nature of land disturbances (Categories 1, 2 or 3) sub-basin wide, within areas of aquifer potential, and in association with potential recharge. Consideration of the coincidence of land use activities with the areas of greatest contributions to groundwater recharge draws attention to locations where groundwater may be vulnerable to impact beyond the limits of surficial aquifers. Additionally, some areas of aquifer potential could be indirectly affected if they receive groundwater from sources outside their limits.

Three indices of groundwater quality disturbance potential were established for each of the 13 sub-basins. A stepwise overview of the calculation of each index, following its definition, is provided below:

Normalized Index of Proportion of Sub-basin Disturbed – a combined representation of the proportional areal extent and severity of disturbance within the entire sub-basin.

1. The total area of disturbance was calculated within each sub-basin [A].
2. All disturbed areas were categorized according to one of three levels (Category 1 ($_{Cat1}$), Category 2 ($_{Cat2}$), Category 3 ($_{Cat3}$)).
3. Each disturbance level was assigned a weighting factor, corresponding to the associated severity of the disturbance (Category 1 – 1, Category 2 – 3, Category 3 – 9). The departure from Levson et al.'s (2018) weights of 1, 1.5 and 2 was deemed necessary to better represent and contrast the increasing severity of potential disturbances across the three categories. For example, the weights of Levson et al. (2018) imply that groundwater is only twice as vulnerable to impact below mining areas as it is below survey cut-lines. The adjusted weighting better draws attention to areas of greatest concern and best satisfies the objective of establishing relative ranks within the study area.
4. Disturbance area values were multiplied by their corresponding weighting factors for each sub-basin, then divided by the *total area of the sub-basin*, to give a proportional weighted disturbance area within each sub-basin:

$$\textit{Sub-Basin-Wide Disturbance Index} = [(A_{Cat1} \times 1) + (A_{Cat2} \times 3) + (A_{Cat3} \times 9)] \,/\, \textit{Total area of sub-basin}$$

5. The index was then normalized to values ranging from 0 to 100 by dividing it by the highest index value for the population, multiplied by 100.

Normalized Index of the Proportion of Aquifers Disturbed – a combined representation of the proportional areal extent and severity of disturbance in areas of surficial aquifer potential.

1. The total area of disturbance in areas of surficial aquifer potential was calculated within each sub-basin [A].
2. Each area of disturbance was characterized both by category (severity) of disturbance and aquifer type (Wei et al., 2009).
3. Weighting factors were assigned to each category of disturbance, as in the previous index, as well as to each aquifer type (Type 1, 3 = 2 and Type 4a, 4b, 5b = 1), as a reflection of its general sensitivity.
4. Disturbance area values were multiplied by both corresponding weighting factors for each sub-basin, then divided by the *total area of aquifers within the sub-basin* (all types), to give a proportional weighted disturbance area of all aquifers in each sub-basin:

$$\text{Aquifer Area Disturbance Index} = \{2 \times [(A'_{Cat1} \times 1) + (A'_{Cat2} \times 3) + (A'_{Cat3} \times 9)] + 1 \times [(A''_{Cat1} \times 1) + (A''_{Cat2} \times 3) + (A''_{Cat3} \times 9)]\} \;/\; \text{Total area of aquifer potential in sub-basin}$$

where A' = Area of Type 1 and Type 3 aquifers, and
A'' = Area of Type 4a, Type 4b, and Type 5b aquifers
(n.b. Type 5b aquifers did not overlap with any disturbance).

5. The index was then normalized to values ranging from 0 to 100 by dividing it by the highest index value for the population, multiplied by 100.

Normalized Index of Proportional Disturbance of Potential Recharge – a combined representation of the proportional areal extent and severity of disturbance within areas of potential recharge.

1. The total area of disturbance was calculated within each sub-basin [A].
2. All disturbed areas were categorized according to one of three levels (Category 1 ($_{Cat1}$), Category 2 ($_{Cat2}$), Category 3 ($_{Cat3}$)).
3. Each disturbance category was assigned a weighting factor, corresponding to the associated severity of the disturbance (Category 1 – 1, Category 2 – 3, Category 3 – 9).
4. The average potential recharge value was calculated over the area of disturbance for each disturbance category, then multiplied by its respective weighting factor. The sum of these products for each basin was then divided by the total sub-basin area, to give a proportional weighted disturbance area for the potential recharge in each sub-basin:

$$\text{Recharge Disturbance Index} = \{[(R_{Cat1} \times A_{Cat1}) \times 1] + [(R_{Cat2} \times A_{Cat2}) \times 3] + [(R_{Cat3} \times A_{Cat3}) \times 9]\} \;/\; \text{Total area of sub-basin}$$

where R = average recharge over the corresponding disturbance area.

5. The index was then normalized to values ranging from 0 to 100 by dividing it by the highest index value for the population, multiplied by 100.

2.4.2 Groundwater Quantity

Land use activities can affect groundwater quantity by withdrawing water at a rate that exceeds the aquifer recharge capacity or at a rate that interferes with other water users or the natural environment. Levson et al.'s (2018) straightforward approach for evaluating potential effects of land use activities on groundwater quantity was applied to establish a **Normalized Index of Water Well Density**. The index was based simply on the water well density for each sub-basin, calculated as its total number of wells divided by the sub-basin area. For ease of comparison, the index was normalized to a value between 0 and 100 by dividing it by the highest index value for the population, multiplied by 100.

Limited data on water withdrawal rates precluded application of a more robust approach for evaluating 'groundwater stress', for example, through a comparison of total annual withdrawals from an aquifer with total recharge potential to the aquifer (as described further in the recommendations in Section 4.3). Even establishment of the Normalized Index of Water Well Density as a meaningful ranking tool was challenged by the limited availability of water well data (3 wells) in the NWT.

2.5 Prioritization of Future Aquifer Mapping and Characterization

Assessment of the potential effects of land use activities on a combination of both groundwater quality and quantity, in accordance with Levson et al. (2018), culminated in the identification of priority areas for future work. A composite rank of disturbance potential was calculated simply by assigning weighting factors to each of the indices of normalized groundwater disturbance potential. For consistency with Levson et al. (2018), weightings of 1.0 and 0.1 were used for disturbances of land surfaces related to water quality and the effects of well density on groundwater quantity, respectively. A total *Index of Groundwater Disturbance Potential* was calculated for each of the three combined representations of groundwater disturbance potential using the following formulae:

> **Index of Groundwater Disturbance Potential (Sub-basin)** = 1.0 x Normalized Index of the Proportion of Sub-basin Disturbed + 0.1 x Normalized Index of Water Well Density

> **Index of Groundwater Disturbance Potential (Aquifers)** = 1.0 x Normalized Index of the Proportion of Aquifers Disturbed + 0.1 x Normalized Index of Water Well Density

> **Index of Groundwater Disturbance Potential (Recharge)** = 1.0 x Normalized Index of Proportional Disturbance of Potential Recharge + 0.1 x Normalized Index of Water Well Density

Normalization of this total index was not required; the calculated values were simply ranked from highest (1) to lowest (13) for the 13 sub-basins. Lower-ranked (i.e. smaller rank number) basins were considered lower priority for future work.

3. Results

3.1 Summary of Data Coverage and Gaps

Table 3-1 summarizes the principal spatial data sources we compiled based on a systematic review of available information pertinent to the assessment of aquifers in the portion of the Liard River basin within Yukon and the NWT. Basic topographic and land cover data are widely available. However, geological, permafrost and subsurface datasets are incomplete and less detailed in comparison to what is available in other jurisdictions such as British Columbia (Levson et al., 2018). In its *State of Knowledge Report* for the Liard and Petitot River Basins, Golder Associates (2017) acknowledges the relative sparseness of groundwater-related information and unavailability of any hydrogeological mapping within its lower Liard River basin groundwater study area.

The bibliography in **Appendix A** identifies various information sources consulted in association with this project, beyond those specifically referenced at the end of this report. The following sub-sections reference and summarize the mapping, as well as associated gaps, of several compilation datasets: topography, bedrock geology, surficial geology, permafrost, land cover, site-specific subsurface data and land use activity.

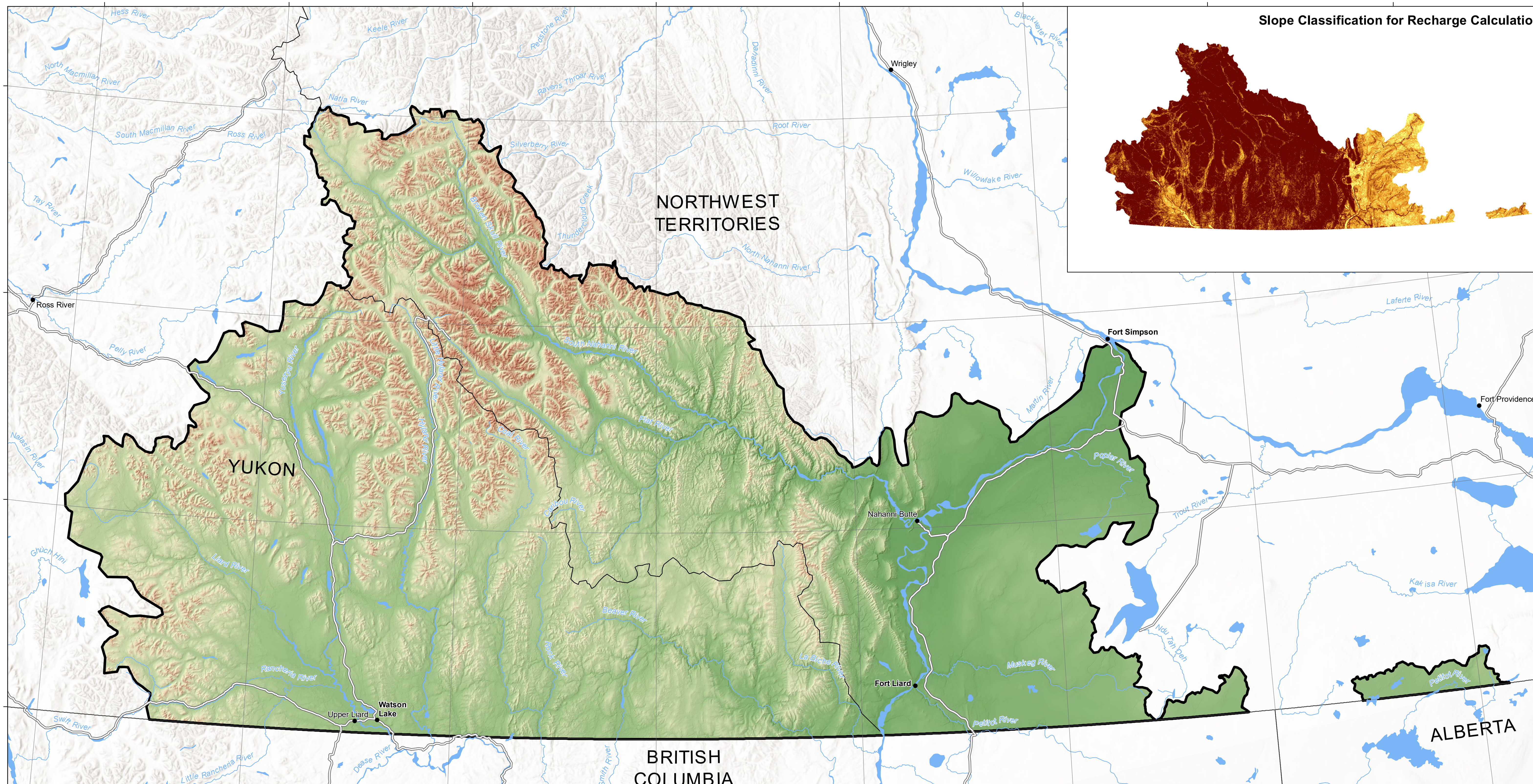
3.1.1 Topography Compilation

Approximately 20 m-resolution CDEM coverage is continuous throughout the study area; it provided an appropriate resolution for the topographic analyses in this basin-wide study (**Figure 3-1**). The 2 m-resolution ArcticDEM (Porter et al., 2018), which provides nearly continuous coverage except for isolated gaps scattered throughout, was only consulted to support interpretations and help calibrate understanding of areas of particular interest. In a broad sense, average elevations decrease in a counterclockwise direction throughout the study area. The Mackenzie and Selwyn Mountains predominate throughout the northern and central portions of the study area, the southern limit of the Pelly Mountains occupy the western portion of the study area, and the markedly lower-relief, low elevation Taiga Plains dominate the southeastern portion of the study area along the lower reaches of Liard River.

Table 3-1. Principal Spatial Data Sources Compiled for the Liard River Basin Transboundary Aquifer Assessment

Theme	Dataset	Source/Publisher	Scale/ Resolution	Relevance	Reference
Bedrock Geology	Yukon Digital Bedrock Geology	Yukon Geological Survey	1:250,000	Aquifer potential and water budget input	YGS Open File 2016-01 (Yukon Geological Survey, 2017)
	Geological (bedrock) Compilation of the Western Mainland and Arctic Islands of the Northwest Territories	Northwest Territories Geological Survey	1:250,000	Aquifer potential and water budget input	NWT Open File 2016-09 (Okulitch and Irwin, 2016)
Surficial Geology	Yukon Digital Surficial Geology (single compilation dataset, extending into NWT)	Yukon Geological Survey & Geological Survey of Canada	1:50,000 – 1:250,000	Aquifer potential and water budget input	Lipovsky and Bond (compilers), 2014
	NWT Digital Surficial Geology (single compilation dataset)	Geological Survey of Canada	1:125,000	Aquifer potential and water budget input	Côté et al., 2013
	Surficial Geology of Canada	Geological Survey of Canada	1:5,000,000	Aquifer potential and water budget input where no larger-scale mapping available	Geological Survey of Canada, 2014
Permafrost	Permafrost Probability Modelling of Southern Yukon	Wiley Online Library	30 m	Regional context and water budget input (Yukon)	Bonnaventure et al., 2012
	Permafrost Probability Modelling of Canada's Taiga Plains Ecozone	Wilfred Laurier University	30 m	Regional context (lack of field validation (to date) and minimal coverage precluded incorporation into water budget analysis)	Carpino et al., in preparation
	Circum-Arctic Map of Permafrost and Ground-Ice Conditions	National Snow and Ice Data Center	1:10,000,000	Regional context and water budget input (NWT)	Brown et al., 2002 (based on Heginbottom et al., 1995)
Elevation	ArcticDEM	Polar Geospatial Center	2 – 10 m	Regional context and site-specific interpretation of representative areas	Porter et al., 2018
	CDEM	Natural Resources Canada	~20 m	Regional context and water budget input	Canadian Digital Elevation Data
Land Cover & Use	Land Cover	Commission for Environmental Cooperation	30 m	Regional context and water budget input	North American Environmental Atlas, 2010
	Land Use Activities (Disturbances)	Various	Various	Assessment of potential vulnerability of groundwater to surface disturbances	Various (GeoYukon, CanVec, Gov't of NWT)
Site-specific Groundwater & Subsurface Information	GIN Water Wells	Groundwater Information Network	N/A	Representative hydrostratigraphic and hydrogeological properties of aquifers	Groundwater Information Network
	Groundwater Monitoring Wells Inventory	GNWT Environment and Natural Resources	N/A	Representative hydrostratigraphic and hydrogeological properties of aquifers (data only available for three wells within NWT portion of study area)	Gov't of NWT
	Yukon YOWN Waterwells	Yukon Well Observation Network	N/A	Representative hydrostratigraphic and hydrogeological properties of aquifers	Gov't of Yukon
	Water Well Records	Yukon Water Registry	N/A	Representative hydrostratigraphic and hydrogeological properties of aquifers	Gov't of Yukon
	Kotaneelee Water Quality Project	Yukon Geological Survey	N/A	Representative hydrostratigraphic and hydrogeological properties of aquifers	Unpublished, Gov't of Yukon
	Seismic Shothole Log Database	Geological Survey of Canada	N/A	Characterization of near-surface materials and ground ice	Smith, 2011 (NB: additional thematic geoscience derivatives available to support future research are identified in Section 4.3.1)
	Orogo Well Data	Office of the Regulator of Oil and Gas Operations	N/A	Characterization of shallow and deep bedrock	Office of the Regulator of Oil and Gas Operations
	Springs	Various	N/A	Site-specific locations of groundwater discharge (including thermal springs, sourced from depth)	Michel, 1986; Caron et al., 2007; Ford, 2009; Grasby et al., 2009; Government of Yukon, 2012; Nahanni River Adventures and Canadian River Expeditions, 2019; Parks Canada, 2019
	Water Quality Data (primarily surface water)	GNWT Environment and Natural Resources, Government of Yukon and Government of Canada	N/A	Site-specific records of water quality (e.g. metals, polyaromatic hydrocarbons, organochlorine pesticides, dioxins and furans, sediment toxicity and enzyme induction) from regional and community-based monitoring	Taylor et al., 1998; Gov't of NWT, 2020; Gov't of Yukon, 2020

*Note: Numerous regional-scale to site-specific reports and publications were also compiled to inform understanding of aquifer potential and characteristics; key references are cited throughout the report and supplemented by a more comprehensive bibliography of available information in **Appendix A**.*



LEGEND:

Elevation (masl)

High : 2752

Low : 120

Slope Classes

- 0 - 0.1 %
- 0.2 - 0.5 %
- 0.5 - 1 %
- 1 - 2.5 %
- 2.5 - 5 %
- 5 - 10 %
- > 10 %

- Study Area
- Provincial/Territorial Border
- Major Road/Highway
- River

Digital Elevation Model provided by Natural Resouces Canada (CDEM).

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

DRAWN: BE | CHECKED: RM | PRINT SIZE: 11 x17 "

Figure 3-1

Basin-wide Topographic Mapping

Project No. 1508907
Date: Mar 19, 2020
Revision: 1

Palmer™

AURORA GEOSCIENCES

Document Path: C:\Egnyte\Shared\Projects\Active\15089 - Government of NWT\1508907 - Liard Aquifer Assessment\Mapping\Figures\5_ArcGIS\Report\1508907_3-1-1_Topography.mxd

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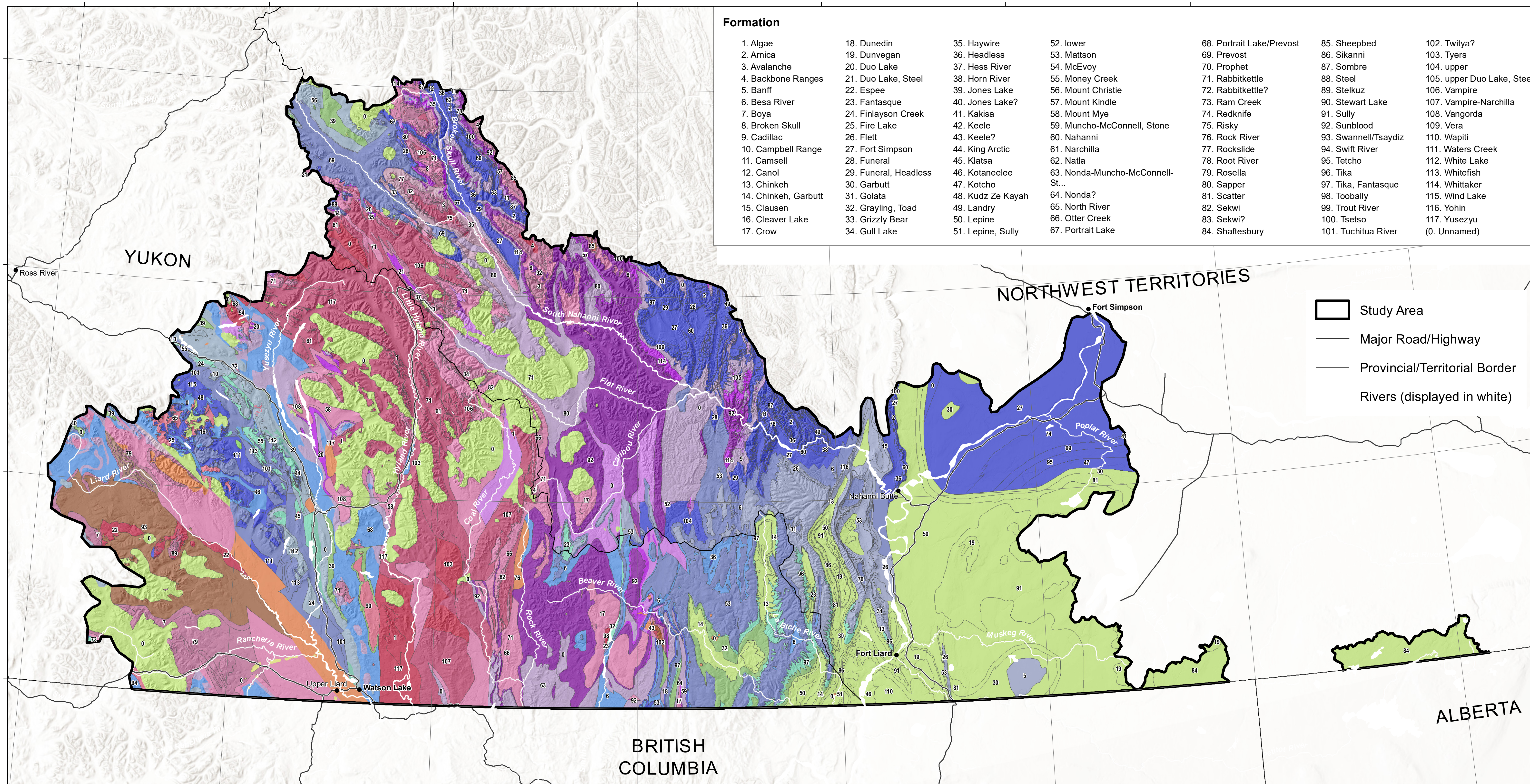
3.1.2 Bedrock Geology Compilation

A territory-wide compilation of bedrock geology mapping was already available for both Yukon (Yukon Geological Survey, 2017) and the NWT (Okulitch and Irwin, 2016). It provides seamless coverage of bedrock formations and associated lithologies, whether exposed at surface or buried by unconsolidated materials, throughout the study area (**Figure 3-2**).

The bedrock geology in the study area is most readily described by its major terranes (**Figure 3-3**). The mountainous regions of Yukon are composed of the Cassiar, Yukon-Tanana and Slide Mountain Terranes. The Neoproterozic to Triassic Cassiar Terrane's tectonic setting was the Laurentian continental margin and is therefore primarily of siliciclastic and carbonate shelf facies, with minor amounts of shale (Colpron and Nelson, 2011). The Late Devonian to Late Permian Intermontane Yukon-Tanana and Slide Mountain Terranes are accreted sequences developed in arc and back-arc basin tectonic settings (Colpron and Nelson, 2011). The Yukon-Tanana Terrane is composed primarily of metasedimentary rocks and unconformably overlain by back-arc and arc sequences (Klondike, Klinkit, and Finlayson) (Colpron and Nelson, 2011). The Slide Mountain Terrane is composed of sedimentary rocks such as argillite and chert, and mafic to ultramafic igneous rocks (Colpron and Nelson, 2011). The Neoproterozoic to Triassic North American basinal strata, which comprise the majority of the study area, are composed primarily of fine-grained siliciclastic rocks, chert and shale that have a continental basin or slope origin, as well as local volcanic rocks (Colpron and Nelson, 2011). The similar-aged North American platform to the east is composed of basinal strata such as marine siliciclastic and carbonate rocks (Colpron and Nelson, 2011).

The geological Liard Basin, part of the North American basinal and platform terranes, is a structurally bounded sedimentary basin sharing borders with British Columbia, Yukon and the Northwest Territories (Petrel Robertson Consulting Ltd., 2013). It is a several thousand-metre, relatively undeformed sequence bounded by the Bovie Fault zone to the east (Petrel Robertson Consulting Ltd., 2013). This region has been researched in more detail because of the world-class hydrocarbon potential in the basin. The easternmost Terrane is the Archean to lower Paleozoic Canadian Shield, which is composed of Precambrian basement terrane and a thin Paleozoic sedimentary cover.

While this study focuses on shallow or surficial aquifers, the bedrock within the Liard River basin is known to host deep aquifer systems that are utilized as source water and water disposal for oil and gas exploration. These include, but are not limited to, Mississippian carbonates, and Permian and Cretaceous sandstones (Petrel Robertson Consulting Ltd., 2013; Golder Associates, 2017). The water in these deep bedrock aquifers is brackish to saline (Petrel Robertson Consulting Ltd., 2013) and is expected to have very limited and isolated interactions with the shallow aquifers utilized for potable source water or that contribute baseflow to river systems.



LEGEND:

Period (Youngest to Oldest)

- Neogene to Quaternary
- Paleogene
- Cretaceous
- Jurassic
- Triassic
- Permian toTriassic
- Permian
- Carboniferous to Permian
- Carboniferous-Mississippian
- Carboniferous
- Devonian to Triassic
- Devonian to Carboniferous
- Devonian to Carboniferous-Mississippian
- Devonian
- Silurian to Devonian
- Silurian
- Ordovician to Devonian
- Ordovician to Silurian
- Ordovician
- Cambrian to Devonian
- Cambrian to Silurian
- Cambrian to Ordovician
- Cambrian
- Ediacaran, Devonian
- Ediacaran to Cambrian
- Ediacaran
- Cryogenian, Cambrian
- Cryogenian, Ediacaran
- Cryogenian

Bedrock geology mapping from 1:250,000 scale data compiled from government sources (see report for references).

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

DRAWN: BE | CHECKED: RM | PRINT SIZE: 11 x17 "

Figure 3-2
Basin-wide Compilation of Bedrock Geology Mapping

Project No. 1508907
Date: May 27, 2020
Revision: 1

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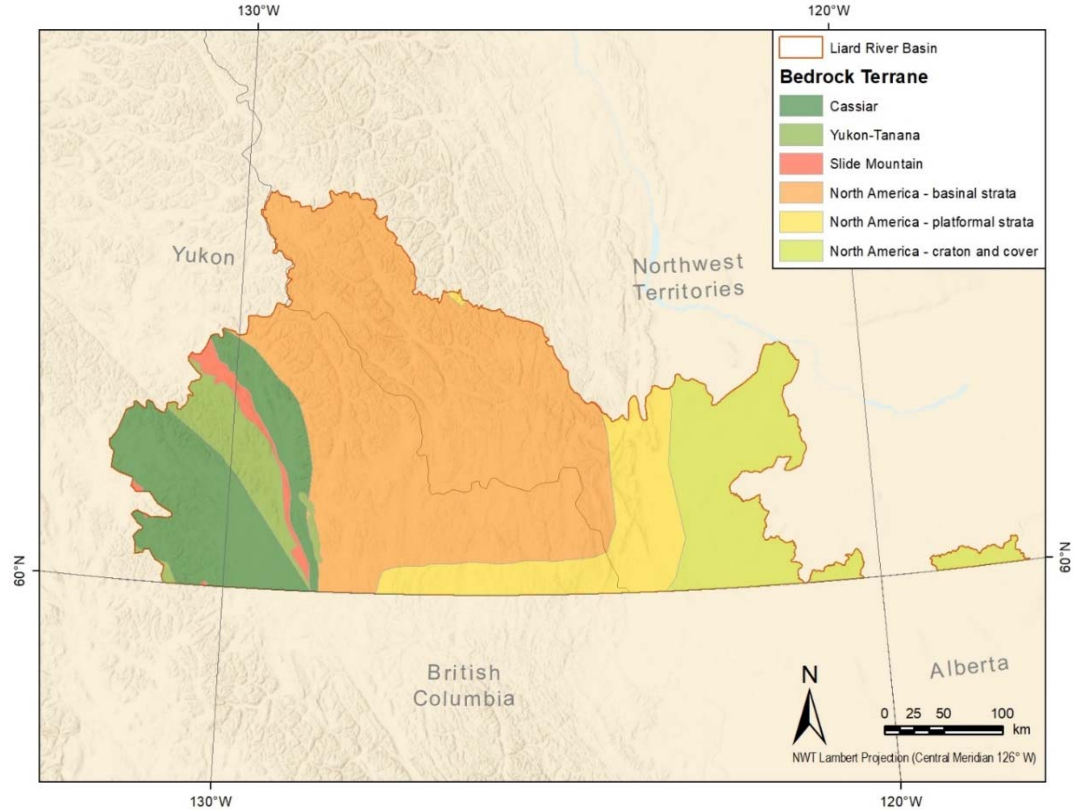
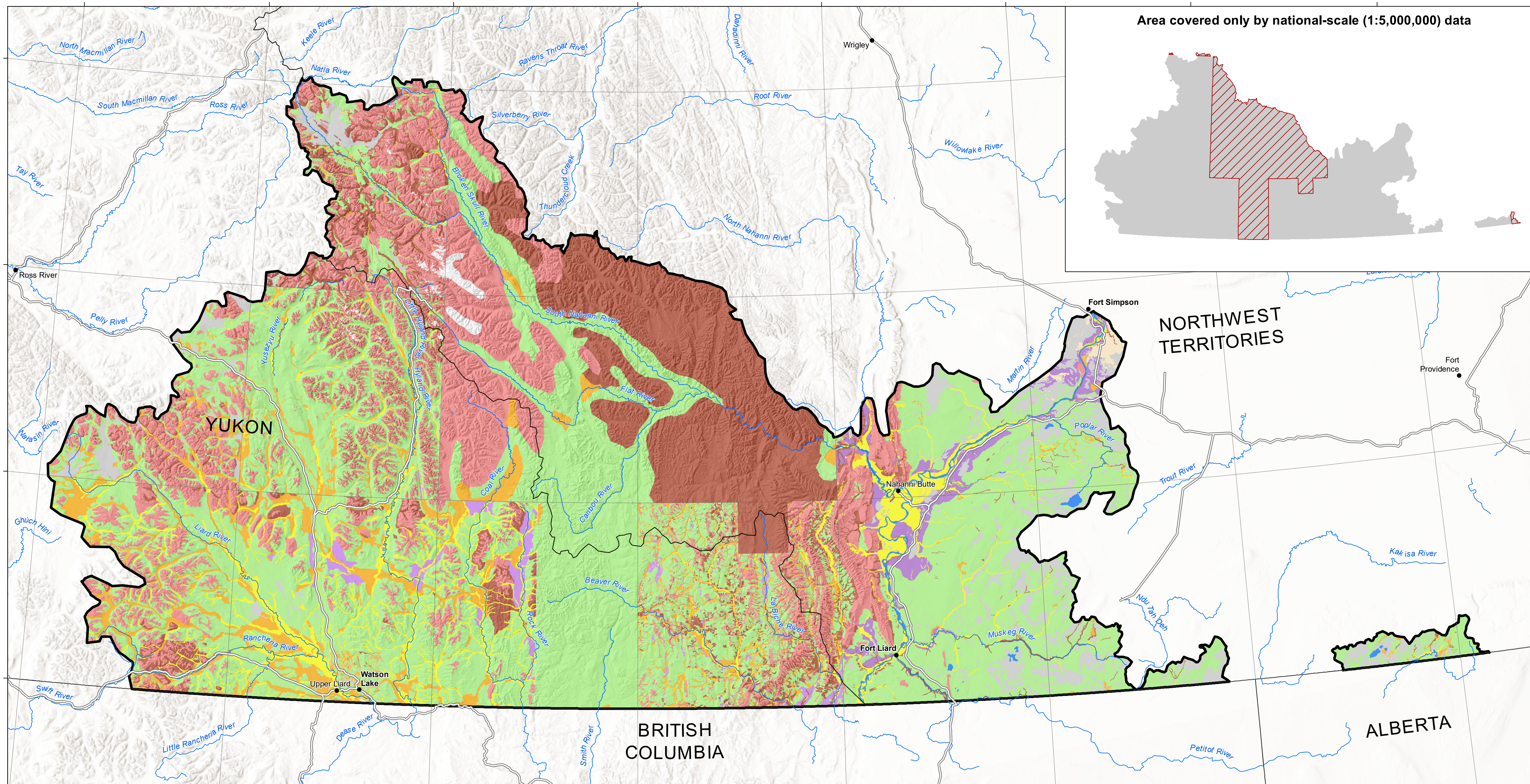


Figure 3-3. Bedrock terranes within the study area.

3.1.3 Surficial Geology Compilation

Figure 3-4 presents the basin-wide compilation of available surficial geology mapping, symbolized by dominant surficial material, with original scales ranging from 1:50,000 to 1:5,000,000. The compilation includes the pre-existing digital compilations of available surficial geology mapping in Yukon (Lipovsky and Bond (compilers), 2014) and the NWT (Côté et al., 2013). Larger-scale mapping (e.g. 1:20,000) was excluded from the compilation due to its very limited coverage and to avoid unnecessary inconsistency in mapping detail for this basin-wide assessment. Of greatest significance is the gap in regional-scale (≥1:250,000) surficial geology mapping, significant in extent (33,910 km^2) and contrast in detail (1:5,000,000), in the north-central portion of the study area encompassing portions of Nahanni National Park (see inset in **Figure 3-4**). Also apparent are straight-edged boundaries between surficial geology units, along the adjoining limits of adjacent map sheets, with inconsistencies associated with contrasting scales. Resolution of poor edge-matching was beyond the scope of this study.

The surficial geology of the study area reflects topographic and bedrock controls, as well as a history of repeated glaciations during the late Pleistocene. Small areas in the north-central portion of the study area, within Nahanni National Park, have not been glaciated for several hundreds of thousands of years (e.g. Ford, 1974; Bednarski, 2008a). The compilation map reveals widespread till cover across most of the study area (**Figure 3-4**), although much of it is characterized as a veneer (<1-2 m thickness) and is of little consequence to surficial aquifer potential. As noted in Section 2.2.1, surficial veneers were disregarded when considering the potential presence and type of underlying bedrock aquifers and infiltration potential.



LEGEND:

Permanent Ice and Snow	Lacustrine
Water	Lacustine or Glaciolacustrine[1]
Organic	Glaciolacustrine
Alluvial	Glaciofluvial
Colluvial	Till
Eolian	Rock

Study Area
Provincial/Territorial Border
Major Road/Highway
River

1 - Not differentiated in Northwest Territories portion of the study area

Surficial geology mapping from 1:50,000 to 1:5,000,000 scale compiled from government sources (see report for references).

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

DRAWN: BE | CHECKED: RM | PRINT SIZE: 11 x17 "

Figure 3-4

Basin-wide Compilation of Surficial Geology Mapping

Project No. 1508907
Date: Mar 19, 2020
Revision: 1

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Exposed bedrock and colluvium dominate the rugged portions of the various mountain ranges (**Figure 3-4**). Glaciofluvial complexes, largely outwash deposits also associated with eolian sediments, occupy many of the large river valleys, especially near major confluences in areas of natural widening. Glaciolacustrine sediments, which are under-represented by the 1:5,000,000-scale mapping encompassing southern Nahanni National Park (McKillop, 2012), occur in isolated areas where drainage was blocked by retreating and thinning glaciers. Fluvial sediments typically follow modern creek and river valleys, and may include terraces in addition to active floodplain environments. Mappable lacustrine sediments are relatively uncommon within the study area. Organic material is likely under-represented in the surficial geology mapping, based on review of satellite imagery and familiarity with ground conditions in the study area, largely because surficial geologists commonly disregard organic veneers (<1-2 m thick) and prioritize characterization of the underlying material (e.g. till). In the areas surrounding Fort Liard and Nahanni Butte, for example, the mapped glaciolacustrine deposits are typically veneered by unrepresented organic material (R. Smith, pers. comm.).

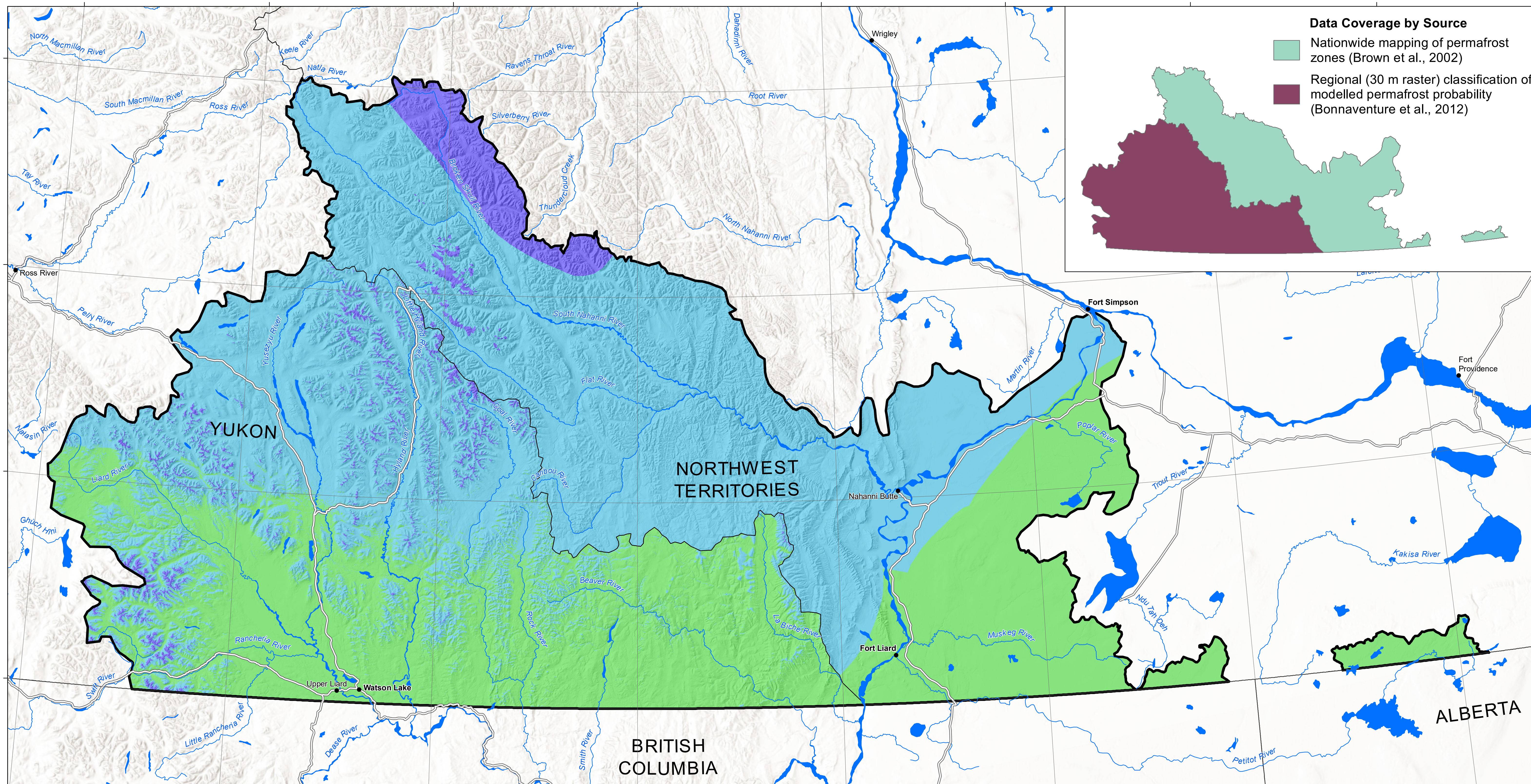
3.1.4 Permafrost Compilation

Figure 3-5 presents the basin-wide compilation of permafrost mapping, symbolized according to the extent-based zonations of sporadic, extensive discontinuous or continuous permafrost. For the purposes of this study, a compilation map of permafrost was created using the Bonnaventure et al. (2012) 30 m raster-based permafrost probability mapping, in Yukon, and the nationwide mapping by Brown et al. (2002), a refinement to the original mapping by Heginbottom et al. (1995), in the NWT. This division avoided intra-basin resolution contrasts, through separation along the watershed-defined border. It also avoided potential inconsistencies or inaccuracies introduced through the incorporation of Carpino et al.'s (in preparation) preliminary mapping, which has not yet been field-validated and only covers the extreme southeastern corner of the study area.

The mapping represents a gradation in the extent from sporadic permafrost (i.e. underlies 10-50% of the area), in the southern portion, to a large band of extensive discontinuous permafrost (i.e. underlies 50-90% of the area) covering most of the remaining study area. Continuous permafrost (i.e. underlies 90-100% of the area) is only found in the northernmost portion of the study area, in the Mackenzie Mountains.

3.1.5 Land Cover Compilation

Continuous mapping of land cover data covering North America at a resolution of 30 m, current to 2010, was available from the Commission for Environmental Cooperation (**Figure 3-6**). It distinguishes land cover according to major types of forests, shrubland, grassland, tundra, wetland and other unvegetated characteristics. Barren lands predominate the highest areas of the Pelly, Selwyn and Mackenzie Mountains, which include a scattered distribution of permanent snow and ice (glaciers). Grasslands and shrublands predominate in middle to upper elevations. Needleleaf (coniferous) forest communities represent the most widespread land cover in the study area, occupying most moderate to low elevation areas. Broadleaf (deciduous) forest communities are mainly limited to the valleys of the southern Mackenzie Mountains and the lower Liard River lowlands. The extent of wetlands is poorly represented by this continent-wide, raster-based, semi-automated classification (purple areas in **Figure 3-6**), based on comparison with the manually interpreted extent of organic material (grey areas in **Figure 3-4**) and familiarity with the ground conditions in the Fort Liard area, for example.



LEGEND:

- Sporadic Discontinuous
- Extensive Discontinuous
- Continuous
- Study Area
- Provincial/Territorial Border
- Major Road/Highway
- River

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

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Liard River Basin Transboundary Aquifer Assessment

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Figure 3-5

Basin-wide Compilation of Permafrost Mapping

Project No. 1508907
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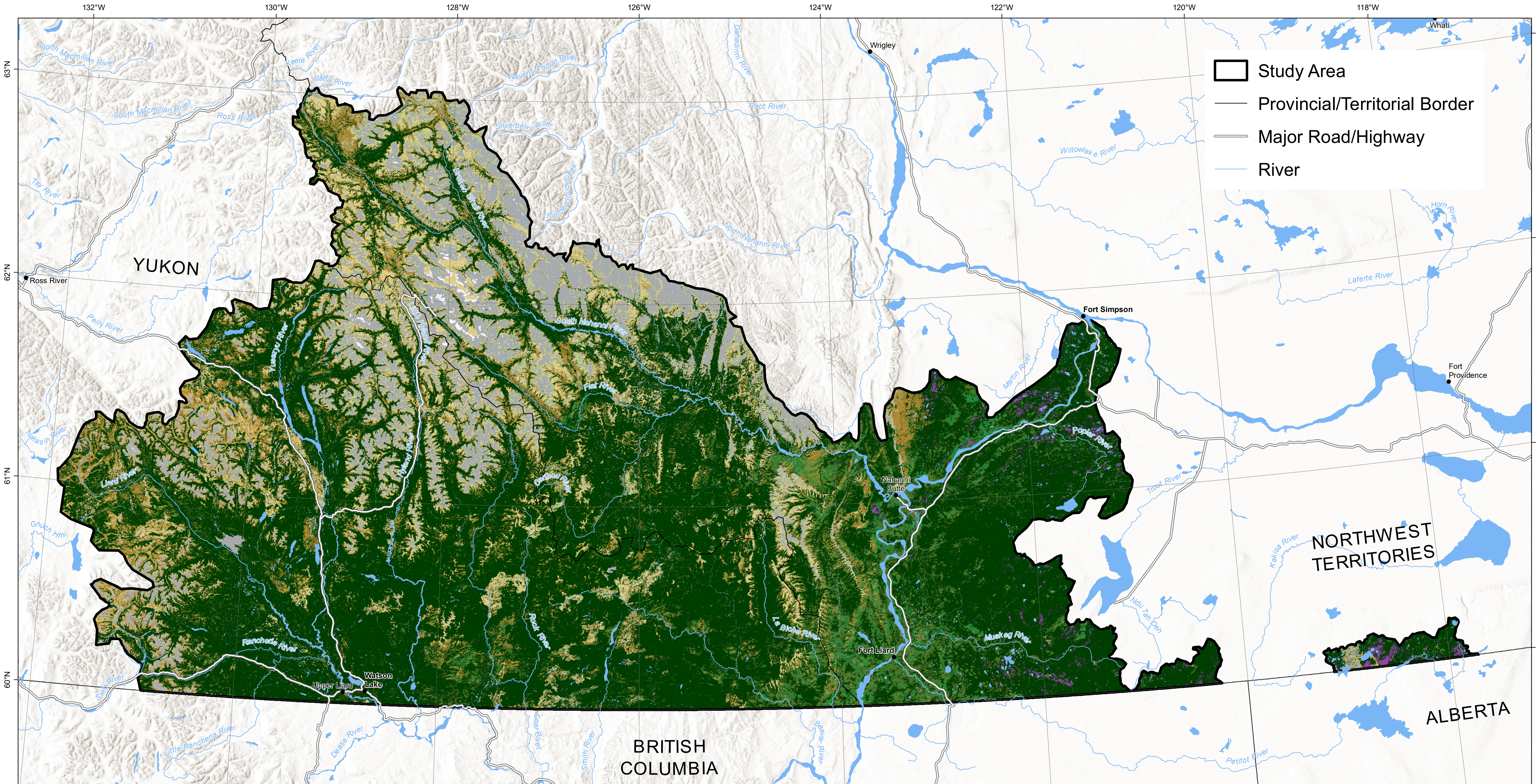

LEGEND:

- Temperate or sub-polar needleleaf forest
- Sub-polar taiga needleleaf forest
- Temperate or sub-polar broadleaf deciduous forest
- Mixed forest
- Temperate or sub-polar shrubland
- Temperate or sub-polar grassland
- Sub-polar or polar shrubland-lichen-moss
- Sub-polar or polar grassland-lichen-moss
- Sub-polar or polar barren-lichen-moss
- Wetland
- Cropland
- Barren lands
- Urban
- Water
- Snow and Ice

2010 Land Cover of North America at 30 meters provided by the Commission for Envirnmental Cooperation.

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

DRAWN: BE	CHECKED: RM	PRINT SIZE: 11 x17 "

Figure 3-6

Basin-wide Land Cover Mapping

Project No. 1508907
Date: Mar 20, 2020
Revision: 1

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3.1.6 Site-specific Subsurface Data Compilation

Subsurface data coverage is sparse and mainly concentrated in the southeastern corner of the study area in association with areas of oil and gas exploration and extraction activity in the geological Liard Basin (**Figure 3-7**). Beyond this concentration of oil and gas wells and seismic shotholes, 220 water wells are scattered throughout Yukon and NWT communities and areas of resource interest. In its comprehensive *State of Knowledge Report* for the Liard and Petitot River Basins, Golder and Associates (2017) acknowledges that "data on groundwater wells are sparse for…Yukon and Northwest Territories" (p. 21). Well records were only available for a small subset of the identified well locations. Documented locations of groundwater springs, commonly with little additional information, were compiled from publications and on-line sources (**Figure 3-7**) listed in **Table 3-1**.

3.1.7 Land Use Activity Compilation

A basin-wide compilation of available mapping of land use activities, categorized according to one of three levels of disturbance (based on Levson et al., 2018), indicates most land use activities occur in association with resource activity and road networks in the southern half of the study area (**Figure 3-8**). The greatest concentration of surface disturbance is in the southeastern corner of the study area, mostly in the *Lower Liard – Mouth* sub-basin, where oil and gas exploration is most widespread. The most conspicuous disturbance pattern in this sub-basin, however, represents seismic cut-line grids, which pose minimal risk to groundwater. A variety of overlapping land use activities occur in association with most communities, such was Watson Lake, Yukon, and constitute a risk to groundwater where underlain by aquifers.

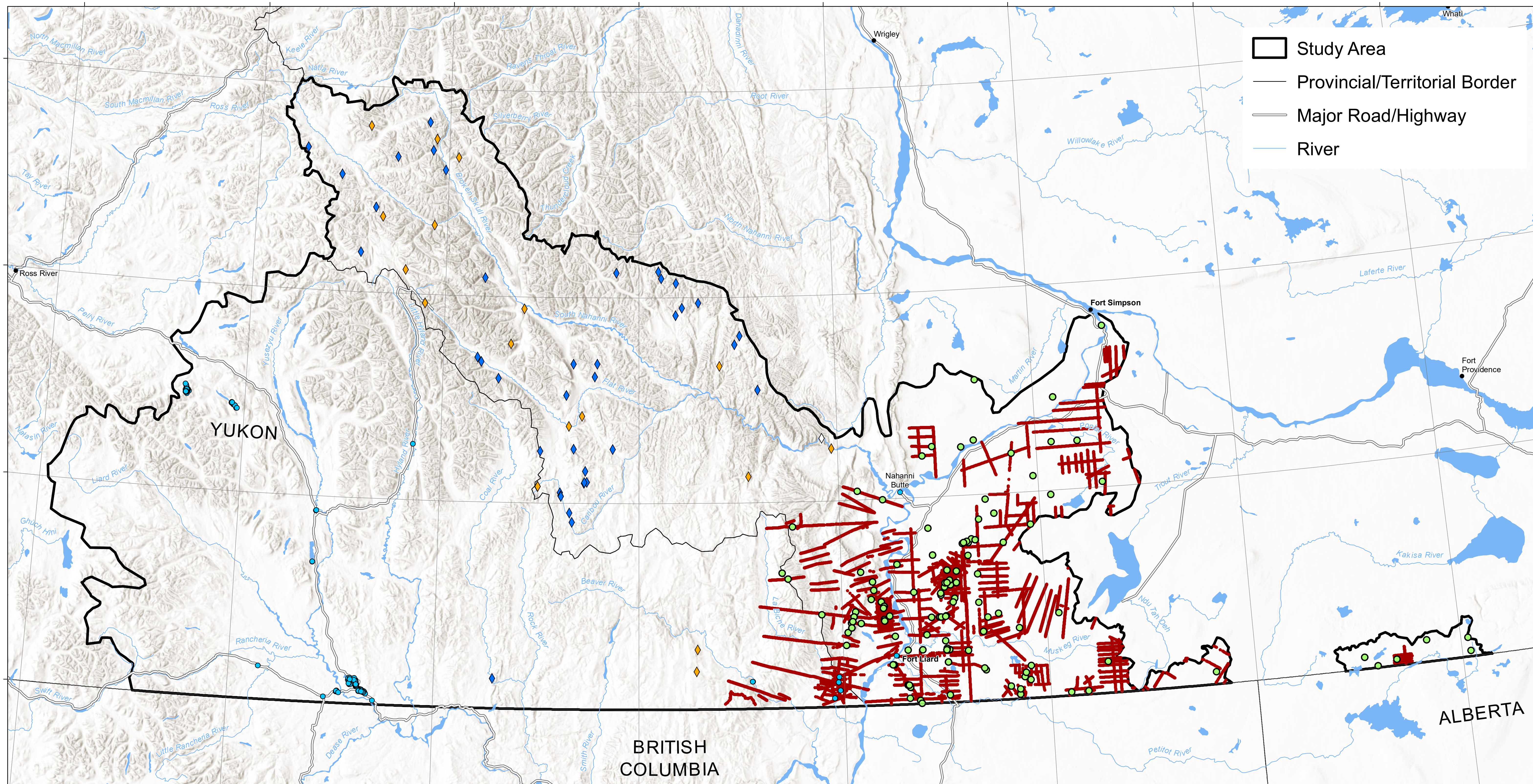
3.2 Surficial Aquifer Potential

3.2.1 Overview

Figure 3-9 presents the compilation mapping of areas with surficial aquifer potential, based primarily on the type, characteristics and distribution of surficial geology units, with consideration for limited subsurface and/or aquifer information available in sparse well records and groundwater-related publications. Shallow groundwater flow systems are controlled by local topography and relative permeability of the surficial and/or upper bedrock materials. Groundwater flow is expected to mimic topography and generally flow from areas of higher elevation to areas of lower elevation.

Potential aquifers within the Liard River basin represent two primary groups and five main types from the classification by Wei et al. (2009) (**Tables 2-1** and **3-2**). **Figure 3-10** provides a schematic cross-sectional representation of the main aquifer types interpreted to occur within the study area. Cross-sections representing actual subsurface stratigraphy and inferred aquifer/aquitard units are included for the Fort Liard, Kotaneelee and Watson Lake areas are provided below in sections 3.2.2, 3.2.3 and 3.2.4.

As noted in Section 2.2.1, a TPI-based analysis was used to approximate the occurrence of potential Type 1 and Type 3 aquifers in the north-central data gap area. The areas of aquifer potential from the raster-based (TPI) analysis contrast in appearance with areas of potential aquifers based on manually delineated surficial geology. The TPI-based Type 1 and Type 3 aquifers inherently have greater granularity and more scattered distribution than those delineated manually. The TPI-based areas of aquifer potential also appear to over-predict total extent by a factor of about 2, based on comparison in the training area of the extents of aquifer potential represented in ≥1:250,000-scale surficial geology mapping and generated by the TPI analysis. Despite the limitations of the attempted delineation of areas of aquifer potential based on the TPI analysis, the general valley-bottom distributions are appropriate and ensure such sensitive environments are not completely overlooked in the assessment of aquifer vulnerability. Areas of Type 4a and Type 4b aquifer potential are not represented in the data gap area, for reasons outlined above in Section 2.2.1, but the relative ruggedness and locally unglaciated history of most of this gap area likely moderate possible under-representation.



LEGEND:

- Water Well
- Oil and Gas Well
- Seismic Shothole

Known Spring Locations

- Thermal (above 15 °C)
- Cool/Cold (below 15 °C)
- Unknown Temperature

Notes
a. Water well and oil & gas well locations provided by the governments of Yukon and the Northwest Territories.
b. Seismic shothole locations (and information from drillers' logs) compiled by Smith (2011).
c. Spring locations from various publications and online sources (refer to report for references).

KILOMETRE SCALE:
0 10 20 40 60 80 100
NWT Lambert Projection (Central Meridian 126° W)

N

Figure 3-7
Basin-wide Compilation of Site-specific Subsurface Data
Project No. 1508907
Date: Jun 01, 2020
Revision: 1

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

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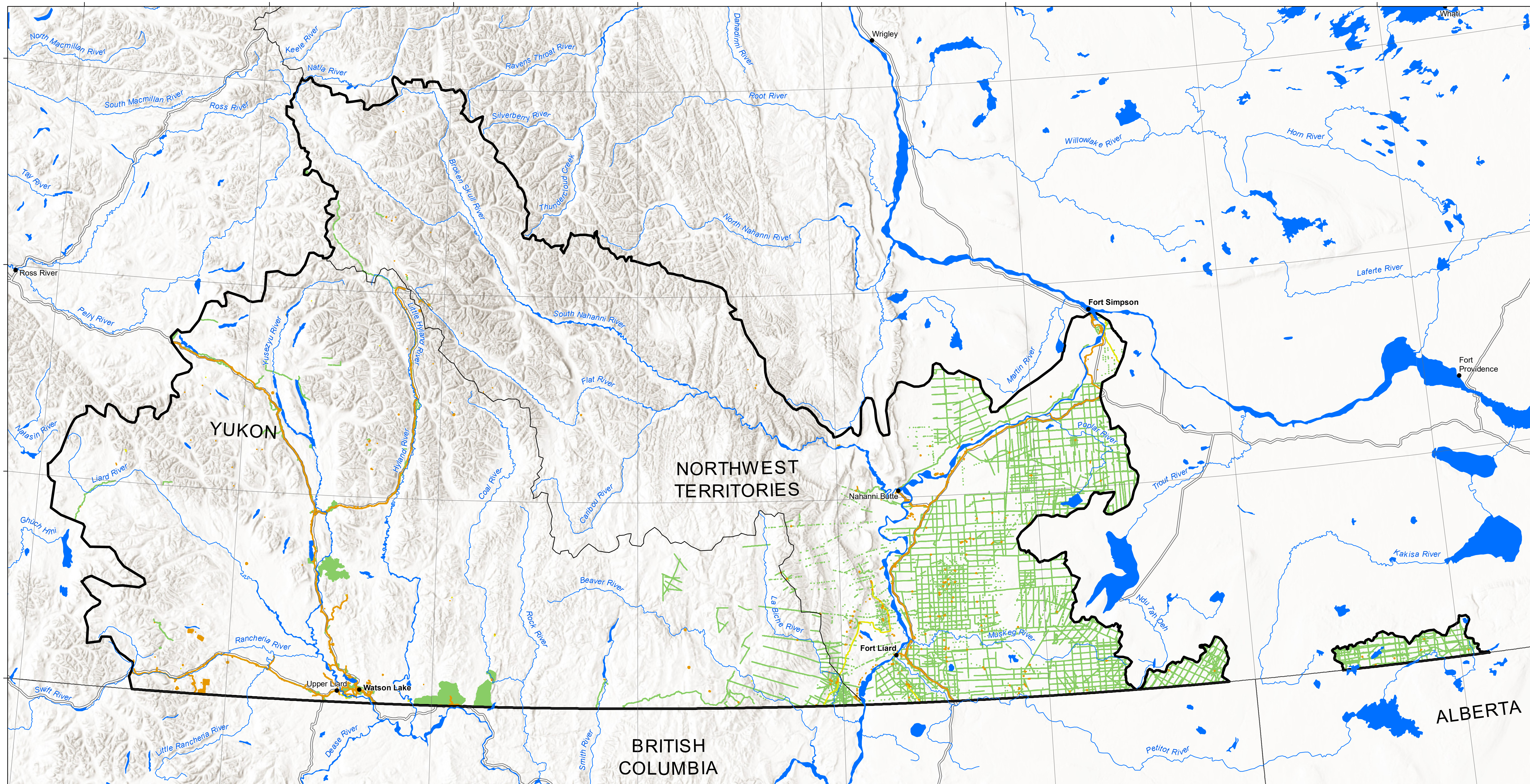

LEGEND:

Category of Disturbance

Increasing relative severity

1

2

3

Study Area

Major Road/Highway

River

Notes:
1. The highest category of disturbance was applied to any areas of overlapping land use activities.
2. "Major Roads/Highways" display data from the 1:1,000,000 scale Atlas of Canada and do not necessarily match the higher resolution data displayed in the categorization of land use activies.
3. See report for definitions and examples of each category of disturbance, based on Levson et al. (2018).

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

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Figure 3-8

Basin-wide Compilation of Land Use Activities

Project No. 1508907
Date: Mar 20, 2020
Revision: 1

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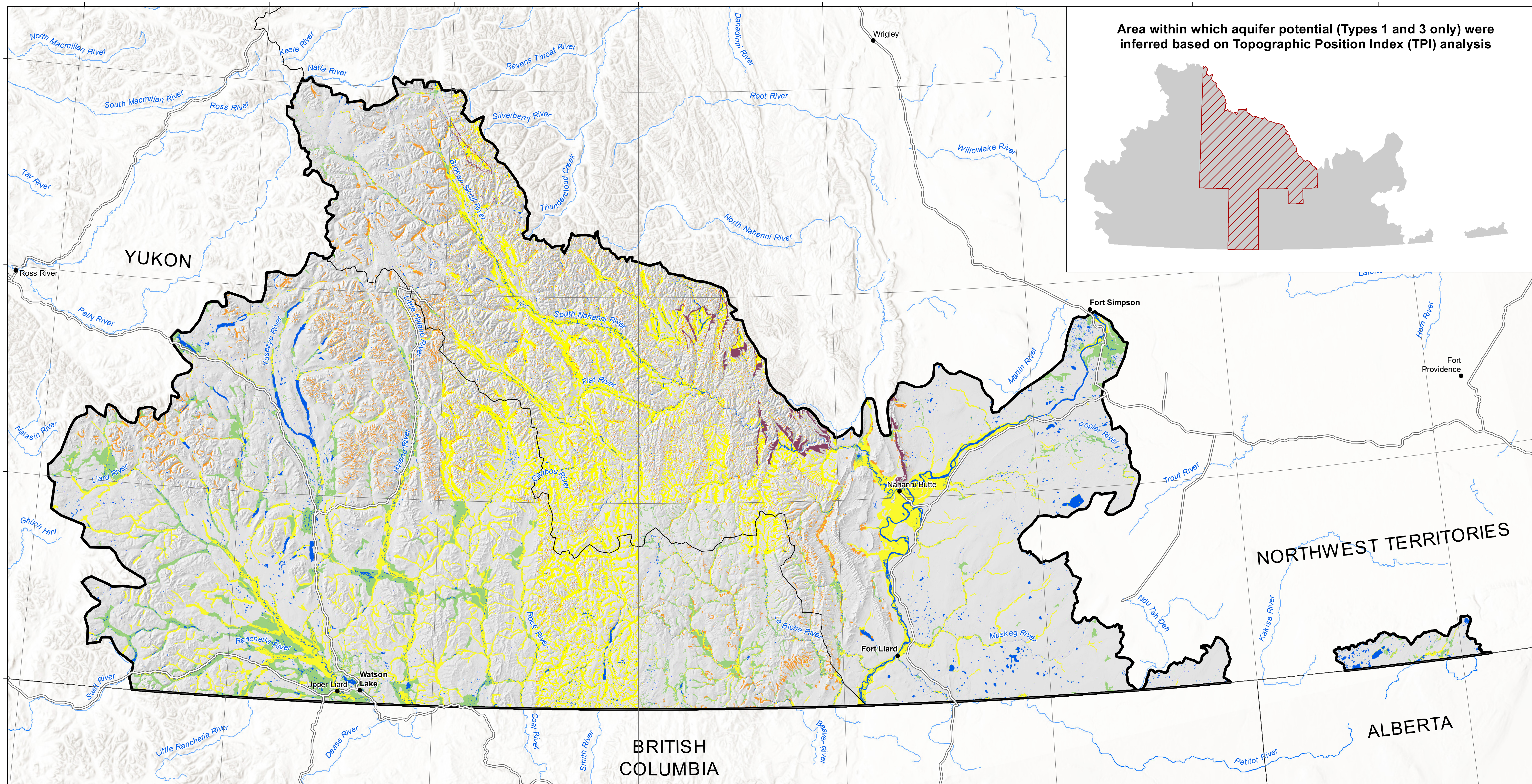

LEGEND:

Type 1	Study Area
Type 3	Provincial/Territorial Border
Type 4a	Major Road/Highway
Type 4b	River
Type 5b	

See report for definitions and examples of each type of aquifer, based on Wei et al. (2009).

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

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Liard River Basin Transboundary Aquifer Assessment

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Figure 3-9
Surficial Aquifer Potential

Project No. 1508907
Date: Jun 02, 2020
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Table 3-2. Areal Proportion of Aquifer Classes (Based on Wei et al., 2009)

Aquifer Type	Area (km^2)	Basin-wide Proportional Area (%)
Type 1	14,218[a]	11.4
Type 3	2,663[b]	2.1
Type 4a	5,247[c]	4.2
Type 4b	4[c]	<0.1
Type 5b	451[d]	0.4
Low Aquifer Potential (poor aquifers & aquitards)	101,713	81.8
Total	124,296	100.0

Notes:

[a] Includes 7,504 km^2 total area from the TPI-based data gap coverage

[b] Includes 915 km^2 total area from the TPI-based data gap coverage

[c] Excludes any potential occurrence in data gap area, because cannot be readily inferred from available information

[d] Includes exposed and veneered areas of karstic/potentially karstic Nahanni Formation

Table 3-2 summarizes the proportional distribution of each potential surficial aquifer type. Areas with potential Type 1 aquifers are the most common and geographically widespread, both within and outside the data gap area. Logically, they are predominantly concentrated along the bottoms of river and creek valleys. Areas with potential Type 3 aquifers typically occur at slope-toe positions in mountainous terrain within and outside the data gap area. Areas with potential Type 4a aquifers, only represented in mapping outside the data gap area, are most widespread in lowlands and broad valleys (e.g. upper reaches of the Liard River), where meltwater became concentrated during deglaciation of the region. Areas with potential Type 4b aquifers are understandably poorly represented in available, regional-scale surficial geology mapping, so their distribution and extent are undoubtedly underestimated (as described further in Section 4.3). Areas with potential Type 5b aquifers are within the north-central portion of the study area underlain by karstic Nahanni Formation limestone bedrock.

Areas with potential unconfined deltaic aquifers (Type 2, **Table 2-1**) likely occur within the study area, in association with deposition of sediments from meltwater draining valleys and entering regressing glacial lakes, but such landforms are not definitively identifiable in the compilation surficial geology mapping on which this assessment was largely based (Côté et al., 2013; Lipovsky and Bond (compilers), 2014). Localized occurrence of Type 2 aquifers may have been included in a Type 4a aquifer classification (e.g. raised deltas mapped as glaciofluvial terraces) or inadvertently as an area of low aquifer potential (e.g. raised deltas mapped as glaciolacustrine terrace). An opportunity to improve recognition and inclusion of such Type 2 aquifers is explored below in Section 4.3.1.

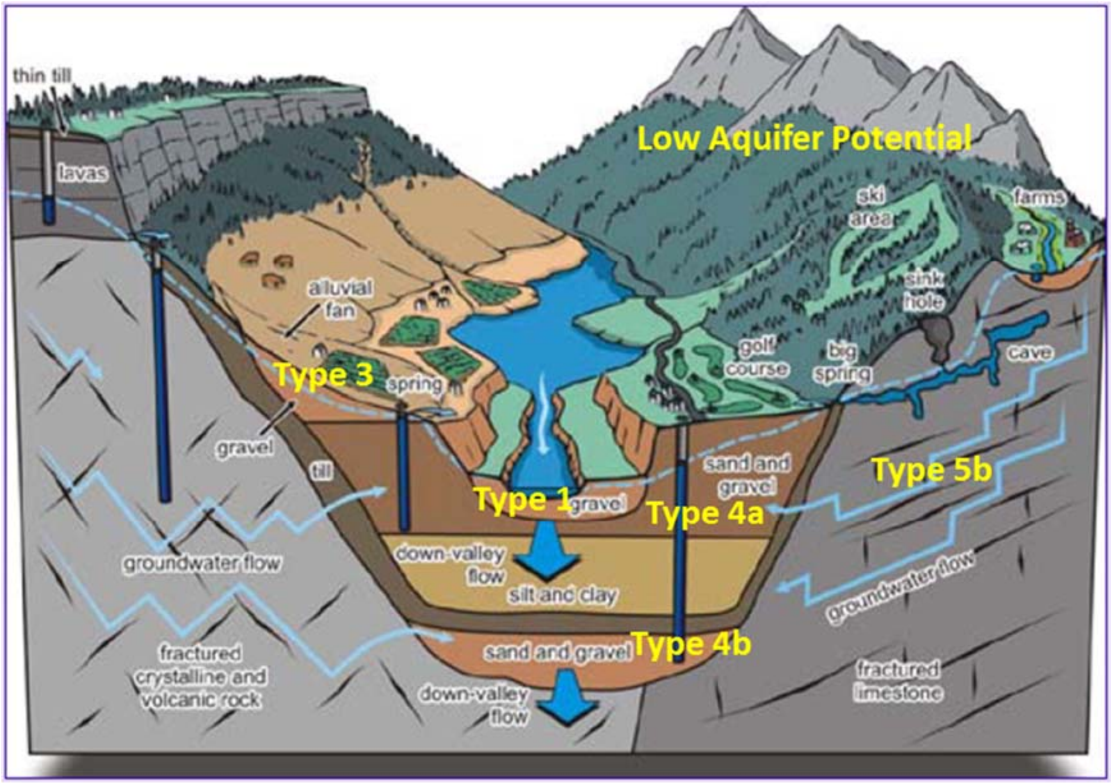


Figure 3-10. Schematic cross-sectional representation of main types of aquifers in valley settings (adapted from Wei et al., 2009; from the Geological Survey of Canada). The five types of aquifers with potential occurrences in the study area are identified with yellow text labels, along with an example of steep colluvial and bedrock terrain with low aquifer potential.

Table 3-3 summarizes the proportional distribution of different aquifer types, by sub-basin. The *Headwaters Liard – 1* sub-basin has the largest area of aquifer potential of all the sub-basins (3,002 km^2), but it is also one of the larger sub-basins (14,953 km^2). Most of this aquifer potential relates to the widespread occurrence and large extent of fluvial (Type 1 Aquifer) and glaciofluvial (Type 4a Aquifer) deposits. Approximately 32% of both the *Headwaters Liard – 2* and *Central Liard - Toad* sub-basins exhibit aquifer potential, the highest proportion of all sub-basins. Type 1 aquifers comprise 31% of the area of potential aquifers in the *Central Liard – Toad* sub-basin. Type 4a aquifers comprise 19% of the area of potential aquifers in the *Headwaters Liard – 2* sub-basin. Seven of the 13 sub-basins have relative proportions of aquifer potential between 20 and 32%. The *Petitot* sub-basin has the smallest total (160 km^2) and proportional (5%) area of aquifer potential due to widespread organics overlying a low-permeability till plain. Type 3 aquifers are most commonly associated with prominent slope-breaks and, thus, most common in the *Hyland* (4%) and *Upper South Nahanni* (4%) sub-basins. Mappable Type 4b aquifers are only represented in the *Headwaters Liard – 2* and *Upper South Nahanni* sub-basins. Type 5b aquifers are most widespread (3%) in the Lower South Nahanni sub-basin.

Table 3-3. Summary of Surficial Aquifer Distribution, by Sub-basin

Sub-basin	Area of sub-basin (km²)	Type 1 Aquifer Potential		Type 3 Aquifer Potential		Type 4a Aquifer Potential		Type 4b Aquifer Potential		Type 5b Aquifer Potential		Total Aquifer Potential	
		Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%
Beaver	8,647	928	11%	210	2%	546	6%	-	-	-	-	1,684	19%
Central Liard - La Biche	5,501	461	8%	176	3%	197	4%	-	-	-	-	834	15%
Central Liard - Toad	2,052	640	31%	12	1%	9	0%	-	-	-	-	661	32%
Coal	8,648	1,791	21%	100	1%	350	4%	-	-	-	-	2,241	26%
Flat	8,543	2,090	24%	241	3%	22	0%	-	-	-	-	2,353	28%
Frances	13,231	536	4%	362	3%	793	6%	-	-	-	-	1,691	13%
Headwaters Liard - 1	14,953	1,362	9%	201	1%	1,439	10%	-	-	-	-	3,002	20%
Headwaters Liard - 2	2,844	359	13%	3	0%	554	19%	1	0%	-	-	917	32%
Hyland	9,479	995	10%	361	4%	582	6%	-	-	-	-	1,938	20%
Lower Liard - Mouth	19,537	1,710	9%	48	0%	469	2%	-	-	25	0%	2,252	12%
Lower South Nahanni	9,459	1,420	15%	308	3%	107	1%	-	-	313	3%	2,148	23%
Petitot	3,271	93	3%	0	0%	67	2%	-	-			160	5%
Upper South Nahanni	18,128	1,842	10%	642	4%	111	1%	3	0%	114	1%	2,712	15%

3.2.2 Type 1 Aquifers

Type 1 aquifers are mostly represented by modern (Holocene-age) fluvial floodplains and terraces along the bottoms of river and creek valleys. They represent approximately 11.4% of the study area (**Figure 3-9** and **Table 3-2**). Most are inferred to be, or have the potential to be, hydrologically connected with modern watercourses due to their spatial association and low relief (**Figure 3-10**). Type 1 aquifers, originating from deposition of sediments within flowing water, most commonly comprise well sorted sand and gravel (active channel deposits) overlain by silt and fine to coarse sand (floodplain deposits). Coarser- and finer-grained deposits may be interbedded, a reflection of spatio-temporal changes in the energies of depositional settings, in thicker fluvial valley fills. Thin layers of organic material, representing relatively stable periods, may be buried and/or at surface.

Permafrost may occur in landforms with Type 1 aquifer potential (e.g. community well at Nahanni Butte, NWT (61º 1' 43.86"N, 123º 22' 59.41"W); UMA Engineering Ltd., 1988), especially within stable terraces capped by silty flood deposits and insulated by organic cover, but it is generally discontinuous due to at least localized talik zones that are maintained by year-round surface and hyporheic flow along associated watercourses. Areas prone to flooding also tend to maintain at least shallow, if not open, taliks.

Type 1 aquifers, especially where representing buried valley aquifers (in some cases in association with Type 4a aquifer complexes), are important for their groundwater resource potential throughout the Western Canadian Sedimentary Basin (Golder Associates, 2017). In this study area, relatively few water wells appear to be screened within Type 1 aquifers (21 or 10% of the 220 wells), however, presumably because nearby Type 4a aquifers provide more reliable and productive sources of groundwater.

Two adjacent groundwater supply wells within about 10 m of the bank of Liard River provide drinking water from a Type 1 aquifer to the community of Fort Liard, NWT (1478-1 and 1478-3; 61º 14' 12.25"N, 123º 29' 0.49"W) (Harris, A., 2019). The wells penetrated dry silts, sands and gravel with some boulders in the upper 10 m, and saturated sands and gravels down to approximately 18 m below ground surface (UMA Engineering Ltd., 1988). This stratigraphy is typical of fluvial deposits, with finer-grained flood deposits overlying coarser-grained active channel deposits. **Figure 3-11** presents a geological cross-section spanning the Liard River valley at Fort Liard and extending eastward across a portion of adjacent till plain. The cross-section depicts an average of approximately 18-20 m of valley-bottom fluvial sediments, which host the Type 1 aquifer that supplies the community with its drinking water. Both valley walls are mantled with colluvium of various origins, with little aquifer potential. Colluvial activity along the valley walls is likely at least locally exacerbated by surface runoff from the adjacent broad till plain (aquitard), which exhibits relatively low permeability and likely a shallow groundwater level. No permafrost was reported during drilling of the groundwater supply wells (UMA Engineering Ltd., 1988). The wells are screened near their bottoms, between 16.7 and 18.2 m below ground surface. Monitoring of water levels in the wells has not surprisingly documented fluctuations around 10 m below ground surface controlled by water level in the adjacent Liard River. Such interaction between surface water and groundwater are commonly associated with Type 1 aquifers. Much of the groundwater likely flows laterally through the valley-bottom fluvial deposits, into the page in **Figure 3-11**, partly through hyporheic exchange with river water. The total volume of water withdrawn from the two wells in the 2018 reporting year was 18,865 m^3 (Harris, A., 2019).

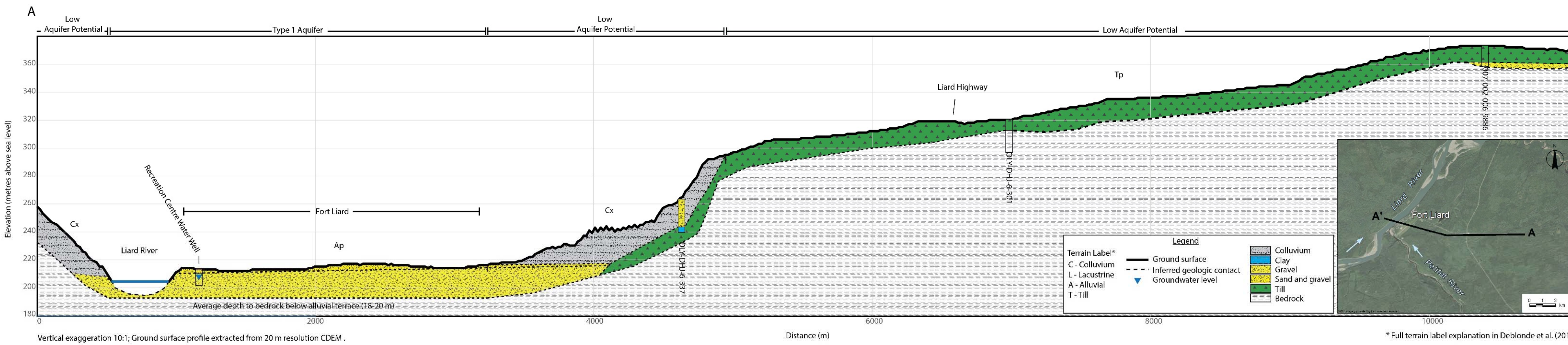


Figure 3-11. Geological cross-section and aquifer classification in the Fort Liard area, NWT.

Residents of the NWT community of Nahanni Butte, situated on the south side of South Nahanni River near the confluence with Liard River, also receive their drinking water from a well withdrawing groundwater from a Type 1 aquifer comprising fine sands, likely deltaic, deposited by the South Nahanni River (UMA Engineering Ltd., 1988; Government of the Northwest Territories, 2002). A shallow layer of permafrost was reported during drilling (UMA Engineering Ltd., 1988). Although water was originally sourced from two wells installed to depths of 33.5 m and 41.5 m, approximately 700 m south of South Nahanni River in a broad fluvial plain, one collapsed in 2009 and is no longer in use. It is not known which of the two is still functional and in use (I. de Grandpré, pers. comm.). Groundwater withdrawn from the remaining well is delivered by truck to the 27 houses in the community, with a total daily usage of approximately 20,000 L.

Water Well 201020115 (60º 2' 58.85"N, 128º 54' 54.06"W), in Upper Liard, Yukon, is another example of a well that appears to be screened in a Type 1 aquifer for domestic water supply. No borehole log was available, however, so the characteristics of the aquifer can only be inferred based on an understanding of the depositional environment and local topography.

3.2.3 Type 3 Aquifers

Type 3 aquifers are mainly represented by modern (Holocene-age) fluvial fans, but also include colluvial fans and aprons, due to their morphological similarity and commonly shared geneses. They represent approximately 2.1% of the study area (**Figure 3-9** and **Table 3-2**). These landforms typically occur at prominent, concave breaks in slope and/or widenings of valleys or gullies. They form fan-like or coalescent wedges of sediment. Sediments comprising mapped fluvial fan (Type 3) aquifers are commonly coarser-grained than adjacent fluvial plain (Type 1) aquifers due to their deposition along higher-gradient channels. Sand and gravel, up to boulder-sized, typically predominate fluvial fans at the base of steep mountain channels. Such landforms may transition with colluvial fans, which are formed mainly by colluvial (landslide) processes.

Rainfall and snowmelt readily infiltrate Type 3 aquifers, but their sediments may not be saturated until considerable depth due to their anomalous thickness of their upper reaches (e.g. fan apex). Groundwater within fans is commonly deepest just downstream of the apex, where water from upslope first encounters thick, permeable substrates, and gradually becomes shallower toward the toe until the fan surface (or incised channel) intercepts the groundwater table itself. Groundwater discharge is common along channels incised into the lower reaches of fluvial fans.

Permafrost is less common and/or generally at greater depth in landforms with Type 3 aquifer potential than those with Type 1 aquifer potential. Landforms with Type 3 aquifers tend to have coarser-grained, better-drained sediments that readily allow heat penetration into the ground during snow-free months. They also exhibit an overall convex surface expression, which improves drainage and helps resist accumulation of thick, insulating organic cover at surface.

Groundwater monitoring well BH95G-29 (61º 27' 19.25"N, 130º 35' 27.05"W), in the *Frances* sub-basin, provides an example of subsurface stratigraphy within a Type 3 aquifer. The well was installed near the base of a fluvial fan in the subalpine valley of the proposed Kudz Ze Kayah mine site. The borehole penetrated approximately 8 m of sand, with traces to some silt/silty sand and gravel and occasional boulders (0-8 m depth), then approximately 10 m of sand, with some gravel and a trace to some silt, cobbles and boulders (8-18 m depth). The borehole terminated in schist (18-19 m). The groundwater monitoring well is screened (including sand pack) between about 14.5 and 18.5 m depth. Water level in the well stabilized just below ground surface.

Figure 3-12 presents a geological cross-section extending westward from the Yukon-NWT border area across the La Biche River valley and up the mountain associated with the Kotaneelee gas plant area. The eastern portion of the cross-section is characterized by veneers to blankets of till (low aquifer potential), where groundwater level is likely in underlying bedrock except in the areas of thicker till. The La Biche River has incised through till and underlying bedrock to form a wide valley along which fluvial sediments (Type 1 aquifer) have been deposited and redistributed over millennia. Lenses of silt and clay occur within the fluvial deposits. A fluvial fan (Type 3 aquifer) has formed at the toe of the western mountainside, where a confined stream gully enters the valley. Groundwater level in the fan is likely relatively deep, given the sandy to gravel composition and convex topography. The lower to upper slopes of the mountain to the west are mantled with colluvial sediments of variable thickness with Type 3 aquifer potential only associated with localized cones or aprons of material below steeper slopes. Bedrock is exposed on the ridge crest. Most infiltration and groundwater flow within the Kotaneelee area likely occurs through the valley-bottom fluvial deposits, given the lower permeability and/or steepness of adjacent terrain.

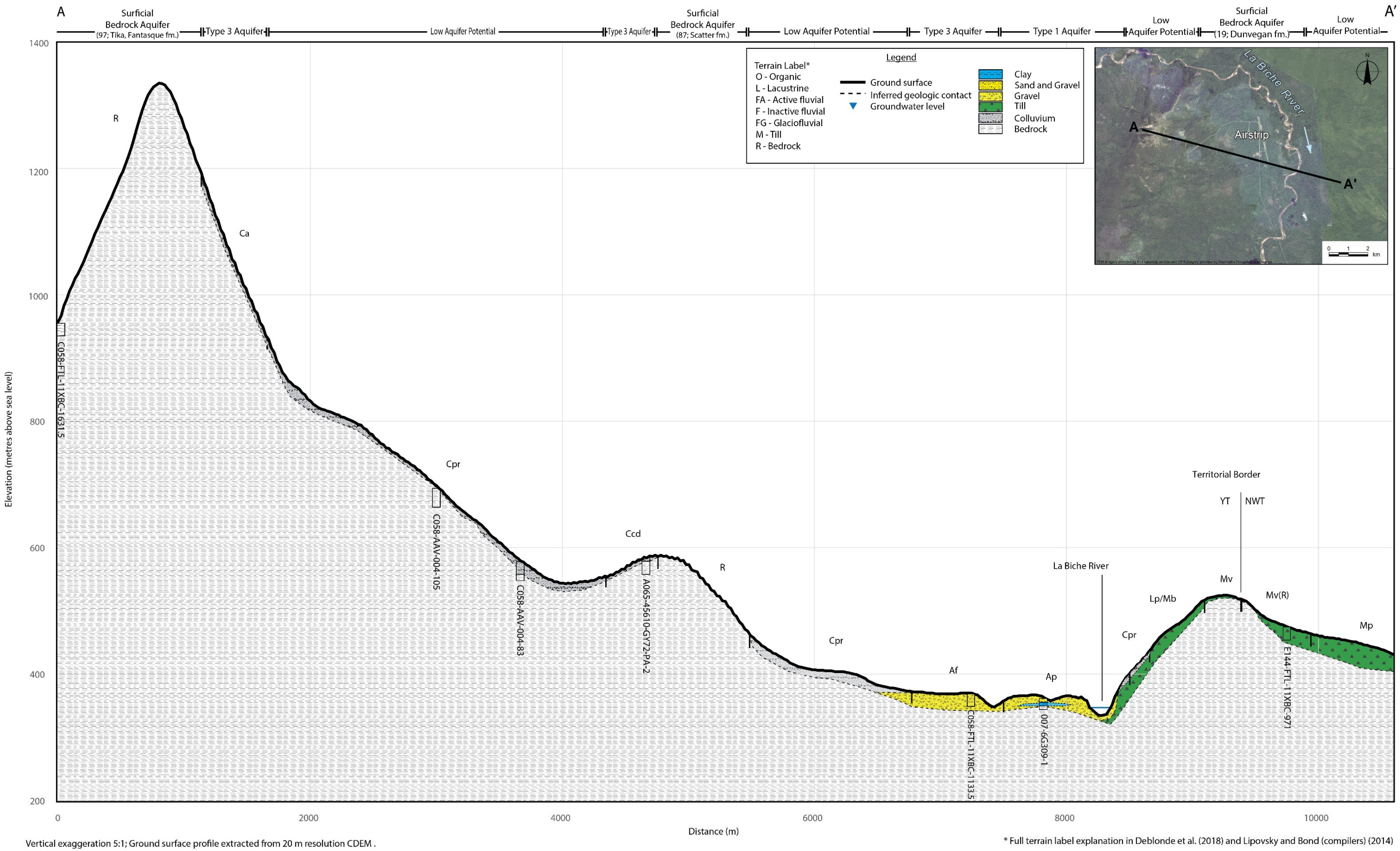


Figure 3-12. Geological cross-section and aquifer classification in the Kotaneelee gas plant area, Yukon. Referenced bedrock formations are shown in Figure 3-2.

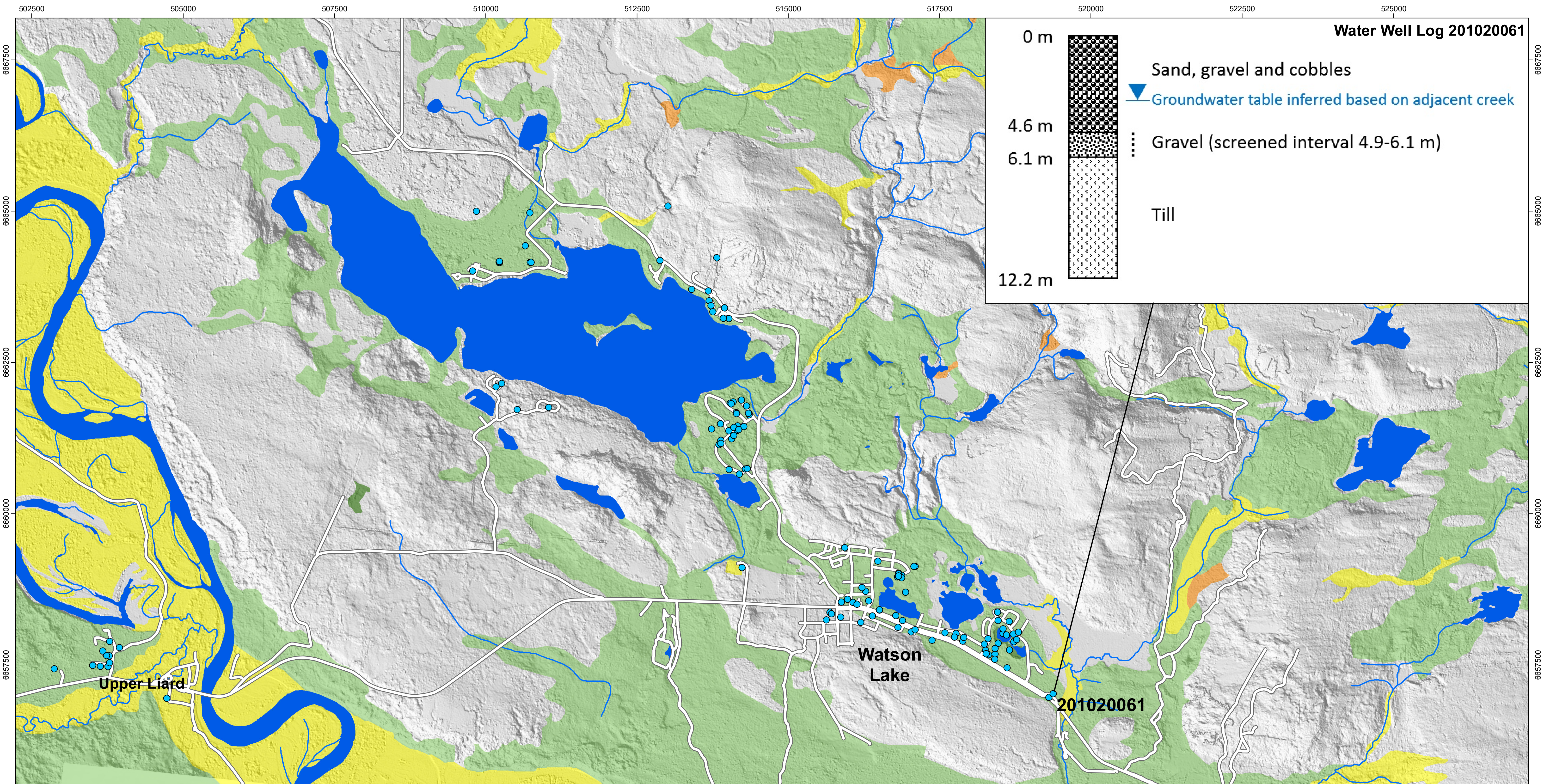
3.2.4 Type 4a Aquifers

Type 4a aquifers are unconfined and associated with surficial glaciofluvial sediments, deposited in proglacial or ice-contact environments. They represent approximately 4.2% of the study area (**Figure 3-9** and **Table 3-2**). Most Type 4a aquifers in the study area are represented by outwash deposited in front of, or alongside, retreating glaciers. Ice-contact deposits in the form of eskers, kames and kame terraces are also represented. Sediments comprising glaciofluvial landforms are typically mixtures of sand and gravel, with the proportion of each reflecting the energy of the depositional environment in which they formed. Eskers tend to have the coarsest-grained sediments (commonly up to boulder in size), owing to their common subglacial origin, followed by kame terraces and outwash. Eolian deposits, typically in the form of sand dunes, were included in this classification of aquifer (as per Levson et al., 2018) due to their common association with glaciofluvial landforms, broadly similar hydrogeological properties and modest areal extent.

Glaciofluvial landforms typically offer maximum opportunity for infiltration of precipitation and snowmelt, but are commonly unsaturated for considerable depth. Groundwater tables in small and/or high-relief glaciofluvial landforms may be near, or even below, the base of the landform given how freely water is able to drain away. Perched water table conditions caused by poor drainage through underlying aquitard materials is also expected to be common. As such, the basin-wide aquifer potential within glaciofluvial landforms may be over-estimated, although these sediments do have an important recharge function.

A representative example of a water well screened in a Type 4a aquifer is located in Watson Lake, Yukon (**Figure 3-13**). Water Well ID 201020061 (60º 2’ 59.69”N, 128º 39’ 7.48”W) is in the yard of the community weigh scale, on a level outwash terrace immediately north of Highway 1 and west of a small tributary incised into the terrace. The well is screened in a layer of (glaciofluvial) gravel, between 4.9 and 6.1 m depth below ground surface, below a layer of (glaciofluvial) sand, gravel and cobble. The unconfined aquifer is underlain by till. No information on groundwater table depth or well yield is available, although the groundwater table is inferred to be just a few metres below surface and only slightly above the adjacent creek level.

Figure 3-14 presents a geological cross-section extending across the Liard River valley and the eastern portion of the community of Watson Lake. The Liard River meanders through its own fluvial sediments (Type 1 aquifer), which are inset within remnant glaciofluvial terraces (Type 4a aquifer). Groundwater elevation is controlled by the water level in the river. Watson Lake is separated from Liard River valley by a rounded, till-mantled hill. Most precipitation likely runs off the surface of the hill, as opposed to infiltrating the low-permeability till. The community of Watson Lake is built on a complex of glaciofluvial plains (Type 4a aquifer) punctuated by kettles, which are locally infilled by lacustrine sediments that now cap the underlying glaciofluvial sand and gravel (Type 4b aquifer). Groundwater may be locally perched on the underlying till, where the rate of inflow exceeds the infiltration capacity of underlying till. Blankets of organics overlying the northern portion of the glaciofluvial deposits are assumed to locally reduce aquifer potential, although site-specific investigations would be required to better determine the influence of organics. Low-permeability till blankets the hill to the north (low aquifer potential).



LEGEND:

Potential Surficial Aquifers

- Type 1
- Type 3
- Type 4a
- Type 4b

- Water Well
- Road
- Watercourse
- Waterbodies

Hillshade basemapping from ArcticDEM (Porter et al., 2018).

KILOMETRE SCALE:

0 0.5 1 2 3

NAD 83 UTM Zone 9 Projection

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

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Figure 3-13

Surficial Aquifer Potential and Water Wells in the Watson Lake Area

Project No. 1508907
Date: Mar 20, 2020
Revision: 1

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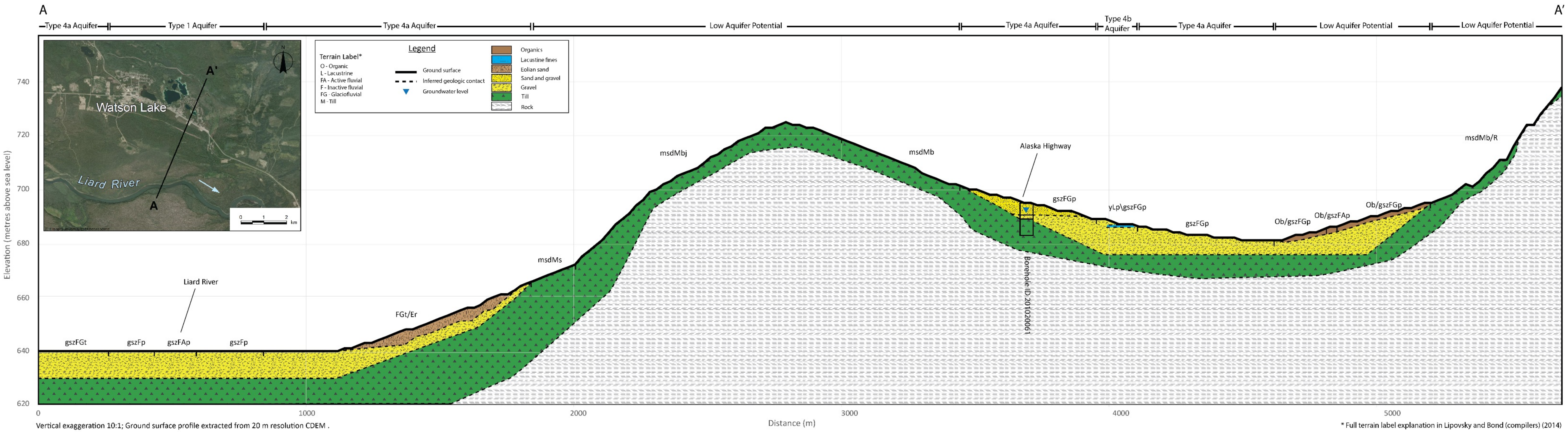


Figure 3-14. Geological cross-section and aquifer classification in the Watson Lake area, Yukon.

3.2.5 Type 4b Aquifers

Type 4b aquifers, confined glacial or pre-glacial aquifers (Wei et al., 2009), are poorly represented in the available surficial geology mapping due to limitations of scale and an emphasis on surface, rather than subsurface, materials and landforms. They represent <0.1% of the study area (**Figure 3-9** and **Table 3-2**). The few Type 4b aquifers that have been inferred from available mapping are characterized by sand and gravel (high permeability) confined beneath till (low permeability). Such aquifers commonly form in association with re-advance of a glacier over meltwater deposits, or burial of meltwater deposits by glaciolacustrine sediments that accumulate in an ice-dammed lake. An example of a small Type 4b aquifer, represented by a lacustrine deposit overlying glaciofluvial material, is shown on the cross-section in **Figure 3-14**. Confined aquifers are likely more extensive especially beneath fine-grained glaciolacustrine sediments that were deposited in the late stages of deglaciation such that they cover underlying materials including potential aquifers (e.g. glaciofluvial outwash).

Type 4b aquifers, where sufficiently thick and laterally extensive, can represent excellent sources of groundwater resource potential. Site-specific groundwater studies commonly target such confined aquifers. No well records are available for the few wells in the study area screened in Type 4b aquifers (e.g. Water Well 201020026 (60º 3' 23.21"N, 128º 39' 53.78"W), in Watson Lake, Yukon).

3.2.6 Type 5b Aquifers

Type 5b aquifers are associated with karstic Nahanni Formation bedrock, a Devonian-aged limestone mainly found within southern Nahanni National Park, and represent only 0.4% of the study area (**Figure 3-9** and **Table 3-2**). It is approximately 180-200 m thick and exhibits thick to massive bedding (Ford, 2009). The regularly spaced bedding planes and fractures make it ideal for karst development through dissolution of the soluble rock by rainwater and snowmelt. Documented karst features include small-scale pits, grooves and runnels at surface, dolines of funnel-shaped sinkholes, and dry gorges and poljes – large, flat-bottomed sinkholes that expand through corrosion of surrounding limestone cliffs (Ford, 1974). The uniqueness and global significance of the karst landscape in the eastern portion of Nahanni National Park are key factors in the decision in 1978 by the United Nations Educational, Scientific and Cultural Organization (UNESCO) to grant the area the first "World Heritage" status (Ford, 1974). **Figure 3-15** provides an oblique aerial view of deeply dissected plateaux of the Nahanni Formation (McKillop, 2012).

Extensive discontinuous permafrost in Nahanni National Park likely influences surface water and groundwater interactions beyond the karst-related controls. Permafrost is hypothesized to have developed subsequent to bedrock dissolution in some areas (Ford, 2009), further complicating groundwater flow patterns.

Karst aquifers occur within the Nahanni Formation, as surface water flows through preferential conduits and caverns into underlying, more massive rock. A lack of water wells within the Nahanni Formation means relatively little is known about the interconnectivity and transmissivity of these aquifers. All karst aquifers can be described as fragile, prone to rapid and severe contamination (Ford, 2009).

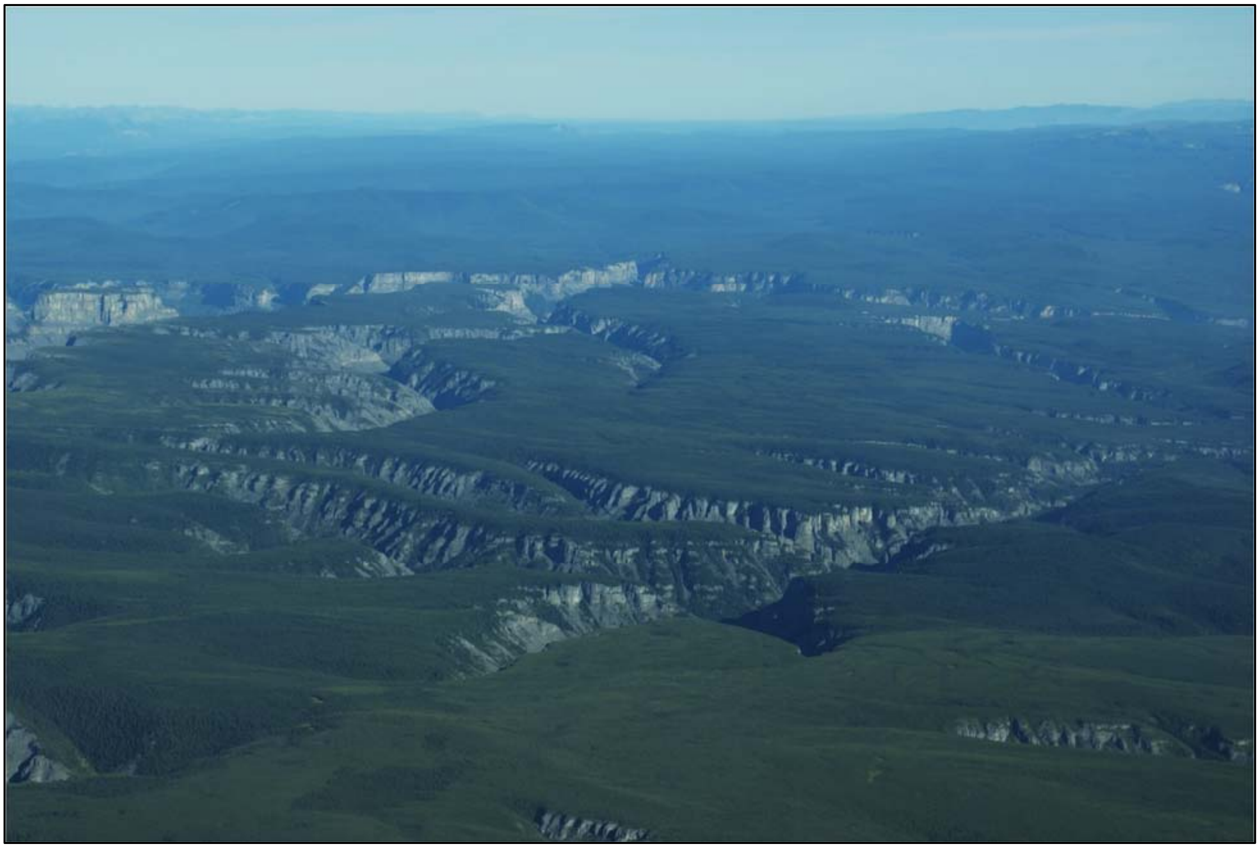


Figure 3-15. Oblique aerial view of deeply dissected plateaux in karstic limestone of the Nahanni Formation, Nahanni National Park, NWT (from McKillop, 2012)

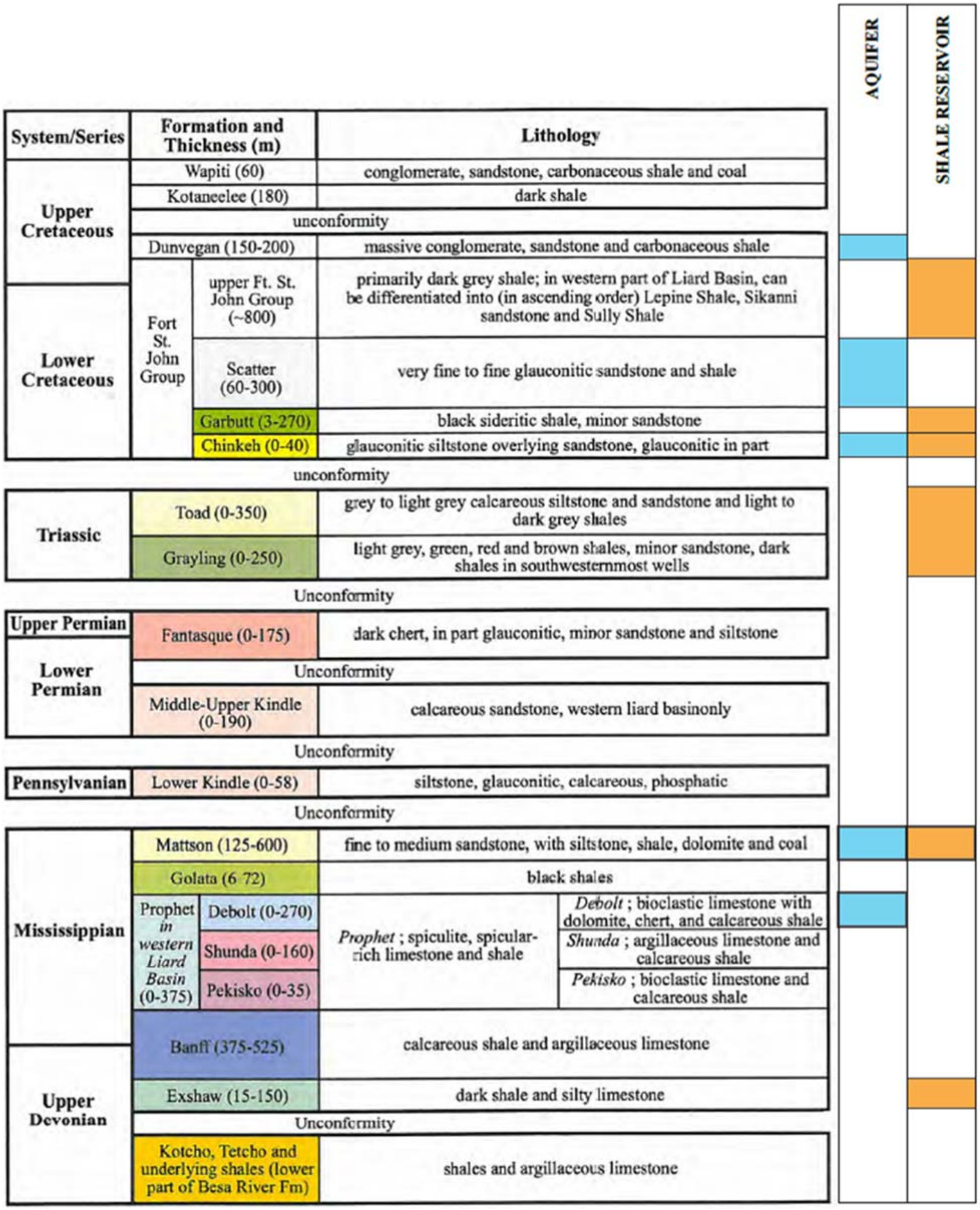
3.2.7 Areas with Low Aquifer Potential

Areas of low surficial aquifer potential, whether poor aquifers or actual aquitards, represent approximately 81.8% of the study area (**Figure 3-9** and **Table 3-2**). Unconsolidated materials generally interpreted to have low aquifer potential in the study area include most tills, lacustrine and glaciolacustrine deposits, organic material and colluvial blankets inferred to comprise predominantly fine-grained sediments, based on McKillop (2012), knowledge of depositional settings and representative well logs. Precipitation and snowmelt predominantly run off the surface of such materials rather than infiltrating, and the small amount of water that does eventually recharge the groundwater table is not readily accessible due to low permeability of the materials. Exceptions exist, such as glaciolacustrine littoral deposits and subglacial melt-out till locally comprising sandier material and higher relief, but they are of limited extent and not well represented by regional-scale mapping, so they have not been explicitly included as potential aquifers. Runoff from wetland areas may actually be moderated by localized storage in organic soils, especially in closed depressions where water level can rise, but considering the implications of such complexities are beyond the scope of this assignment.

Most bedrock formations, except for the karstic Nahanni Formation, were also assumed to have relatively low surficial aquifer potential in the absence of information on shallow fracturing, porosity or water quality trends. Golder Associates (2017) reports that "poor quality aquifers are present [in the geological Liard

Basin] with respect to Upper Cretaceous shale bedrock (low permeability) and Lower Cretaceous and Paleozoic formations with saline porewaters (low water quality)" (p. 101). Crystalline bedrock in the mountains of both territories was similarly assumed to have low surficial aquifer potential.

Although not the focus of this study, it is important to recognize the presence of deep saline aquifers within the bedrock underlying any surficial aquifers or aquitards (e.g. **Figure 3-16**, Petrel Robertson Consulting Ltd., 2013). While these aquifers generally have limited interaction with surface water features and are not expected to be suitable for potable water supply (due to brackish or saline nature, Petrel Robertson Consulting Ltd., 2013), they can be an important resource for oil and gas development as water supply for hydrofracking and for water disposal. Sandstones of the Mattson Formation (500 – 2,000 m depth) and Dunvegan Formation (~200 m depth), for example, exhibit water sources and disposal potential (Petrel Robertson Consulting Ltd., 2013). Chinkeh, Chinchaga and Scatter Formation sandstones offer limited aquifer potential due to their depth and limited characterization (Petrel Robertson Consulting Ltd., 2013). The scattered occurrence of 62 springs (Michel, 1986; Ford, 2009; Caron et al., 2007; Grasby et al., 2009; Government of Yukon, 2012; Nahanni River Adventures and Canadian River Expeditions, 2019; Parks Canada, 2019), including thermal springs (**Figure 3-7**), indicates at least localized interaction of relatively deep groundwater with surface water. Investigating the potential linkages between surficial aquifers and those at depth in bedrock is beyond the scope of this assignment, yet highlighted for future research in Section 4.3.1.



System/Series	Formation and Thickness (m)	Lithology
Upper Cretaceous	Wapiti (60)	conglomerate, sandstone, carbonaceous shale and coal
	Kotaneelee (180)	dark shale
	unconformity	
	Dunvegan (150-200)	massive conglomerate, sandstone and carbonaceous shale
Lower Cretaceous	Fort St. John Group: upper Ft. St. John Group (~800)	primarily dark grey shale; in western part of Liard Basin, can be differentiated into (in ascending order) Lepine Shale, Sikanni sandstone and Sully Shale
	Fort St. John Group: Scatter (60-300)	very fine to fine glauconitic sandstone and shale
	Fort St. John Group: Garbutt (3-270)	black sideritic shale, minor sandstone
	Fort St. John Group: Chinkeh (0-40)	glauconitic siltstone overlying sandstone, glauconitic in part
	unconformity	
Triassic	Toad (0-350)	grey to light grey calcareous siltstone and sandstone and light to dark grey shales
	Grayling (0-250)	light grey, green, red and brown shales, minor sandstone, dark shales in southwesternmost wells
	Unconformity	
Upper Permian	Fantasque (0-175)	dark chert, in part glauconitic, minor sandstone and siltstone
Lower Permian	Unconformity	
	Middle-Upper Kindle (0-190)	calcareous sandstone, western liard basinonly
	Unconformity	
Pennsylvanian	Lower Kindle (0-58)	siltstone, glauconitic, calcareous, phosphatic
	Unconformity	
Mississippian	Mattson (125-600)	fine to medium sandstone, with siltstone, shale, dolomite and coal
	Golata (6 72)	black shales
	Prophet *in western Liard Basin* (0-375): Debolt (0-270)	*Prophet*; spiculite, spicular-rich limestone and shale. *Debolt*; bioclastic limestone with dolomite, chert, and calcareous shale
	Prophet *in western Liard Basin* (0-375): Shunda (0-160)	*Shunda*; argillaceous limestone and calcareous shale
	Prophet *in western Liard Basin* (0-375): Pekisko (0-35)	*Pekisko*; bioclastic limestone and calcareous shale
	Banff (375-525)	calcareous shale and argillaceous limestone
Upper Devonian	Exshaw (15-150)	dark shale and silty limestone
	Unconformity	
	Kotcho, Tetcho and underlying shales (lower part of Besa River Fm)	shales and argillaceous limestone

Figure 3-16. Stratigraphic column, Upper Devonian through Cretaceous, of the eastern Liard Basin (from Monahan, 1999).

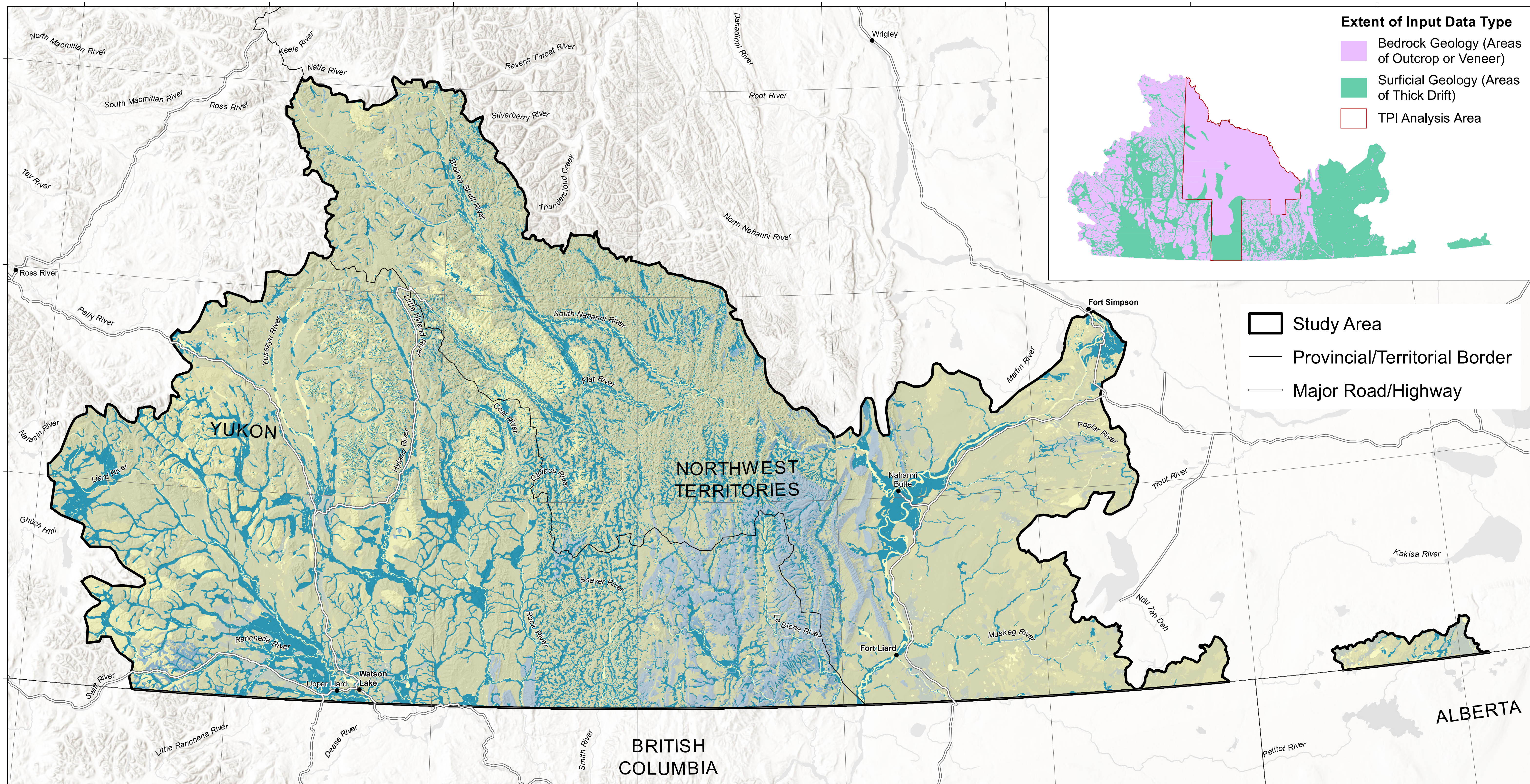
3.3 Groundwater Recharge and Discharge

The permeability of surficial geological units and the presence of permafrost are the most important factors influencing groundwater recharge rates within the study area. Groundwater recharge has the potential to occur everywhere within the study area. Practically, however, only higher permeability materials with at least discontinuities in permafrost (where present) can transmit enough recharge to support a groundwater resource or provide significant contributions to stream baseflows. In the Liard River basin, groundwater recharge varies seasonally, with recharge only occurring during unfrozen (thawed) conditions. Areas that are covered by continuous or extensive discontinuous permafrost have continuously low groundwater recharge rates because permafrost promotes runoff and limits infiltration.

Surficial hydrogeology mapping (**Figure 3-17**) represents the ranking of both unconsolidated and bedrock hydrostratigraphic units to which infiltration factors were assigned as a basis for spatial calculation of potential recharge. Application of the water budget methodology outlined in Section 2.3 indicates potential recharge within the Liard River basin, on average, is about 28.8 mm/yr (**Figure 3-18**). The total estimated potential annual recharge in the study area is $3.6x10^{10}$ m^3/yr. Therefore, on average, recharge accounts for approximately 18% of the estimated water surplus within the study area.

These values are reflective of the widespread distribution of lower permeability surficial materials such as bedrock or till, as well as permafrost. Glaciofluvial sands and gravels (Type 4a aquifers) and fluvial deposits (Type 1 aquifers) have the highest groundwater recharge potential and have the highest potential for groundwater resource development. It is clear from both **Figure 3-17** and **Figure 3-18** that groundwater recharge is generally concentrated within valleylands near surface water features where glaciofluvial and fluvial materials are present. These areas have a relatively short groundwater flow path and residence time from locations of recharge to locations of discharge within surface waterbodies and at discrete features such as coldwater springs and seeps along breaks in slope. A noteworthy clarification is that permafrost is a major factor controlling groundwater recharge but does not significantly affect the distribution of groundwater discharge (Michel, 1986).

Recharge to deep bedrock aquifers is generally considered to be very low, with the vast majority of recharge to surficial aquifers eventually discharging to watercourses as baseflow. Water balance methods that model stream flow based on monthly and annual precipitation, runoff and ET can accurately predict stream flows (Moore et al., 2011). Some of the bedrock units within the study area are known to have significant aquifer potential at depth (e.g. the Mattson and Dunvegan Formations), but these waters are generally brackish (e.g. Petrel Robertson Consulting Ltd., 2013), indicating a very long residence time between surface recharge and the deep aquifer unit. It is expected that the percentage of groundwater recharge that reaches deep geological units is low, and the majority of groundwater flows within the upper weathered portions of the bedrock.



LEGEND:

Hydrostratigraphic Unit and Generalized Surficial/ Bedrock Geology Input Type (Ranked from Lowest to Highest Infiltration)

- 0: Waterbodies
- 1: Igneous (plutonic) bedrock
- 2: Metamorphic or igneous (volcanic) bedrock; organic deposits*
- 3: Lower permeability sedimentary bedrock; lacustrine or glaciolacustrine sediment and sub-glacial till
- 4: Moderate permeability sedimentary bedrock; melt-out till
- 5: Higher permeability sedimentary bedrock
- 6: Karst formation bedrock; colluvial sediments
- 7: Fine-grained glaciofluvial or coarse-grained lacustrine deposits
- 8: Surficial deposits with aquifer potential: primarily glaciofluvial, fluvial deposits

** Refer to report for rationale for low infiltration in areas of organics*

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT: Government of the Northwest Territories

PROJECT: Liard River Basin Transboundary Aquifer Assessment

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Figure 3-17

Surficial Hydrogeology

Project No. 1508907
Date: Jun 02, 2020
Revision: 1

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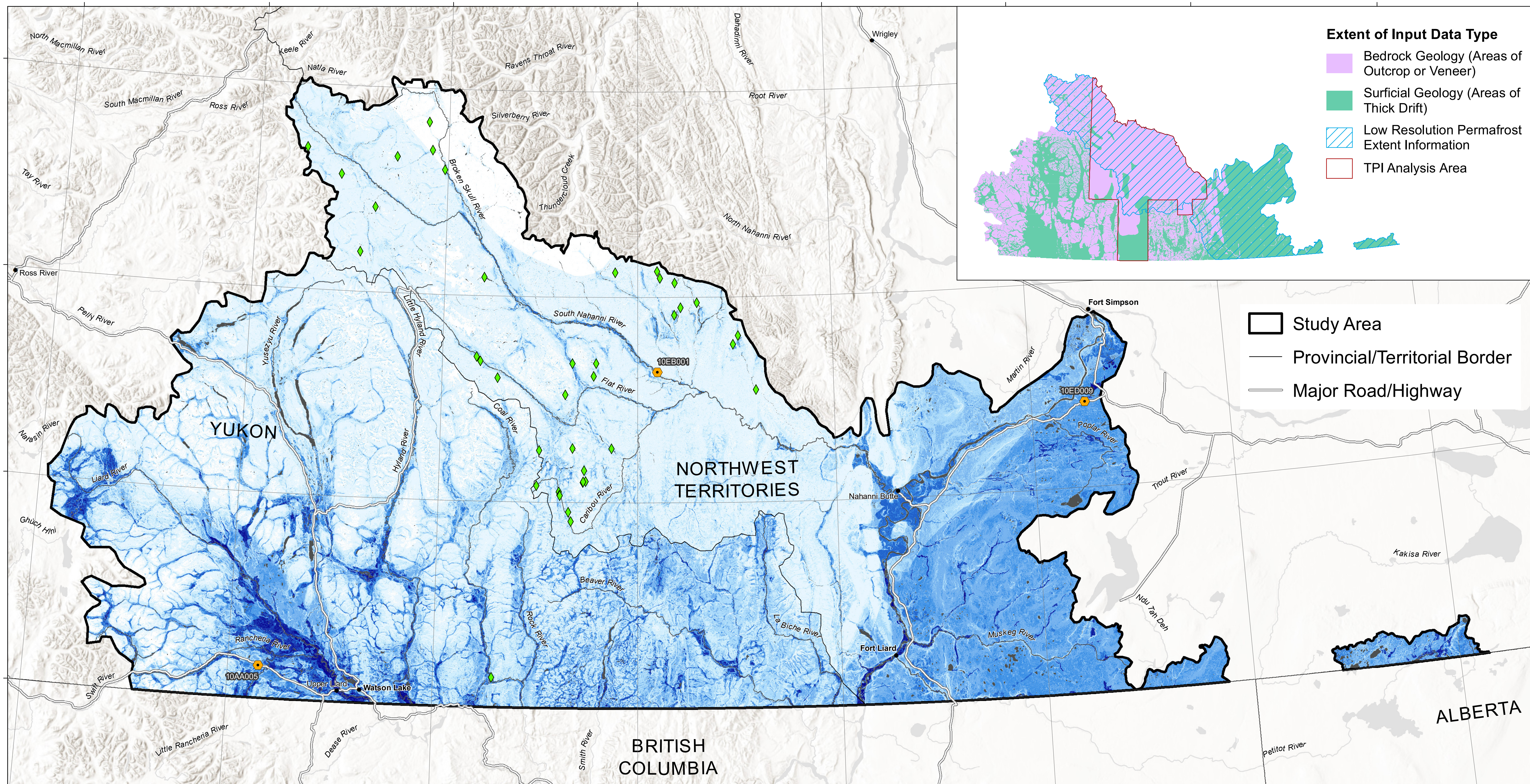

LEGEND:

Potential Recharge in mm/yr

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
- 60 - 70
- 70 - 80
- 80 - 90

- Hydrometric Station (Water Survey of Canada)
- Cool/Cold (<15 °C) Spring
- Waterbody

KILOMETRE SCALE:

0 10 20 40 60 80 100

NWT Lambert Projection (Central Meridian 126° W)

N

CLIENT:
Government of the Northwest Territories

PROJECT:
Liard River Basin Transboundary Aquifer Assessment

DRAWN: BE CHECKED: RM PRINT SIZE: 11 x17 "

Figure 3-18
Potential Recharge

Project No. 1508907
Date: Jun 01, 2020
Revision: 1

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AURORA GEOSCIENCES

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The presence of karst within the Nahanni Formation was well documented by Ford (2009) and observed by McKillop (2012). Secondary porosity features such as limestone pavements, solution-enhanced fractures and corridors, collapsed sinkholes, as well as seasonal lakes and poljes where identified by Ford (2009). The relationship between porosity and permeability is well understood, so the limestones and dolostones of the Nahanni Formation were identified as a significant groundwater recharge area within the Liard River basin. The precipitation that infiltrates here was found to form well developed underground karst systems and discharge at two major springs (Ford, 2009).

A total of 62 springs has been documented within the study area through publications and on-line sources (Michel, 1986; Caron et al., 2007; Ford, 2009; Grasby et al., 2009; Government of Yukon, 2012; Nahanni River Adventures and Canadian River Expeditions, 2019; Parks Canada, 2019) (**Figure 3-7 and Figure 3-18** (cool springs only)). Approximately one-third of these are thermal springs, with temperatures between about 15 and 64ºC, indicative of localized surface discharge of groundwater from relatively deep sources. Perhaps the best known thermal springs within the study area are the Rabbitkettle Hotsprings, located near the mouth of a tributary to South Nahanni River in Nahanni National Park, due to their association with two prominent tufa mounds that have formed in association with precipitation of dissolved minerals, primarily calcium carbonate. Coal River Springs is an example of a cool spring (~13ºC), located along the east bank of Yukon's Coal River, where groundwater discharges to surface after infiltrating and flowing through limestone mountains to the immediate east (Government of Yukon, 2012). The continual build-up of tufa, at a rate of about 2 to 3 cm/year, has created terraced travertine formations around the springs (Government of Yukon, 2012).

Traditional knowledge would provide valuable insights into areas of groundwater recharge and discharge, an important recommended follow-up given the limited availability of aquifer mapping and stream flow gauging data (as described further in Section 4.3). Important areas of groundwater discharge can be identified as river systems or areas with limited winter ice cover, for example, and important recharge areas can be identified in association with 'sinking' or 'losing' streams in karstic terrain.

3.3.1 Model Calibration to Baseflow

To validate the groundwater recharge values estimated from the GIS-based preliminary water budget analysis, a comparison was made with established streamflow values. At the watershed scale, as previously described in Section 2.3.1, it is generally reasonable to assume that groundwater recharge eventually discharges to surface as stream baseflow. Assuming that groundwater loss to deep aquifers and across watershed boundaries is negligible, the average annual recharge within a watershed should be equal to the average annual baseflow value of the surface water body draining the watershed.

A comparison between groundwater recharge and baseflow was completed for the South Nahanni River, Scotty Creek and the Frances River (**Table 3-4**). In the two largest watersheds, the South Nahanni River (above Virginia Falls, 14,500 km^2) and the Frances River (12,800 km^2), the baseflow estimated from groundwater recharge compared well with the average baseflow estimated from the long-term hydrometric data (within +/-5%). This provides confidence that over a large area the precipitation, ET, infiltration factors and permafrost reduction factors are reasonable to estimate groundwater recharge and discharge values within the overall watershed.

For the small (168 km^2) Scotty Creek watershed, in contrast, the baseflow estimated based on groundwater recharge did not compare well with the baseflow hydrograph. This is not expected to be a reflection of the input values of the model, as the average precipitation for the watershed in cited publications of 390 mm/yr (Haynes et al, 2018) aligns well with the overall average value used for this study. Furthermore, the infiltration factors for peat-dominated wetland and till soils, which dominate the Scotty Creek watershed, appear to provide accurate recharge estimates for the South Nahanni River and the Frances River watersheds. It is most likely that the assumption in the model calibration that all groundwater recharge that occurs in the Scotty Creek watershed discharges to Scotty Creek is not valid for this small watershed. Groundwater recharge to deeper aquifers that discharge directly to the Liard River is likely a significant source of the overestimated baseflow values from the groundwater recharge model. In addition, the presence of sporadic permafrost may also have reduced groundwater recharge more than was assumed.

These results suggest that the methodology used herein to estimate groundwater recharge trends are best suited to very large drainage areas, such as the Liard River basin, where average values better represent overall data trends. We have confidence in the estimates of groundwater recharge and overall water balance, at this scale. The approach may be less well suited to individual small catchment areas, however, without refinements using local data.

Table 3-4. Water Budget Comparison to Baseflow

Watershed	Area (km^2)	Surplus (mm/yr)	Total Average Annual Groundwater Recharge (m^3/yr)	Baseflow Estimate from Total Average Annual Recharge (m^3/s)	Average Baseflow (Recursive Filter) (m^3/s)	Baseflow % Difference
South Nahanni River (above Virginia Falls)	14,452.89	161	2.16×10^9	68.5	71.5	-4%
Scotty Creek	168.32	161	8.33×10^7	2.6	0.18	93%
Frances River	12,924.25	161	2.82×10^9	89.5	87.4	2%

3.4 Assessment of Potential Groundwater Vulnerability

Mapping of a variety of land use activities, each classified according to one of three disturbance categories, was combined into a comprehensive, single dataset. Application of the findings of the inventory and categorization of land use activities to the assessment of groundwater vulnerability are described in the following sections of groundwater quality (Section 3.4.1) and groundwater quantity (Section 3.4.2).

3.4.1 Groundwater Quality

An assessment of potential vulnerability of groundwater quality to land use activity, within each sub-basin, is presented as indices for sub-basin level disturbance, disturbance within aquifer areas and potential recharge disturbance (**Table 3-5**). The *Headwaters Liard – 2* sub-basin emerges as the sub-basin within which groundwater quality is most vulnerable to land use activities, irrespective of the metric used to characterize vulnerability, largely due to the presence of the community and associated development of Watson Lake in expansive fluvial (Type 1 aquifer) and glaciofluvial (Type 4a aquifer) deposits (**Figures 3-8** and **3-9**). Both the Alaska Highway and Robert Campbell Highway also cross this sub-basin.

The *Francis* and *Lower Liard – Mouth* sub-basins also rank highly with respect to their potential for disturbance to groundwater. The Robert Campbell Highway accesses mining areas within the *Frances* sub-basin. The *Lower Liard – Mouth* sub-basin is also ranked with a relatively high groundwater quality vulnerability due to its anomalous concentration of resource (mostly oil and gas) activities, some of which coincide with the extensive fluvial (Type 1) aquifers along the lower reaches of Liard River. The communities of Fort Liard and Nahanni Butte have also been built on fluvial (Type 1) aquifers within this sub-basin (**Figures 3-8**, **3-9** and **3-11**).

All three indices identify the *Upper South Nahanni* sub-basin as the least vulnerable to impact, which reflects (i) its virtually pristine, undisturbed condition (only ~1 km^2 of mapped land use activity, **Figure 3-8**), part of which is explained by protection as a National Park Reserve, (ii) its ruggedness and associated rarity of unconsolidated deposits with aquifer potential (**Figure 3-9**), and (iii) the continuity of permafrost along its northeastern portion (**Figure 3-5**).

Table 3-5. Indices of Groundwater Quality Disturbance Potential, by Sub-basin

Sub-basin	Sub-basin Level Disturbance			Disturbance within Aquifer Areas			Potential Recharge Disturbance		
	Sub-basin Wide Disturbance Index	Normalized Index of the Proportion of Sub-basin Disturbed	Rank*	Aquifer Area Disturbance Index	Normalized Index of the Proportion of Aquifers Disturbed	Rank*	Recharge Disturbance Index	Normalized Index of Proportional Disturbance of Potential Recharge	Rank*
Beaver	0.0028	1.2	10	0.0013	1.20	11	0.00071	1.11	9
Central Liard - La Biche	0.0146	6.4	7	0.0087	7.76	6	0.00323	5.03	7
Central Liard - Toad	0.0004	0.2	12	0.0004	0.35	12	0.00012	0.19	12
Coal	0.0073	3.2	8	0.0040	3.62	7	0.00175	2.72	8
Flat	0.0035	1.5	9	0.0030	2.64	9	0.00049	0.77	11
Frances	0.0376	16.5	2	0.0383	34.30	2	0.00800	12.47	4
Headwaters Liard - 1	0.0317	13.9	5	0.0204	18.29	4	0.00634	9.87	5
Headwaters Liard - 2	0.2280	100.0	1	0.1117	100.00	1	0.06416	100.00	1
Hyland	0.0260	11.4	6	0.0266	23.84	3	0.00481	7.50	6
Lower Liard - Mouth	0.0348	15.2	4	0.0148	13.21	5	0.00944	14.71	3
Lower South Nahanni	0.0024	1.0	11	0.0040	3.58	8	0.00062	0.96	10
Petitot	0.0353	15.5	3	0.0015	1.33	10	0.00994	15.49	2
Upper South Nahanni	0.0002	0.1	13	0.0000	0.01	13	0.00002	0.03	13

Notes:

An explanation of how each index was calculated is provided in Section 2.4.1.

* Highest priority = 1; lowest priority = 13.

3.4.2 Groundwater Quantity

Most water well data were available for Yukon; only three wells were documented in the NWT portion of the study area. The number of documented wells located in each type of aquifer are tallied for each sub-basin in **Table 3-6**. Of the 220 water wells, 136 (62%) are located in the *Headwaters Liard – 2* sub-basin, 115 (85%) of which appear to be screened in Type 4a aquifers.

Table 3-6. Summary of Water Well Counts within Each Aquifer Potential Area, by Sub-basin

Sub-basin	Type 1	Type 3	Type 4a	Type 4b	Low Potential	Total
Beaver	0	0	0	0	6	**6**
Central Liard - La Biche	14	5	0	0	0	**19**
Central Liard - Toad	0	0	0	0	0	**0**
Coal	0	0	0	0	0	**0**
Flat	0	0	0	0	0	**0**
Frances	0	1	8	0	45	**54**
Headwaters Liard - 1	1	0	0	0	0	**1**
Headwaters Liard - 2	2	0	115	3	16	**136**
Hyland	1	0	0	0	0	**1**
Lower Liard – Mouth	2	unknown	unknown	unknown	unknown	**2**
Lower South Nahanni	1	unknown	unknown	unknown	unknown	**1**
Petitot*	unknown	unknown	unknown	unknown	unknown	**unknown**
Upper South Nahanni*	unknown	unknown	unknown	unknown	unknown	**unknown**
Total	**21**	**6**	**123**	**3**	**67**	**220**

* No water well data are available.

No water wells are known to be located in areas of Type 5b aquifers.

The results of the assessment of the potential vulnerability of groundwater quantity to land use activity, within each sub-basin, are provided based on the density of water wells within each sub-basin area (**Table 3-7**). The sub-basin within which groundwater quantity is most vulnerable to impact from land use activities appears to be *Headwaters Liard – 2*, where groundwater is being withdrawn from more than double the number of wells of any other sub-basin. Most are in the community of Watson Lake within Type 4a aquifers, which is logical given their extent and typical productivity. The *Frances* sub-basin supports the next highest density of wells, many of which are likely screened in confined or at least deeper aquifers based on their locations in areas mapped as Low Aquifer Potential. The *Central Liard – La Biche* sub-basin has the third highest density of wells and, interestingly, the highest number located in areas of Type 3 aquifers. These wells take advantage of fluvial fans along the base of the prominent north-south trending mountain ridges of sedimentary bedrock.

Table 3-7. Index of Groundwater Quantity Disturbance Potential, by Sub-basin

Sub-basin	Well density (per 1,000 km^2)	Normalized index of well density
Beaver	0.7	1.5
Central Liard - La Biche	3.5	7.2
Central Liard - Toad	0.0	0.0
Coal	0.0	0.0
Flat	0.0	0.0
Frances	4.1	8.5
Headwaters Liard - 1	0.1	0.1
Headwaters Liard - 2	47.8	100.0
Hyland	0.1	0.2
Lower Liard – Mouth	0.1	0.2
Lower South Nahanni	0.1	0.2
Petitot*	unknown	unknown
Upper South Nahanni*	unknown	unknown

* No water well data are available.

It is important to recognize that using well density as a basis for evaluating potential vulnerability to groundwater quantity, given the limited availability of groundwater use data, overlooks actual ‘groundwater stress’ based on a quantitative comparison between permitted (or practiced) water withdrawal rates and the rate of groundwater recharge within the catchment. Areas that have high well densities are generally located within areas associated with high groundwater recharge potential. Because the relatively few water well records available commonly lack information on pumping rates or specific yields, a comparison between groundwater withdrawals (in m^3/yr) with groundwater recharge volumes within a basin (also in m^3/yr) cannot be directly made. Future comparison of groundwater use with predicted groundwater recharge rate would strengthen the groundwater quantity vulnerability assessment (as described further in Section 4.3).

3.4.3 Overall Ranking by Sub-basin

The indices of combined groundwater quality and quantity disturbance potential have been tabulated for each of the 13 sub-basins (**Table 3-8**) and visually depicted in **Figures 3-19, 3-20** and **3-21**. The *Headwaters Liard – 2* sub-basin is ranked highest according to all three indices of disturbance potential. The small size of this sub-basin (in this case truncated at the border with British Columbia), combined with its extensive areas of aquifer potential (mostly Type 1 and Type 4a) and land use activities in the broad Liard River valley encompassing Watson Lake, largely explain this consistent ranking. By far, the largest concentration of water wells in Yukon’s portion of the study area is in the community of Watson Lake.

Table 3-8. Indices of Combined Groundwater Quality and Quantity Disturbance Potential, by Sub-basin

Sub-basin	Index of Groundwater Disturbance Potential (Sub-basin)	Rank*	Index of Groundwater Disturbance Potential (Aquifers)	Rank*	Index of Groundwater Disturbance Potential (Recharge)	Rank*
Beaver	1.39	10	1.34	10	1.26	9
Central Liard - La Biche	7.12	7	8.48	6	5.75	7
Central Liard - Toad	0.16	12	0.35	12	0.19	12
Coal	3.18	8	3.62	7	2.72	8
Flat	1.53	9	2.64	9	0.77	11
Frances	17.33	2	35.16	2	13.32	4
Headwaters Liard - 1	13.91	5	18.31	4	9.89	5
Headwaters Liard - 2	110.00	1	110.00	1	110.00	1
Hyland	11.41	6	23.86	3	7.52	6
Lower Liard - Mouth	15.27	4	13.23	5	14.73	3
Lower South Nahanni	1.06	11	3.61	8	0.99	10
Petitot	15.48	3	1.33	11	15.49	2
Upper South Nahanni	0.08	13	0.01	13	0.03	13

Notes:

An explanation of how each index was calculated is provided in Section 2.5.

* Highest priority = 1; lowest priority = 13.

The *Francis* and *Lower Liard – Mouth* sub-basins emerge next in the overall rankings, despite being among the largest sub-basins. The *Francis* sub-basin is traversed by the Robert Campbell Highway along the bottom of a broad valley. It includes the Wolverine and Kudz Ze Kayah mining areas, as well as their access roads. The *Lower Liard – Mouth* sub-basin exhibits the most conspicuous concentration of land use activities related to oil and gas exploration, although most (e.g. seismic shotholes) represent only minor (Category 1) disturbances. Widespread, thick till cover in this low-relief, gently sloping to level sub-basin moderate potential groundwater vulnerabilities. The *Upper South Nahanni* sub-basin is consistently the lowest-ranked of all 13 sub-basins due to its almost pristine (undisturbed) condition (despite its large size), ruggedness with runoff-dominated terrain dissected by relatively narrow valleys limiting the extent of Type 1 aquifers, and the continuity of permafrost in its northern extent.

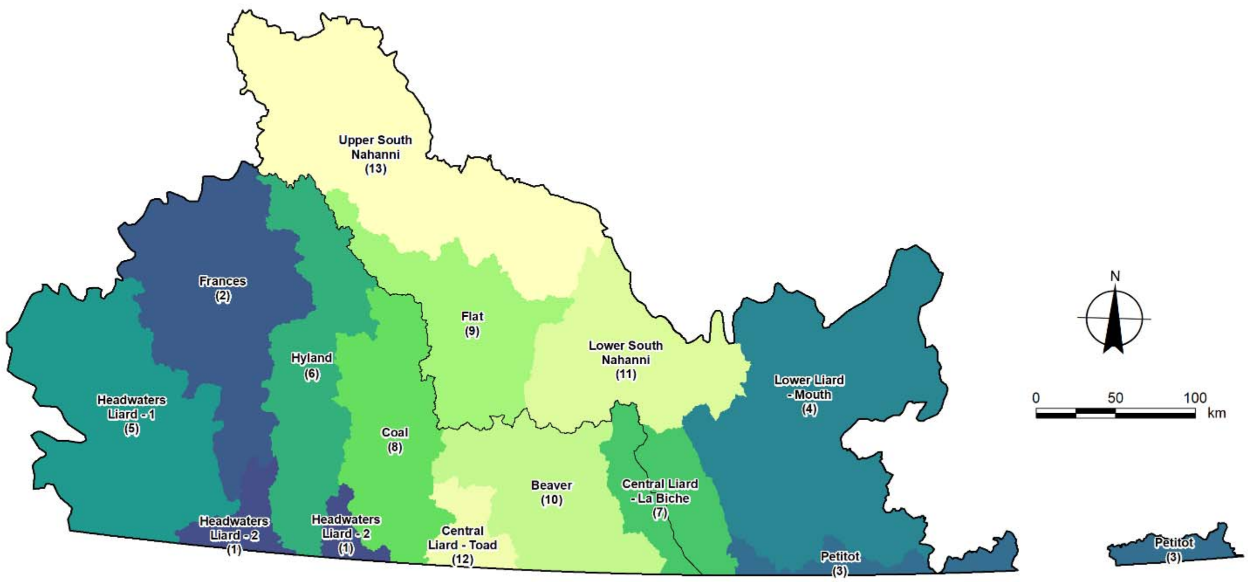

Figure 3-19. Sub-basins ranked by Index of Groundwater Disturbance Potential (Sub-basin). Rank out of 13 sub-basins provided in parentheses and symbolized by colour gradient, from lightest (tan, lowest rank) to darkest (navy blue, highest rank).

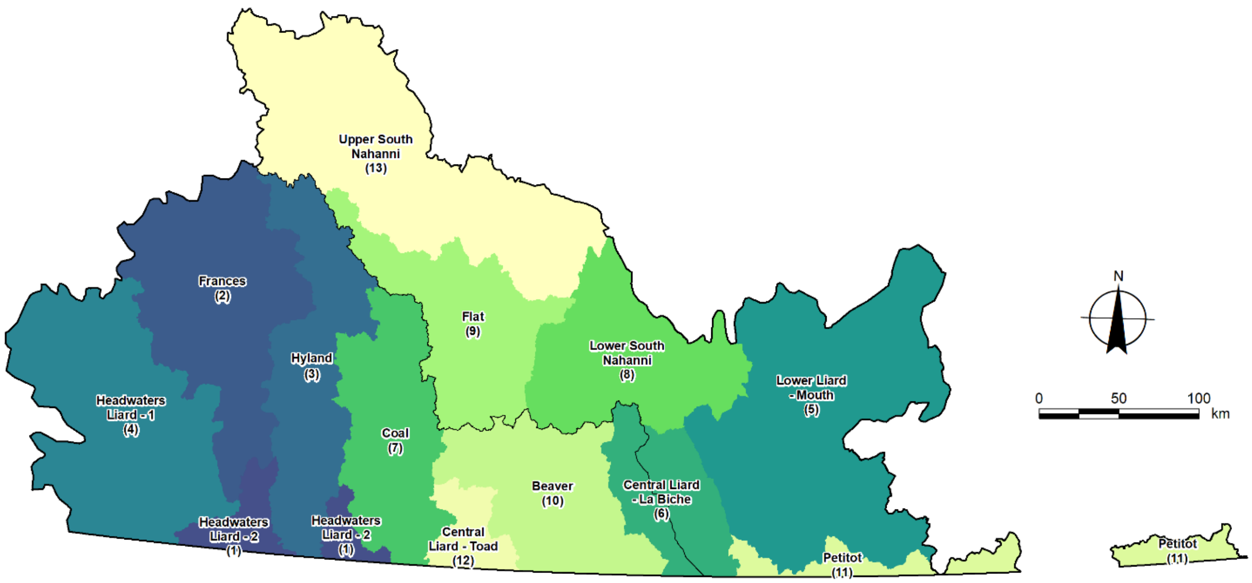

Figure 3-20. Basin-wide map of Index of Groundwater Disturbance Potential (Aquifers). Rank out of 13 sub-basins provided in parentheses and symbolized by colour gradient, from lightest (tan, lowest rank) to darkest (navy blue, highest rank).

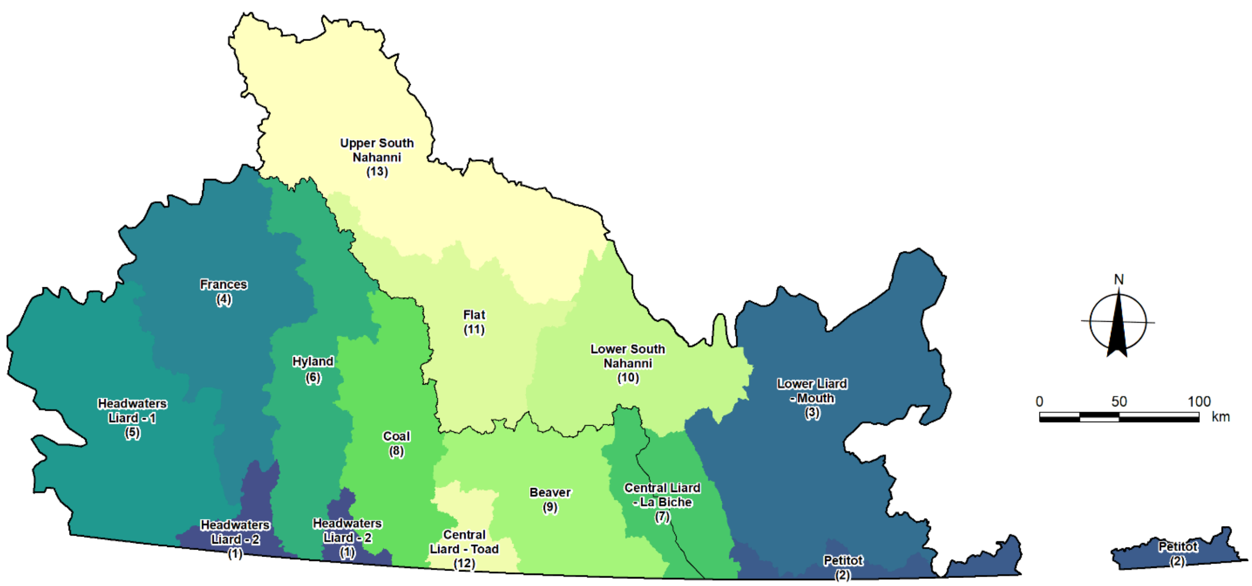

Figure 3-21. Basin-wide map of Index of Groundwater Disturbance Potential (Recharge). Rank out of 13 sub-basins provided in parentheses and symbolized by colour gradient, from lightest (tan, lowest rank) to darkest (navy blue, highest rank).

4. Discussion

4.1 Summary of Key Findings

Several key findings and implications of this project warrant highlighting:

- **Significant data gaps** – The compilation of available groundwater-related information completed following project commencement revealed significant gaps in the coverage and resolution of datasets on which aquifer delineation and characterization were to be at least partly based. More than one-quarter of the study area is covered by only 1:5,000,000-scale surficial geology mapping (inset in **Figure 3-4**), with a resolution incomparable to the 1:50,000 to 1:250,000-scale coverage available elsewhere. Only nationwide mapping of permafrost zones covers the NWT half of the study area, whereas 30 m-resolution mapping of permafrost probability is available for southern Yukon (inset in **Figure 3-5**). An attempt was made to refine the interpretation of areas of aquifer potential within the main data gap area through semi-automated topographic modelling, which yielded improvements that still need to be considered in the context of how they were derived.
- **Dominant types, distribution and characteristics of surficial aquifers** – Five main types of surficial aquifers occur within the study area. Areas with Type 1 aquifer potential are most widespread (11.4% of study area), generally associated with the floodplains and terraces of creeks and rivers. Areas with Type 3 (2.1%), Type 4a (4.2%), Type 4b (<0.1%) and Type 5b (0.4%) aquifer potential are more localized. More than half (123 or 55.9%) of the 220 documented water wells appear to be screened in Type 4a glaciofluvial aquifers, which tend to be productive. Glaciofluvial deposits are also strong contributors to groundwater recharge due to their permeable material and level to gently sloping surfaces.
- **Preliminary water budget** – A basin-wide spatial partitioning of surplus precipitation to runoff and infiltration was completed based on available climate data and mapping of surficial material, permafrost, topography and land cover, in order to better understand contributions to groundwater recharge within and beyond the delineated limits of potential aquifers. Most recharge appears to occur in the southern half of the study area, where permeable materials are more extensive, slopes are gentler and permafrost is only sporadic. Potential recharge within the study area is about 28.8 mm/yr, on average, or approximately 3.6×10^{10} m^3 annually. Relatively little is known about the exact distribution of groundwater discharge, which typically occurs within localized lowland areas or along creeks and rivers. The occurrence of 62 springs within the study area indicates specific locations where groundwater discharges to surface from relatively shallow (cool spring) or deep (thermal spring) sources.
- **Groundwater vulnerability to land use activities** – A variety of indices were adapted from Levson et al. (2018) to facilitate comparison of the vulnerability of groundwater to land use activities within each of the 13 sub-basins comprising the study area. The *Headwaters Liard – 2* sub-basin emerged as the sub-basin within which groundwater quality is most vulnerable to disturbance, irrespective of the index used, largely because it encompasses the community and associated development of Watson Lake on fluvial (Type 1) and glaciofluvial (Type 4a) deposits. The comparatively high density of water wells in this sub-basin also drove its top ranking with respect to its potential vulnerability to groundwater quantity impacts. The *Upper South Nahanni* sub-basin was consistently ranked lowest, with respect to its groundwater disturbance potential, due to its virtually

pristine (undisturbed) condition (much of it is protected by Nahanni National Park), its ruggedness and limited extent of unconsolidated deposits, and its continuity of permafrost along its northern margin.

- **Potential for transboundary groundwater flow** – Political boundaries (e.g. territorial borders) generally do not reflect groundwater flow patterns, which roughly follow surface topography. This assessment has highlighted a number of principal settings typified by transboundary groundwater flow through aquifers. Groundwater recharging and then flowing through the extensive glaciofluvial (Type 4a) and largely inset fluvial (Type 1) aquifers in the broad valleys of Yukon's Watson Lake area (**Figures 3-14** and **3-18**) almost certainly continues southeastward into British Columbia as groundwater or discharges into Liard River and crosses the border as surface water. Hyporheic exchange is common in fluvial settings, so water likely transitions between surface water and groundwater (through-flow) regimes as it enters British Columbia. Southwest of Fort Liard, groundwater sourced in British Columbia likely crosses the southeasternmost corner of Yukon and enters the NWT within the fluvial (Type 1) aquifer corridor encompassing the meandering channel of Liard River. Hyporheic exchange likely predominates water flow in this setting. Comparatively little groundwater is likely conveyed across borders through areas beyond the main aquifers, where surface runoff and aquitards predominate. Relatively little direct transboundary groundwater flow likely occurs between Yukon and the NWT due to their shared territorial border largely following the topographic and rough groundwater divide between the Liard River and South Nahanni River watersheds.

4.2 Priorities for Future Groundwater-related Research

The ranking of each of the 13 sub-basins within the study area according to their groundwater disturbance potential – whether considered at the sub-basin level, solely within areas of surficial aquifer potential, or in association with groundwater recharge potential – provides one basis for prioritizing areas for groundwater-related research. The highest-ranked sub-basins intuitively warrant greater and sooner attention than the lowest-ranked sub-basins. Accordingly, the *Headwaters Liard – 2*, *Francis* and *Lower Liard – Mouth* sub-basins should be the initial geographic focus of research. Little to no attention need be given to the lowest-ranked sub-basins, such as the *Upper South Nahanni* sub-basin, solely on the basis of improving understanding of groundwater recharge and vulnerability.

Another perspective for prioritizing groundwater-related research is to consider the availability of spatial and site-specific data on which to base understanding of groundwater vulnerability. Consideration could be given to the geographic distribution of existing data, which could justify effort being spent on filling critical spatial gaps, or to the type or quality of available information. A key priority, based on the methods through which this study was completed, should be the preparation of regional-scale (≥1:250,000) surficial geology mapping within the large data gap in the north-central portion of the study area. Mapping could be based on traditional expert interpretation of aerial photography and/or semi-automated predictive methods. The permafrost modelling team headed by authors at the University of Laurier (Carpino et al., in preparation) should be encouraged and supported to field-validate and expand their permafrost probability mapping within a region that fully encompasses the NWT portion of the study area.

Cold climate hydrogeology, more specifically hydrogeology in regions of permafrost, is increasingly becoming a focus for researchers interested in water movement in ground underlain by discontinuous to continuous permafrost (e.g. Morse (compiler), 2017). The presence and distribution of permafrost impart an additional factor affecting the flow of groundwater above (supra-permafrost groundwater), within (intra-permafrost groundwater), and below (sub-permafrost groundwater) permafrost. As described in this study, permafrost has a fundamental influence on infiltration that lacks understanding for application to regional studies. A principal catalyst for heightened interest in permafrost hydrogeology is better understanding the hydrological response of northern environments to climate change and, more specifically, permafrost degradation. **Figure 4-1** provides a schematic representation of forecasted changes in permafrost in response to climatic warming (Walvoord and Kurylyk, 2016). Supra-permafrost groundwater that has been restricted to the active layer, until now, may become connected with sub-permafrost groundwater through open taliks. Groundwater recharge and discharge are also likely to be enhanced through active layer thickening, as more volume of ground becomes available for storage and less surplus is lost to runoff. Additional predictions of the hydrological effects of climate change, specific to a portion of the Liard River basin, are highlighted by Golder Associates (2017). Improving estimation of groundwater recharge and mapping of surficial aquifers in northern environments relies on fundamental understanding of surface water and groundwater interactions, even without the added complexity introduced by climate change.

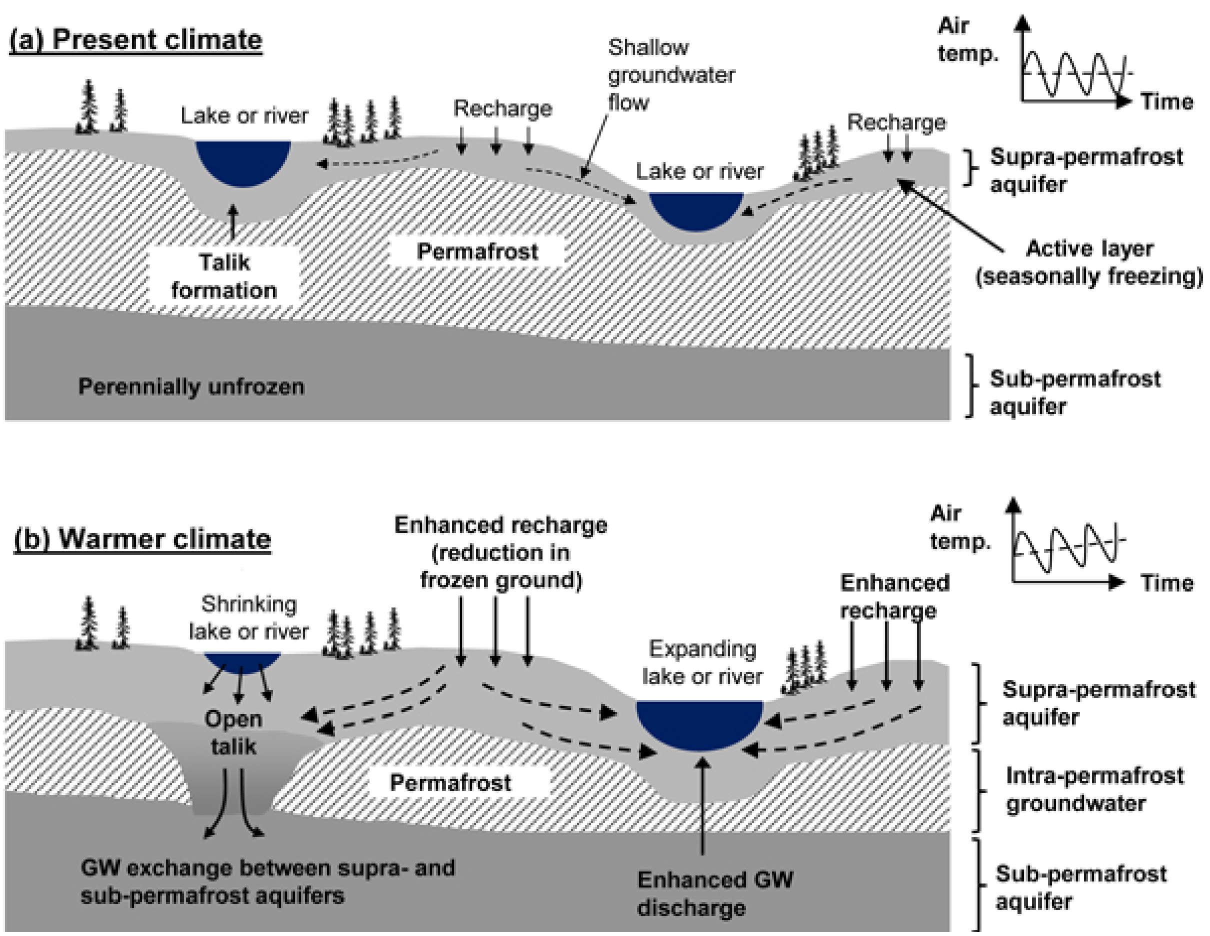

Figure 4-1. Schematic representation of possible changes in permafrost in response to climatic warming (from Walvoord and Kurylyk, 2016).

4.3 Recommended Follow-up Opportunities

This project has culminated in a number of specific recommendations for follow-up research in the Yukon and NWT portions of the Liard River basin, consistent with one or more of the overarching priorities identified above in Section 4.2:

- **Preparation of better-resolution surficial geology mapping** – Regional-scale (≥1:250,000) surficial geology mapping should be completed to fill the main data gap area in the north-central portion of the study area (e.g. inset in **Figure 3-4**). Such mapping has applications well beyond hydrogeological research, but it has also been shown to serve as a foundation for delineating and characterizing aquifer potential in regions with limited to no subsurface information. In addition to improving the resolution of surficial geology information, new mapping could also be better tailored to aquifer research by more consistently representing stratigraphic relationships that can be inferred based on an understanding of depositional environments and the glacial and deglacial history of a region. As noted in Section 3.2.5, Type 4b aquifers are undoubtedly under-represented in their extent due to inconsistent and/or poor identification of permeable strata blanketed by an aquitard material.
- **Improved storage of, and accessibility to, water well data** – Additional water well data would obviously benefit research on surficial (and deep) aquifers. More simply, existing water well databases in Yukon and the NWT should be more comprehensive and maintained in such a way that individual borehole logs and any associated well yield data are readily accessible. Hyperlinks accessing well logs from individual well records were commonly invalid when checked during searches in this project. More user-friendly access to well logs represents a critical first step toward better protection and management of groundwater resources.
- **Improvement and updates to land use activity/disturbance mapping** – Recent advancements in spatial data analysis tools are improving automated mapping of anthropogenic disturbances (e.g. Chen et al., 2014). Government of Yukon recently commissioned a desktop-based study to map all linear (e.g. seismic cut-lines) and areal (e.g. exploration staging areas) disturbances in the Eagle Plains area. Similar mapping projects would benefit groundwater-related research, especially if the prioritization of the types and areas of mapped disturbances was established in the context of groundwater vulnerability.
- **Groundwater stress analysis** – At least in select areas where reliable information on water withdrawal rates is available, a more refined representation of groundwater quantity vulnerability could be determined than is possible solely based on consideration of water well density. A comparison should be made between the actual, or permitted, groundwater withdrawals from a given well and the estimated groundwater recharge in the associated catchment. The resultant 'groundwater stress' would draw attention to areas where continued withdrawal may not be sustainable.
- **Refinement of water budget** – The GIS-based preliminary water budget prepared for the study area was necessarily based on a number of simplifying assumptions. For example, the use of a single study area-wide average of mean annual precipitation from only four climate stations fails to account for the climatological heterogeneity related primarily to topography and geographic position. More rigorous analysis of appropriate spatial partitioning of climate data could help improve the overall water budget. In addition, the baseflow estimates used to validate the water

budget are based on published techniques with uncertainties that can only be resolved through field data collection. Empirical data from tracer studies (e.g. Gonzales et al., 2009), for example, would help improve precision of baseflow within different sub-basins and, in turn, the basin-wide water budget. Further refinement of the model input parameters tested against site-specific groundwater recharge/discharge studies could improve the model results for small watersheds, especially where permafrost is discontinuous.

- **Incorporation of traditional knowledge into groundwater studies** – As noted above in Section 3.3, incorporating traditional knowledge into this aquifer assessment was beyond the scope of this study. However, traditional knowledge should be explored and used to improve understanding of the distribution of groundwater recharge and discharge areas based on generations of repeated, seasonal observations. The locations of groundwater springs, sourced shallowly or deeply (e.g. thermal springs), may be part of traditional knowledge. Understanding where and how water has been used, traditionally, is also fundamental to evaluating proposed project applications with the potential to compromise traditional water uses. It provides another means of helping to prioritize sub-basins, or portions of sub-basins, for groundwater-related research.

4.3.1 Additional Considerations and Alternate Approaches

Feedback from reviewers of the draft version of this report drew attention to a number of additional considerations and potential alternate approaches to the analysis and interpretation of areas of potential aquifers in the Liard River basin. Several comments are explored, below, for consideration during future groundwater-related research and more site-specific studies:

- **Limitations of surficial geology mapping compilations** – Pre-existing digital compilations of individual surficial geology maps largely formed the basis for aquifer delineation in this basin-wide study (Section 2.2.1). Most of the detail from the original surficial geology PDF maps is represented in the digital compilations, but certain information was not retained in the conversion from PDF to GIS files and through adaptation of inconsistent legends into a universal legend protocol. Although minor, the corresponding information loss is spatially variable and means that certain refinements to the mapping of surficial aquifer potential (**Figure 3-9**) may be possible in future, more detailed studies. Furthermore, some surficial geology mapping completed by the Geological Survey of Canada that is unpublished or only available online in PDF may be requested (R. Smith, pers. comm.). Most notably, the Geological Survey of Canada can provide access to GIS (vector) formats of the 1:50,000-scale surficial geology mapping within the Fort Liard area (95B) by Bednarski (2002, 2003a, b, c, d, e, f, g, h, i, j, k, l, m, n, o). Additional improvements to delineation of areas of aquifer potential could also be made through review and incorporation of various thematic geoscience reconstructions derived from the latest database of seismic shothole drillers' logs (Smith, 2011), such as potential granular aggregate resources (Smith et al., 2011); drift isopach, till isopach and till facies (Smith and Lesk-Winfield, 2010a); bedrock outcrop/subcrop and muskeg thickness (Smith and Lesk-Winfield, 2010b); and ground ice and permafrost geology (Smith and Lesk-Winfield, 2012). For future local- to site-scale studies, characterizations of the Quaternary geology of Yukon (Kennedy, 2009) and NWT (Bednarski, 2008a, b) portions of the study area also provide valuable information on which refined interpretations could be based.
- **Area-specific aquifer characterization** – Additional characterization of aquifers within the study area could also be provided for specific physiographic areas or each of the 13 sub-basins, if helpful

to future research, especially where subsurface data are available (e.g. *Headwaters Liard – 2*, *Lower Liard – Mouth*). The spatial limits of additional characterizations should be tailored to the application.

- **Deep bedrock aquifers and potential surface interactions** – The focus of this study was delineation and characterization of surficial aquifers within the study area, although the possibility of groundwater within deep bedrock aquifers interacting with surficial aquifers is noted (Section 3.2.7). The scattered occurrence of thermal springs corroborates this notion (**Figure 3-7**). Information on bedrock stratigraphy is readily available for the geological Liard Basin in northeastern British Columbia, in relation to oil and gas exploration, development and operations (e.g. Petrel Robertson Consulting Ltd., 2013), so it would be worth more systematically examining this information in the context of the results of this study and overall assessment of groundwater resources and potential vulnerabilities.

5. Conclusion

A desktop-based assessment of the potential occurrence and vulnerabilities of surficial aquifers in the Liard River basin in Yukon and the NWT has been completed based on the best available spatial datasets and limited subsurface information. Areas of potential surficial aquifers classified as Type 1, Type 3, Type 4a, Type 4b or Type 5b (Wei et al., 2009) were delineated in approximately 22,583 km^2 (18%) of the study area, despite the absence of regional-scale ($\geq$1:250,000) surficial geology mapping in the north-central portion of the study area and the absence of permafrost probability mapping in the NWT. A preliminary water budget demonstrates that the greatest contributions to groundwater recharge occur in the southern half of the study area, where permeable surficial materials are more widespread, slopes are gentler and permafrost is only sporadic. Groundwater quality and quantity are most vulnerable to disturbance from land use activities in the *Headwaters Liard – 2*, *Francis* and *Lower Liard – Mouth* sub-basins, where surface disturbances are commonly underlain by fluvial (Type 1 aquifer) and glaciofluvial (Type 4a) deposits. The *Upper South Nahanni* sub-basin is consistently ranked lowest according to its groundwater vulnerability due to its nearly pristine (undisturbed) condition, ruggedness and associated rarity of unconsolidated deposits, and continuity of permafrost along its northern margin. Future groundwater-related research should focus on the most at-risk sub-basins and aim to resolve critical gaps in spatial data coverage and knowledge of permafrost hydrogeology especially in response to climate change.

6. Certification

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Appendix B

List of Compiled Land Use Activity Mapping and Associated Disturbance Footprints

Appendix B. List of Compiled Land Use Activity Mapping and Associated Disturbance Footprints

Land Use Activity	Category of Disturbance	Buffer (m)	Buffer Comment
Forestry_Activity_and_Cutlines_PG_NT_YT	1	5	Average between modern day cutlines and historical
Oil_and_Gas_Seismic_Lines_PG_NT_YT	1	5	Estimate from imagery
Parks_and_Leisure_Areas_All_PG_NT_YT	1	200	Estimate
Powerline_PG_NT_YT	1	5	Average between modern day cutlines and historical
Seismic_Shotholes_PG_NT_YT	1	5	Permitted size
Trail_PG_NT_YT	1	5	Estimate
Agricultural_Land_UN_PG_YT	2	n/a	Actual areal extent
Water_Wells_PG_YT	2	5	Estimate
Drillhole_Location_PG_YT	2	5	Typical size
Pipelines_PG_NT_YT	2	30	Right of way
Aggregate_Gravel_and_Quarrying_PG_NT_YT	3	250	Estimate from imagery
Areas_for_Notification_of_Class_1_Mining_Activity_PG_YT	3	n/a	Actual areal extent
Buildings_PG_NT_YT	3	30	Average shape area, calculated radius
Cemetery_PG_NT_YT	3	n/a	Actual areal extent
Energy_Sites_PG_YT	3	n/a	Actual areal extent
Miscellaneous_Human_Development_Activity_PG_NT	3	n/a	Actual areal extent
Mining_Exploration_Oil_and_Gas_Footprints_PG_NT_YT	3	50	Estimate
Oil_and_Gas_Wells_PG_NT_YT	3	250	Estimate from imagery
Ore_PG_NT_YT	3	250	Estimate from imagery
Residential_Area_PG_NT_YT	3	n/a	Actual areal extent
Road_PG_NT_YT	3	60	Most legal descriptions of NWT highways say 60m
Runway_PG_NT_YT	3	n/a	Actual areal extent
Tank_PG_NT_YT	3	5	Estimate from imagery
Tower_PG_NT_YT	3	5	Estimate from imagery
Waste_PG_NT_YT	3	n/a	Actual areal extent

Appendix C

Digital Spatial Data Files (provided separately)