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Liard and Petitot Sub Basins Transboundary Groundwater Resources Assessment

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EXECUTIVE SUMMARY

The Liard-Petitot project is designed to provide geological and hydrogeological data to aid in groundwater resource assessments in the Liard and Petitot sub-basins trans-boundary water management areas. The purpose of the project is to compile, synthesize and analyze groundwater related information from NTS map sheets 94I, 94J, 94O and 94P including surficial geology maps, water well records, geology, hydrology, current development activities and groundwater use. All map data including surficial and bedrock geology maps, terrain and soils maps, vegetation resource inventory and predictive ecosystem maps were acquired in digital format and incorporated into the GIS database (>35 Gigabytes). Other relevant literature and data were compiled and reviewed including: water well data, oil and gas exploration well data, geophysical data and surface land use data. All of the surficial geology map data were compiled into a single data set for the region and the main aquifer units were characterized in as much detail as possible. A total of 6418 aquifers were mapped comprising almost 3 billion square metres (292,178 ha) but only 5.7% of the entire study region (5,121,701 ha; 51,217 km^2).

The approach used a fact-based or reality-based methodology rather than a theoretical or hypothetical modelled approach. The primary premise has been to use tested and verifiable data based on high quality factual information wherever possible. As such, a strong geological basis has been applied to the analysis using data sets that have been produced by highly qualified experts at detailed scales and field tested and verified with ground surveys.

Aquifers mapped using surficial geology data in the area consist of alluvial (mainly fluvial) aquifers, where the potential for hydraulic connectivity with a river is high, and upland (mainly glaciofluvial) aquifers that may or may not be hydraulically connected to modern streams and rivers. Alluvial aquifers comprise 57.3% of all mapped aquifers and upland aquifers comprise 42.7%. Sub-surface aquifers are classified as either confined glacial, pre-glacial aquifers or confined, fractured sedimentary bedrock aquifers. A total of only 208 water-well records were obtained for the area; 27% (56 wells) are in surficial aquifers and 33% are in bedrock aquifers (68 wells). The aquifer type is unknown for 32% (66 wells) and 9% were dry (18 wells).

To determine priority areas for future study, two land use indices were generated, and then combined to make a third. First, general land surface impacts were quantified by considering data on the area of land use impact, land use type and general surficial hydrogeology type. This index is mainly a proxy of land use impacts on groundwater quality. Secondly, an index of water well density was generated by considering the density of wells. This index is a proxy for land use impacts on groundwater quantity. Finally, the two indices were normalized and combined to create a total index of land disturbance and well density, and then ranked for each of 28 drainage basins in the study area.

The calculated indices of land use impacts on aquifers, use weightings by aquifer type (alluvial aquifers, upland aquifers and aquitards), and weightings by level of disturbance (3 increasing categories of disturbance level are used). These index scores were then normalized by dividing by the highest score for any one basin. This last step allowed a direct comparison between land use data and wells data. Finally, total disturbance indices were generated by combining the land use index data with the water well index data. Disturbance indices were determined by evaluating disturbance in the entire basin as well as disturbance only within aquifers.

The top ranked (high priority) basins as a proportion of the entire basin area are the Lower Prophet (1), Middle Fort Nelson (2), Lower Muskwa (3), Lower Fort Nelson (4), Lower Liard (5) and Upper Muskwa (6) river basins. As a proportion of only aquifer area, they are the Lower Fort Nelson (1), Middle Fort Nelson (2), Lower Muskwa (3), Lower Prophet (4), Upper Fort Nelson (5) and Lower Liard (6) river basins.

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1. INTRODUCTION

This report was commissioned by the British Columbia Ministry of Environment and Climate Change Strategy (ENV). The stated aims of the project are to compile and analyze groundwater related information in the Liard and Petitot sub-basins transboundary water management areas in northeastern-most BC, specifically from four 1:250,000-scale National Topographic Series (NTS) map sheets: 94J, 94I, 94O and 94P (Figure 1). Data collected includes: surficial geology maps, water well records, geology, hydrology, current development (oil and gas development, surface disturbances, agricultural and mining) activities and groundwater use to infer and prioritize potential transboundary aquifers/groundwater areas for future aquifer mapping and characterization. Limited knowledge on aquifers in this region is considered by ENV to be a major impediment to the sustainable management of transboundary groundwater resources. The assessment is intended to support the implementation of the Mackenzie River Basin Bilateral Water Management Agreements as well as provide key information for the implementation of the *Water Sustainability Act* (WSA) and the Northeast Water Strategy (NEWS).

1.1 Objectives

The objectives of the project as specified in Schedule A of ENV Contract Number PA18JHQ131 are:

1. Compile and review all the relevant literature and data at local and regional scales including: surficial and bedrock geology maps; terrain and soils maps; hydrogeology and geophysical maps, reports and cross-sections, geotechnical borehole records, exploration well logs for minerals and natural gas, surface disturbances, and agricultural activities for the study area in a Geographic Information System (GIS) format for all map data.
2. For each of the four map sheets in the study area (NTS map sheets 94I, 94J, 94O and 94P), compile and analyze all available surface and subsurface information related to the bedrock and surficial geology, hydrogeology, hydrology, water use and management, development activity and disturbances, and construct representative cross-sections to characterize the main aquifer units.
3. Propose priority trans-boundary areas for future aquifer characterization, drilling and pumping tests.
4. Categorize trans-boundary groundwater areas (map polygons) as low, medium or high priority for future aquifer mapping and characterization.
5. Produce a report detailing all data sources and methods including a complete discussion of data synthesis and interpretation
6. Produce maps and detailed descriptions of inferred and prioritized potential trans-boundary aquifers/groundwater areas:
    - a compilation map of the surficial geology of the region with the main shallow aquifers identified;
    - a data base and map of all subsurface data collected and general descriptions and cross-sections of subsurface aquifers where the data density is sufficient to warrant their development;
    - a map of the surface DEM (Digital Elevation Model) as a colour hill-shade with relevant data in the foreground;
    - a map showing topography, hydrology, roads, oil and gas wells, mine sites, logged areas, and surface and groundwater extraction sites, and
    - a map identifying areas of low, medium or high priority for future aquifer mapping based on geological characterization of potential aquifers in comparison with the density of past and current development activities and groundwater use.

1.2 Basic Premises

A number of fundamental premises have guided the analyses in this project. Most importantly, all data used in this work is considered high quality data derived from ground tested surveys and by expert interpretation wherever possible. This provides a strong geological basis to the analysis by relying on data sets that have been produced at detailed scales and are field tested. Theoretical and generalized data derived from statistical models, using uncalibrated and often geographically distant and disparate data sources, are intentionally excluded from the study as this information is not field verified, e.g. modelled distributions of precipitation based on one or two weather stations. Likewise, assumptions on future land use or water consumption are also excluded. In addition, highly generalized (very broad scale) data that can be misleading at more detailed scales are not used. A review of a number of regional aquifer assessments revealed that, although interesting, significant and large errors were introduced by using modelled and theoretical data. In the absence of actual ground verification or quality assurance data, hypothetical studies can produce incorrect results ("garbage in, garbage out"). Thus, the primary premise in this study is to use tested and verifiable data based on factual information whenever possible.

The analyses in this study rely on a fact-based approach based on the following guiding principles:

1. Use the highest quality data available at the most detailed scale possible. The first choice is to use data sets that have been ground-verified by professionals rather than data sets derived from models or data at generalized scales. Although the latter are more convenient and may provide broader regional coverage, the former are much more reliable and higher quality. The first assessment criterion of a data set used here is based on quality and the second level of assessment is based on scale. Thus, for example, high quality data at 1:50,000 scale is used instead of lower quality data at 1:20,000 scale.
2. Use only past and current land use data sets, avoiding use of uncertain and speculative land use projections; for example, gas development projections in the Horn River Basin that did not materialize.
3. Use the most up to date and complete data sets available. This necessitates consideration of multiple data sources rather than a single default data set. Although more time consuming, this provides the most accurate picture for the assessment. An example of this approach is analysis of road coverage used here. Initially, roads derived from Natural Resources Canada (CANVEC) and the National Topographic Data Base (NTDB) as well as provincial coverage from BC Terrain Resource Inventory Management program (TRIM II) were used. Although this provided good road coverage, additional road segments were acquired from the Oil and Gas Commission (OGC) data sets. Use of multiple data sources required manual time-consuming removal of duplicate road segments but in the end provided a high quality and unique roads data set.

2. METHODOLGY

2.1 Literature Survey and Data Compilation

Relevant literature and data was compiled and reviewed at local and regional scales including: surficial and bedrock geology maps; terrain and soils maps; hydrogeology and geophysical maps, reports and cross-sections, including: maps published by the British Columbia Geological Survey (BCGS) (e.g. Levson and Fournier, 2012; Trommelen and Levson, 2011; Blyth and Levson 2003), the Geological Survey of Canada (GSC) (e.g. Levson et al., 2016, 2015; Bednarski, 2005-2011; Smith, 2009a,b,c,d); journal papers (e.g. Levson, 2008; Trommelen and Levson, 2008; Bednarski, 2008; Bednarski and Smith, 2007); and reports (Levson et al., 2012, 2006, 2004; Johnsen et al., 2004; Best et al., 2004). A more complete list of relevant publications is provided in the reference list. All ENV water well records in the area were compiled in a database. In addition, water wells acquired directly from Anderson Drilling Ltd. by the British Columbia Ministry of Energy, Mines and Petroleum Resources (EMPR) in the early 2000's were retrieved and entered into the data base.

Since there are relatively few water wells that penetrate the entire Quaternary sequence in the region, readily accessible geotechnical borehole records were also compiled that provide higher quality and, in some cases, deeper well records. Such data were requested from public agencies such as the British Columbia Ministry of Transportation and Infrastructure (TRAN), Procurement Canada (Transport Canada, Engineering Assets) and private agencies such as BC Rail and natural gas exploration companies. Other data sources investigated included exploration well logs for minerals and natural gas housed by EMPR. Water well data and descriptions are provided in Appendix A.

Key information on land use activities was also compiled including: information on oil and gas development (e.g. wells, seismic lines, pipelines, facilities), agricultural and mining activities, forestry activities and other surface disturbances both natural, such as burned areas, and anthropogenic, such as roads, railroads, townsites, airstrips and power transmission lines. All data were compiled in a GIS format (see Section 2.4) and included in the appendices.

2.2 Data Synthesis and Interpretation

For each of the four map sheets in the study area (NTS map sheets 94I, 94J, 94O and 94P), all available surface and subsurface information related to the bedrock and surficial geology, hydrogeology, hydrology, water use and management, development activity and disturbances was compiled and analyzed. Initially a geological database was created including surface and subsurface data from previous studies. Surficial geology, soils and terrain data were then compiled and used to identify the aquifers in the region. In the subsurface database, major geologic/hydrogeologic units were identified and correlated where possible and a series of representative cross-sections were then constructed to characterize the main aquifer units. The shallow geology in the cross-sections was correlated with the mapped surficial geology.

2.3 Aquifer Mapping

Most aquifers in the study area were identified from surficial geology map data or from other less reliable data sources such as soil texture or vegetation (e.g. Vegetation Resource Inventory, VRI) mapping. Since a large proportion of the study area has relatively little subsurface data, subsurface conditions are interpreted based on knowledge of the Quaternary stratigraphy and surficial geology to create the aquifer maps. Where no reliable existing surficial geology map data were available, interpretations were supplemented with digital elevation model (DEM) topographic analysis and landform mapping to help delineate shallow aquifer map units. Mapping began in areas with the highest quality data and moved into areas with lower-quality data using all available data sets. For example, alluvial aquifers mapped along major rivers and streams were traced from areas with high quality surficial geology map data into adjoining areas using topographic data and VRI mapping that identified alluvial floodplain vegetation types.

2.4 Geographic Information System Analysis

All data were compiled and analyzed in a Geographic Information System (specifically on an ArcGIS platform). Aquifer map units, identified from surficial geology and other data sets, were compared in the GIS with overlain layers of land use data including roads, oil and gas wells, sand and gravel mine sites, logged areas and many other types of disturbance to determine the aquifer areas with the greatest density of development activities. After compilation in ArcGIS, the various land use activity layers were clipped to the aquifer boundaries using QGIS software and statistics on each aquifer layer were generated. The details of this analysis are presented in the results section below.

Information on hydrology and groundwater use (well sites, OGC water withdrawal permit sites, etc.) were also incorporated into the analysis to identify areas of greatest water demand. Aquifers were grouped by drainage basins for both the water quality and water quantity analysis. By combining geologic and aquifer mapping with land use density, all aquifer areas (map polygons) were evaluated and categorized. Priorities for future aquifer mapping and characterization were determined for each of 28 drainage basins defined in the study area.

3. <u>RESULTS</u>

3.1 Surficial Geology Map Compilation

The primary goal in the data compilation process was to use the highest quality data available for any one area. Thus, all available and relevant map data sets were compiled, reviewed and ranked by quality (in terms of suitability for defining aquifer boundaries) as discussed below. The highest quality data were always used in preference over lower quality data, even if the lower quality data sets were at a more detailed scale. Map data, listed in order of quality, included: published surficial geology maps (BCGS and GSC), terrain/slope stability maps (GSC), soil science maps (BC Soil Survey), terrain ecosystem maps (TEM), vegetation inventory (VRI) maps and predictive ecosystem maps (PEM). All mapping data sets were collected and compiled in digital GIS format files.

3.1.1 High Quality Surficial Geology Mapping

This type of mapping was conducted by the BCGS and GSC (see yellow coloured polygons on Figure 1 for coverage) at 1:50,000 to 1:100,000 scales. The maps were produced by highly specialized professional geologists trained in surficial geology mapping and verified with extensive field studies. Maps of this type in the study area include:

- several GSC maps on NTS 94P (Bednarski, 2005a, b; 2007a, b; 2008a, b, c; 2011)
- four 1:50,000 scale GSC maps on maps on 94I/NW (Smith, 2009 a-d)
- one 1:50:000 surficial geology map of the Komie Map area (NTS 94P/05) (Demchuk, 2008)
- one 1:100:000 scale map surficial geology map of the Ft. Nelson Map area (94J/NE; Levson and Fournier, 2012)
- two 1:100:000 scale surficial geology maps of NTS 094J/SE (Trommelen and Levson, 2011) and 094I/SW (Trommelen and Smith, 2007) map areas
- one 1:100,000 scale Geological Survey of Canada map of 94I/SE (Smith, 2009)

Coverage of high quality surficial geology maps in the study area is shown in Figure 1. A total of 67,384 surficial geology polygons were included in the geology database.

A sample of a high quality surficial geology map is shown in Figure 2. These maps are produced by experienced professionals and derived from air photo interpretation combined with extensive field studies and field verification. Field sites are typically plotted on the maps and subsurface stratigraphic information is provided in accompanying reports.

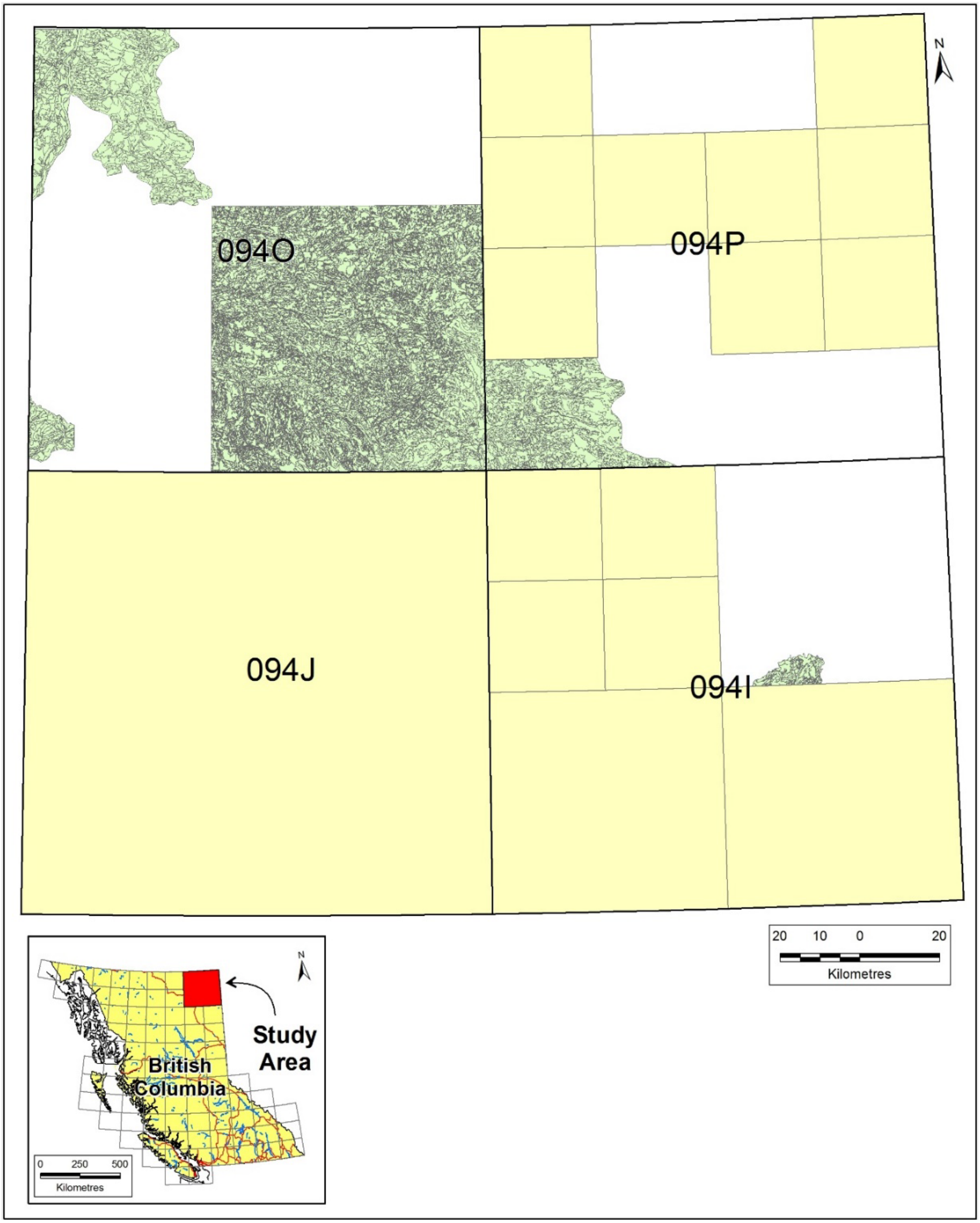

Figure 1: High quality surficial geology mapping conducted by the B.C. Geological Survey of Canada at 1:50,000 to 1:100,000 scales (yellow) and medium to high quality 1:20,000 scale surficial geology information obtained from terrain mapping (green with fine black linework showing the detail of this mapping). Note: where there is significant overlap of these data sets, only the highest quality data are used for analysis.

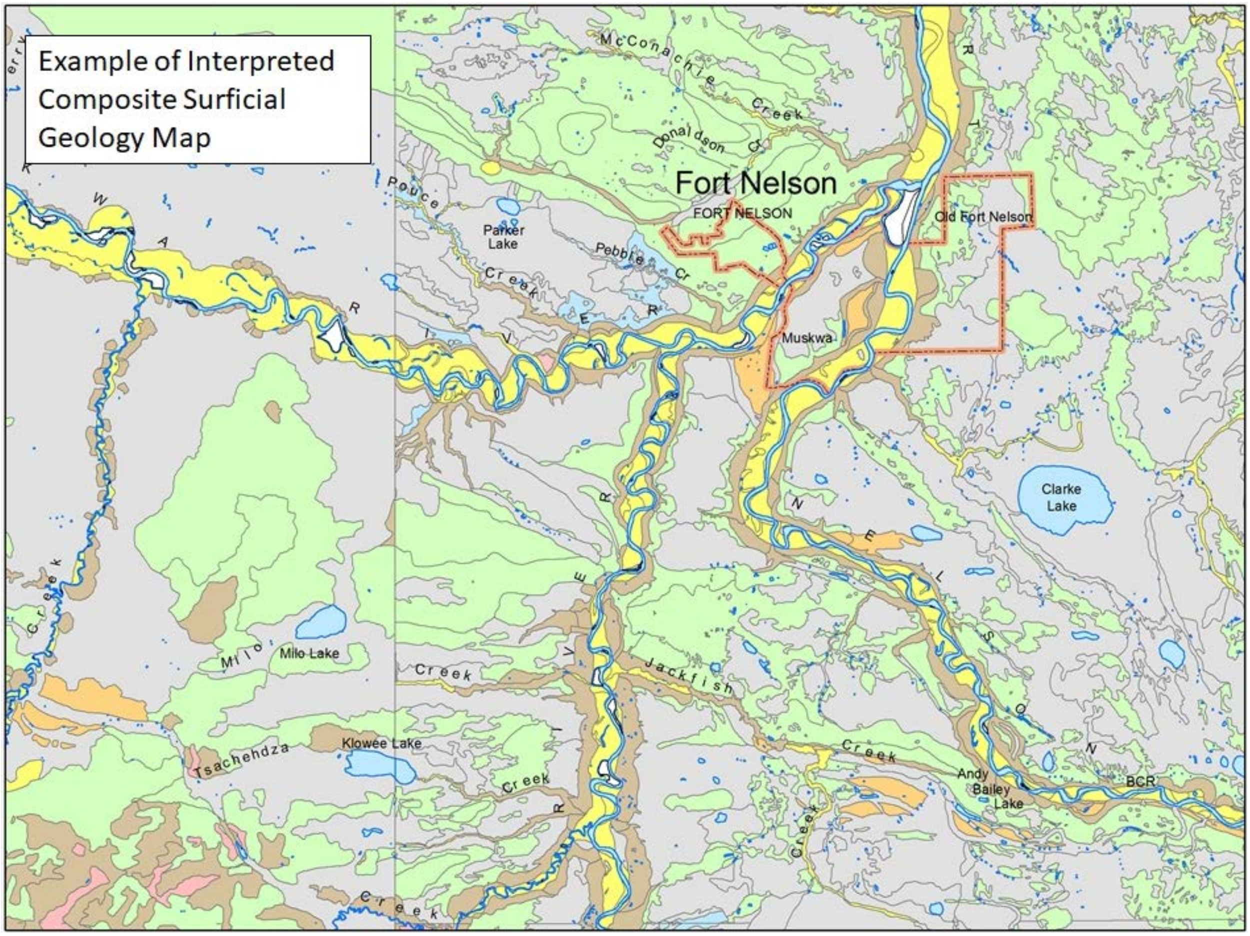

Figure 2: Example of a simplified version of a high quality surficial geology map. (Yellow represents alluvial map units, orange is glaciofluvial, green is glacial (till), brown is colluvial, grey is organic, pink is bedrock).

3.1.2 Medium to High Quality Terrain Mapping

This type of mapping was conducted at 1:20,000 scale mainly by private consultants and map data were obtained from provincial terrain ecosystem map data sets (TEM, see Figure 1). These maps are stored in the BC government warehouse. These types of maps are mainly produced for forestry companies and they are used primarily for terrain stability assessments and for ecosystem mapping. The terrain mapping data from these maps is not always retained by the government and in some cases, forest companies had to be approached to obtain the original data. Unfortunately, in some areas, neither the government nor the forest companies had retained the required terrain mapping data. However, useful data was obtained for most of the TEM study areas including the Sahtaneh, Labiche-Sandy, Dunedin, Kahntah and Snake-Sahtaneh TEM's (Figure 3). The terrain layers of TEM maps are generally produced by trained professionals and field verification is usually included in most mapping projects, especially if the maps are to be used for slope stability analysis. However, in other cases such as ecosystem mapping, the details and extent of the field testing are not always well documented.

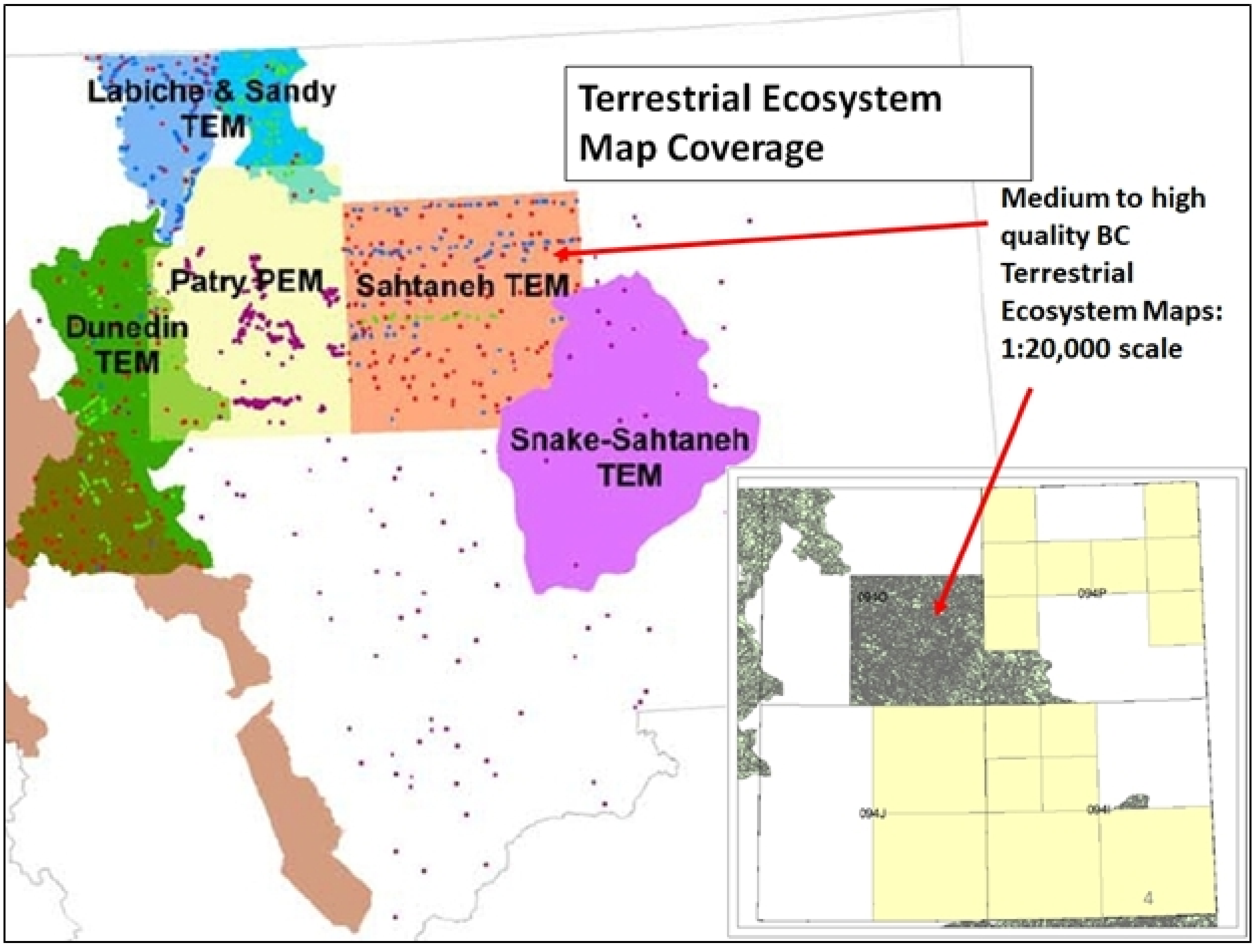

Figure 3: Coverage of medium to high quality terrain mapping data sets available in the study area completed as part of various Terrain Ecosystem Mapping projects (shown in various colours); Inset map shows terrain map areas (shaded) in comparison to surficial geology maps (in pale yellow).

3.1.3 Medium to High Quality Aggregate Mapping

This type of mapping was conducted at 1:20,000 scale by EMPR and map data were obtained for parts of 14 different 1:50,000 map sheets within the study area (Blyth and Levson, 2002a-h). These maps were produced as part of a sand and gravel mapping project for the Resource Development and Geoscience Branch at EMPR in the early 2000’s. Figure 4 provides an example of an aggregate potential map of part of NTS 94P/7 (Blyth and Levson, 2002). Aggregate potential is somewhat analogous to aquifer potential because sand and gravel units with good aggregate potential are highly permeable units and have a high likelihood of containing groundwater at depth. These maps were field verified with documented field sites and observations.

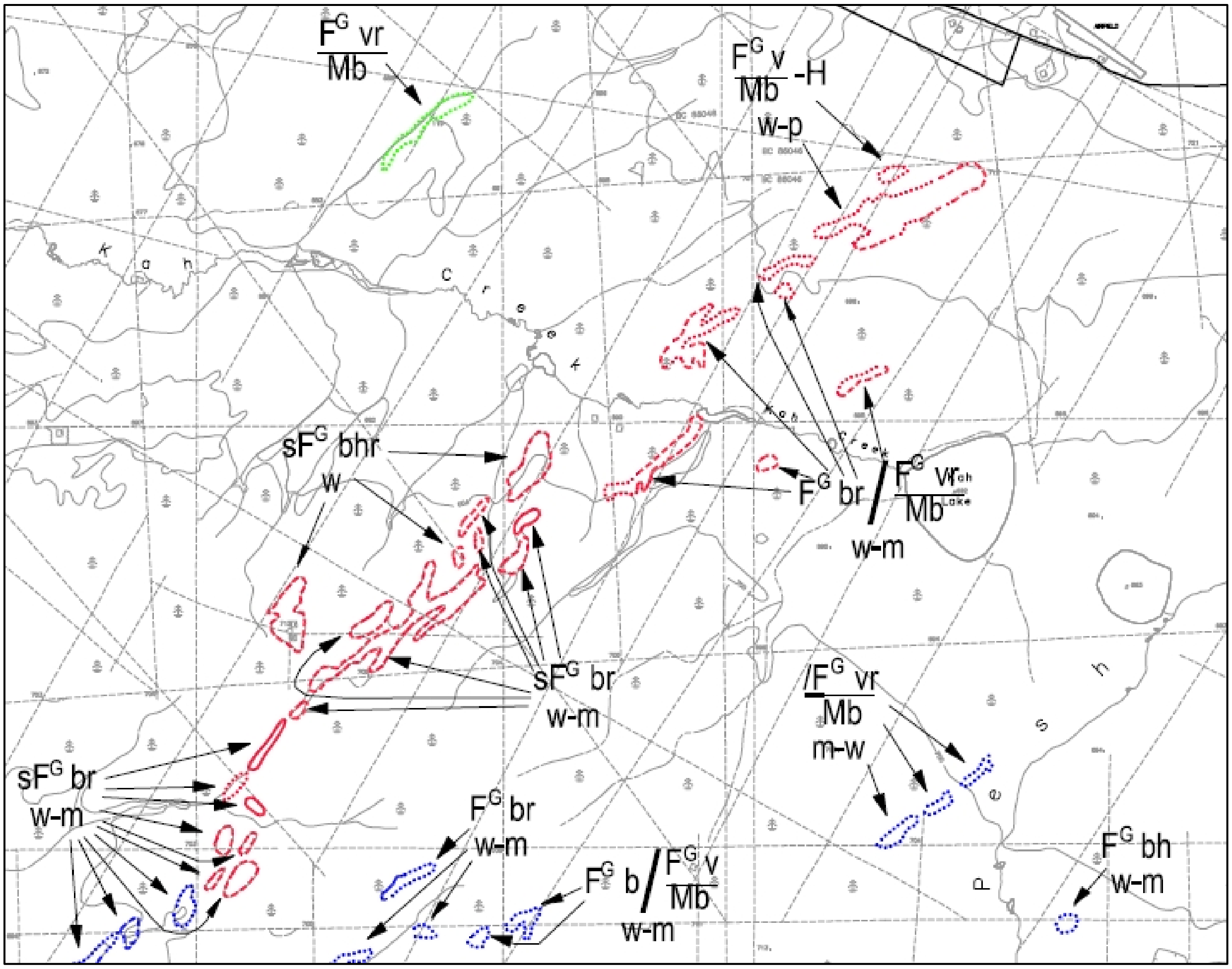

Figure 4: Example of an aggregate potential map of part of NTS 94P/7 (Blyth and Levson, 2002); aggregate potential is ranked as high (red), medium (blue) and low (green).

3.1.4 Medium to High Quality Soils Mapping

This type of mapping was conducted at 1:50,000 to 1:100,000 scale by experienced soil scientists from the British Columbia Soil Survey and Agriculture Canada. These maps focus mainly on shallow soils (used for agricultural assessments) but they generally also include reasonably good quality surficial geology and terrain information. Field checking is extensive but usually only focusses on relatively shallow data (e.g. upper metre). Figure 5 shows the coverage of soil science maps in the study area and also shows a sample of soil science map units (Kowall and Valentine, 1979). Accompanying reports to soil survey maps often include valuable information on subsurface materials and provide schematic cross-sections (e.g. Figure 6; Kowall, 1982). Unfortunately, soil science maps usually have very complex legends and deriving terrain information from the legend or accompanying report is challenging.

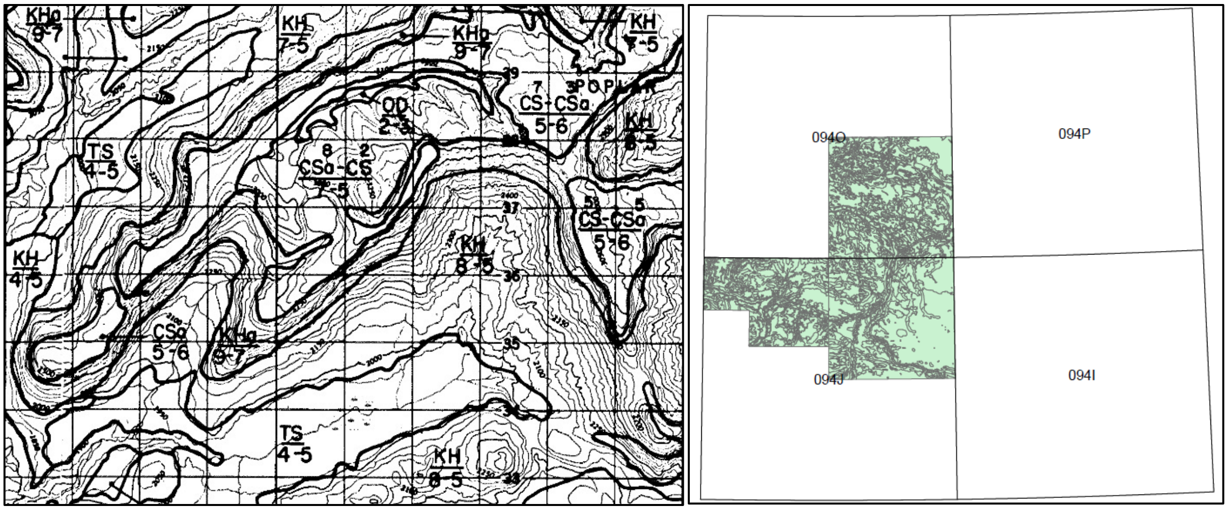

Figure 5: An example of a soil science map covering part of NTS 94J/NW (left) (Kowall and Valentine, 1979), and coverage of digital soil science maps in the study area (right).

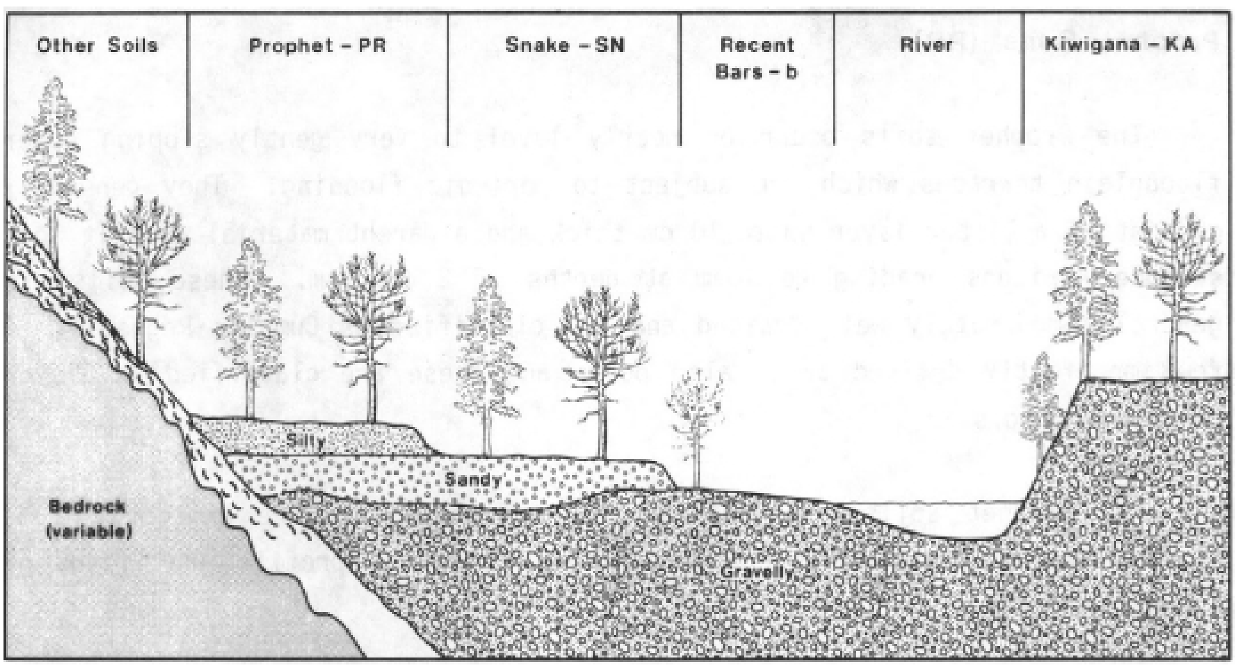

Figure 6: Schematic cross-section of coarse-grained soils (with good aquifer potential) in the 94J/NW and 94O/S half (from Kowall, 1982).

3.1.5 Medium to High Quality Slope Stability Maps

This type of mapping was conducted at 1:50,000 scale by the GSC as a base layer for slope stability mapping. These types of maps were produced by experienced professionals with some field verification. However, since emphasis was placed on slope stability, these maps are more generalized and not as high quality as surficial geology maps. An example of this type of mapping in the study area (part of 94J/01) is shown in Figure 7 (Dyke et al., 2011).

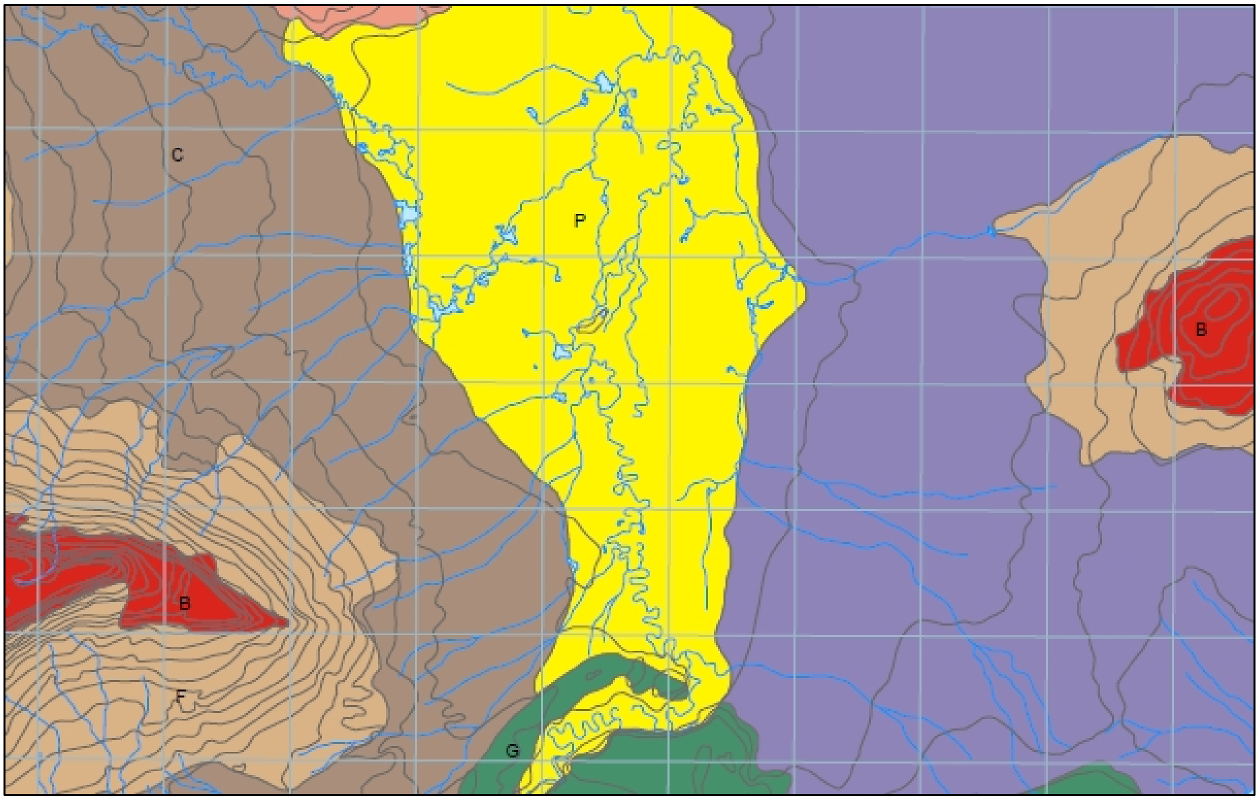

Figure 7: An example of terrain mapping conducted for slope stability assessments in the study area (94J/01) showing alluvial plain (P, in yellow), glacial materials (G, in green), colluvium (C, in brown), colluvial flows (F, in beige), bedrock (B, in red) and lacustrine (L, in purple) sediments (Dyke et al., 2011).

3.1.6 Medium Quality Vegetative Resource Inventory (VRI) and Terrestrial Ecosystem (TE) Maps

This type of mapping was conducted at 1:20,000 scale mainly for the forest industry and map data provide limited surficial geology information. Although there is almost complete coverage of VRI and TE maps in the study area, useable information from these maps was limited to soil texture data (allowing for the identification of coarse-grained soils) in upland areas where no other map data were available. Over one-half million (558,619) polygons with soil texture data (Soils, PEM and VRI data) were compiled in the data base from which coarse-grained soil sites were identified. In addition, the maps provided some land use information from the VRI land cover code data (e.g. gravel pits, roads, exposed soils, airports, urban areas).

3.1.7 Low Quality Predictive Ecosystem Mapping (PEM)

This type of mapping was conducted by consultants in the forestry sector and map data were obtained that provide 1:20,000 scale coverage of all four map sheets in the study area (Figure 8). These maps are produced in automated systems from satellite data and only provide limited surficial geology information. They are of low quality as indicated by an internal quality assessment of only 40% and an overall accuracy of the entire data set of only 35% based on field plots (Forest Ecosystems Solutions Ltd., 2005). Selected information from these maps was only used when no other data sets were available. One type of information from these maps that initially appeared to be useful was slope position (e.g. Figure 8) but unfortunately these data were not readily derived from the available digital data sets and were not used.

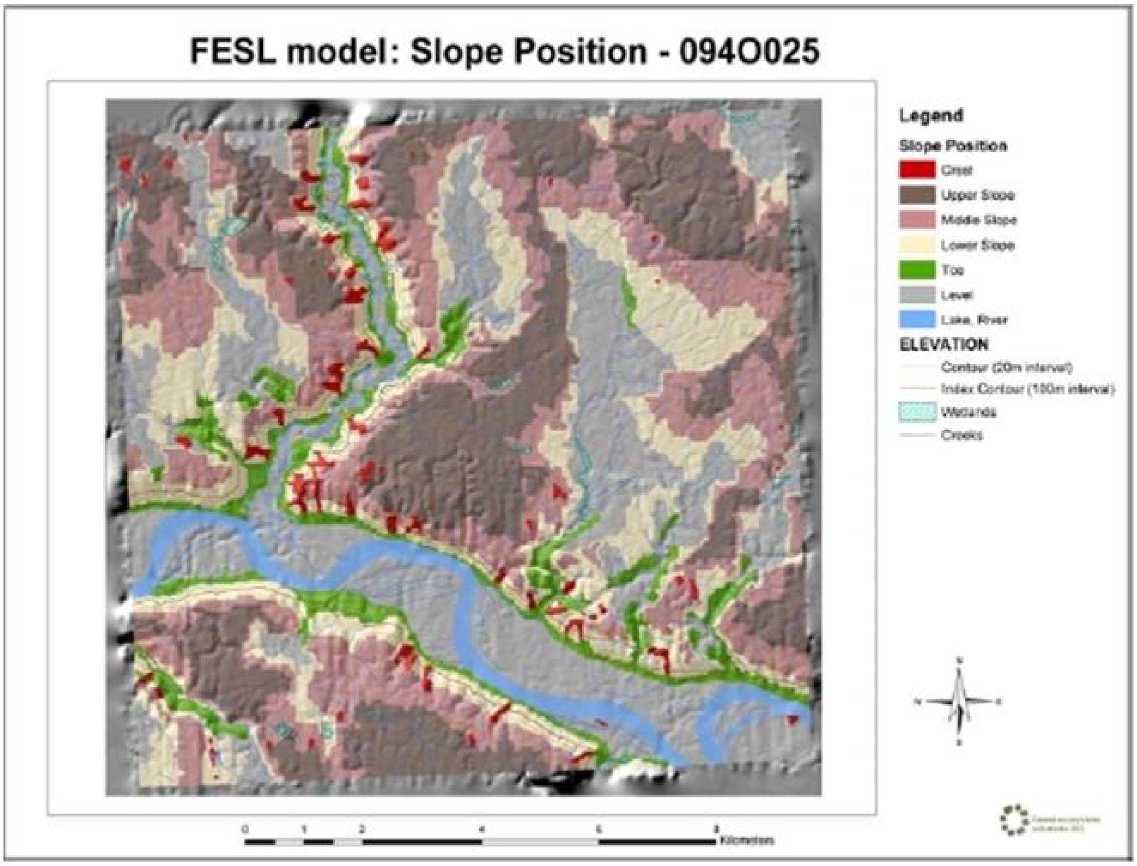

Figure 8: Slope position map for 1:20,000 scale TRIM map 94O/025 derived by modelling by Forest Ecosystems Solutions Ltd (2005) as part of a predictive ecosystem mapping project covering much of the study area.

3.2 Surficial Geology Map Data Synthesis and Interpretation

The surficial geology information from the above map data sources was analyzed and compiled and into a single composite surficial geology data set. Map legends were interpreted and combined to form a unique common legend. This required a significant amount of data analysis and interpretation because of the wide variety of map types (surficial geology, terrain, soils, slope stability, VRI, TE and PEM), various map qualities (low to high), wide variety of map scales (1;20,000 to 1:100,000) and many (>20) different map authors.

Many significant data quality and map boundary issues were resolved by expert interpretation and, in some cases, re-interpretation. One issue that always arises in map compilations of this type are boundary conflicts that occur as a result of slightly different locations or designations of mapped polygons across map boundaries. This results mainly from the use of different map types, scales and qualities. Wherever possible, original map unit boundaries and designations were retained but many significant boundary issues were resolved, usually by reinterpretation of what was considered to be the lower quality data set. In the case of boundary issues due to scale changes across the boundary, it was sometimes necessary to generalize the more detailed data but generally these types of boundary issues are small and could be ignored.

Some new map polygon definition and interpretation was required in areas where only low-quality data were available. In these areas, the definition of alluvial and glaciofluvial polygons was derived from soil texture data as well as vegetation and ecosystem data. These data were combined with topographic data (digital elevation model data) in order to map inferred surficial geology polygons. Wherever possible, adjoining high-quality map data were used as a guide to aid in interpretation of map units in areas with low quality data.

All mapped geology units were compiled and synthesized into a GIS map data base. All original data were retained in the root files (>35 Gigabytes of data) and, of course, they are available in full detail in the published and source maps. The study area comprises 5,121,701 hectares and includes: 3332 forestry cut blocks covering 102,576 ha, a total of 159,858 ha of parks, 10,390 ha of municipalities and 9,930 ha of First Nation Reserves. The area contains a total of approximately 10,445 km of roads, 90,780 km of cut lines and 11,123 km of pipelines, 10,080 well sites (gas 6676; oil 404) and 3,526 oil and gas facilities locations.

3.3 Other Data Compilation and Interpretation

Other types of compiled information include bedrock geology, hydrogeology, geophysical, topographic and land use data. Numerous Quaternary stratigraphic studies, land and water use studies and other relevant reports and papers also have been compiled (see reference list). Details and data sources for all acquired information is included in the appendices. Specific data sets include:

- bedrock geology maps of the entire study area (Figure 9)
- GIS data for all oil and gas wells in the study area (Figure 10)
- all water wells available in the BC WELLS database (Figure 10)
- additional water wells acquired from Anderson Drilling not in the WELLS database (Figure 10)
- topographic maps and digital elevation model data of the entire study area
- public subsurface geophysical maps for 94I/15 (Fugro Airborne Surveys, 2003a, 2003b, 2004a-e)
- petroleum land use information including data on road locations, pipelines, seismic lines, oil and gas plants, sump locations, water use permits, etc.
- other land use activities including logging activities, agriculture, aggregate operations, roads, rail roads, power lines, etc.

3.4 Bedrock Geology

The bedrock geology of the study region was compiled from the BCGS data base (Figure 9). Most of the original bedrock geology mapping in the study region was completed by the GSC at a scale of 1:250,000. Original maps have been compiled by both organizations into modern digital data sets incorporating the most recent stratigraphic terminology (Massey et al., 2013; Cui et al., 2017).

Most of the study area is underlain by fine-grained sedimentary rocks of the Cretaceous Fort St. John Group (KF) including the Sulley (KFSU) and Buckinghorse (KFBS) marine shales, mudstones, siltstones and minor sandstones (Figure 9). These are overlain by coarse-grained clastics of the Upper Cretaceous Dunvegan Formation (uKD) mainly including conglomerates, sandstones and minor carbonaceous shales. The Dunvegan Formation comprises a significant upland area known as the Kotcho Lake Upland covering large parts of NTS map sheets 94I, O and P (Figure 9). In the western part of the study area (especially on NTS map sheet 94I), where there is more topography and better exposure of rock, the Fort St. John Group (KF) is more finely subdivided on the geology maps into the shale-dominated Buckinghorse (KFBS) and Sulley (KFSU) formations and intervening Sikanni Formation (KFSi). In the foothills in the southwest corner of the study area, the bedrock geology is dominated by older rocks, notably including the clastic Triassic Toad (TrTd) and Liard (TrL) formations, Upper Devonian shales of the Besa River Formation (uDB) and Mississippian Prophet River Formation limestones (Appendix B).

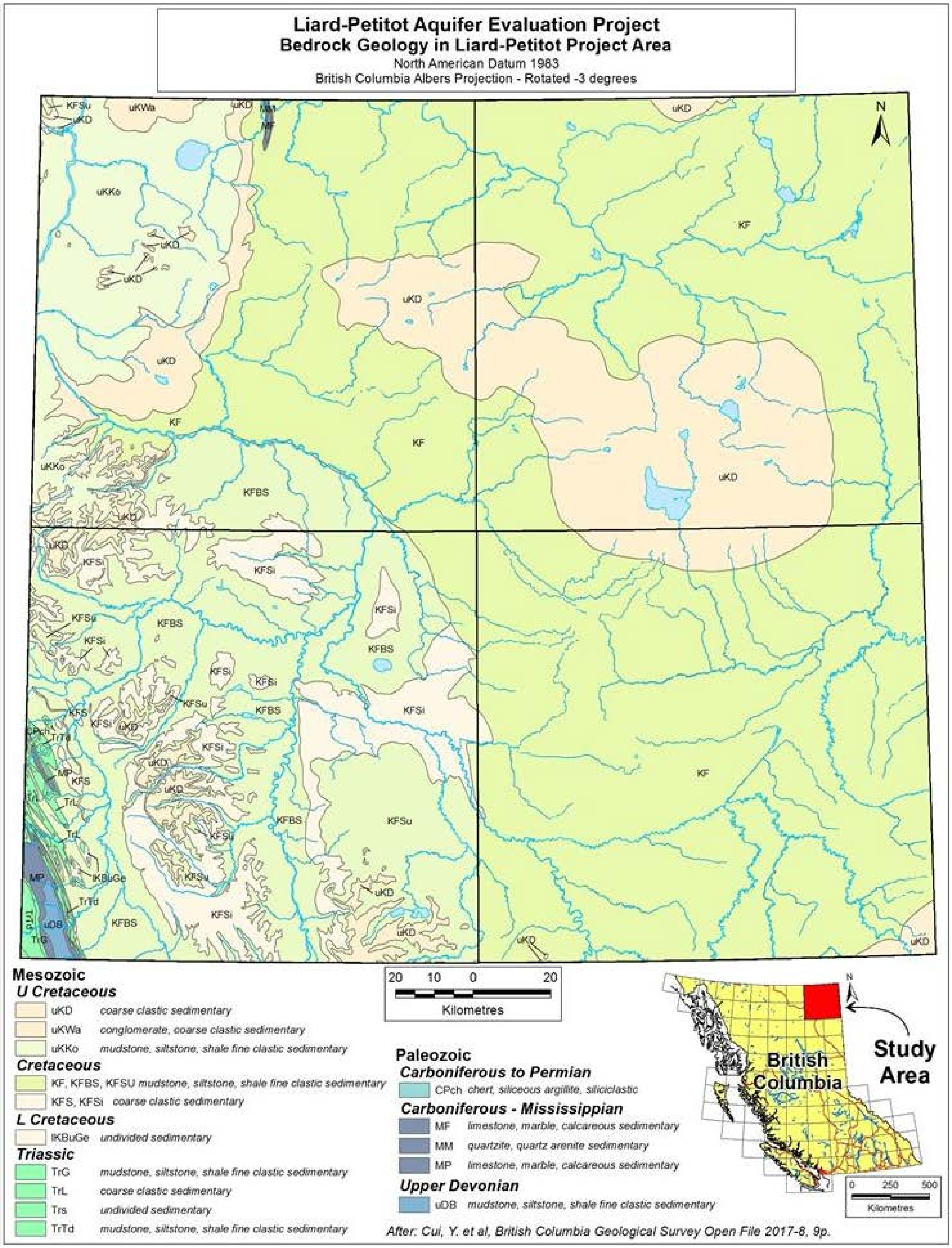

Figure 9: Bedrock geology map of the study area.

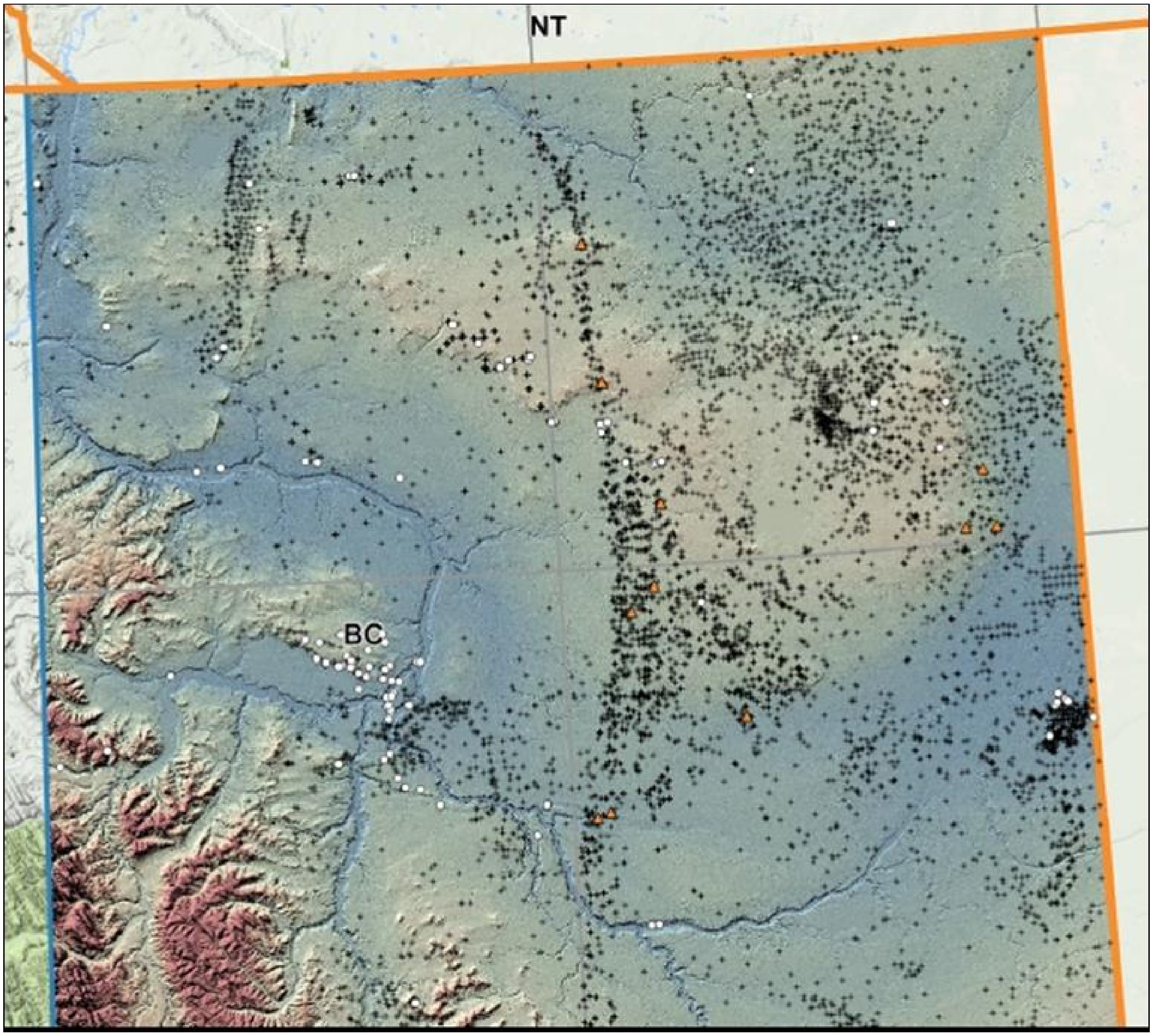

Figure 10: Compilation map of subsurface data sets including all oil and gas wells (black crosses), water wells in the BC WELLS database (white circles), new water well data acquired (orange triangles).

3.4.1 Bedrock Aquifer Potential

Most bedrock units in the study area are dominated by low permeability shales with little aquifer potential. Most notably these include the Cretaceous Sulley (KFSU) and Buckinghorse formations (KFBS) within the Fort St. John Group (KF), and the Upper Cretaceous Kotaneelee Formation (uKKo), all shown in various shades of green on Figure 9. These units are all dominated by fine-grained clastic rocks: marine shales, mudstones and siltstones. They locally include minor sandstone, coal and conglomerate units with some aquifer potential but only four aquifers have been identified in the Fort St John Group in the BC aquifer data base including three in the Peace River region and one in the study area just north of Fort Nelson (aquifer number 1034 described below in Section 5.4). The latter is described as a low productivity aquifer averaging only 4.2 USGPM (Kohut, 2013). Likewise, the aquifers in the Fort St. John Group in the Peace River region are low productivity aquifers except one small (2.3 km^2) moderately productive aquifer in the mountains south of Tumbler Ridge. It is important to note that the Fort St. John Group includes two formations dominated by sandstone (Sikanni and Scatter formations, see below) and numerous thin unmapped sandstone beds and fractured zones that locally are potential aquifers. Riddell (2012) also noted that although much of the Fort St. John Group and Kotaneelee Formation generally behave as regional aquitards, they locally contain fractured shale and coarse clastic intervals that may host aquifers.

Formations with low to moderate aquifer potential in the study area mainly include coarse clastic sedimentary rocks of the Upper Cretaceous Dunvegan (uKD) and Wapiti (uKWa) formations. These formations are composed of conglomerate, fine to coarse grained sandstone, carbonaceous shale and coal. They are the most important prospective bedrock units for freshwater aquifers in northeast BC (Riddell, 2012). In addition, sandstones within the Sikanni (KFSi) and Scatter (KFS) formations, both part of the Fort St. John Group, have some aquifer potential. All these formations are shown in various shades of pink on Figure 9. In the BC aquifer data base, nine aquifers have been identified within the Dunvegan Formation and three within the Kaskapau and Dunvegan formations. All occur in the Peace River region and are classified as either low or moderate productivity. Dunvegan sandstones and conglomerates may offer good water source potential in the north-central part of the Liard Basin where the formation is shallow, thick and very coarse-grained but Scatter Formation sandstones there have very limited aquifer potential (Petrel Robertson Consulting Ltd., 2013).

In the deformed mountain belt in the southwestern most corner of the study area (Figure 9), mapped bedrock units with aquifer potential include: sandstone, siltstone and minor limestone of the Triassic Liard Formation (TrL); limestones and calcareous sedimentary rocks of the Mississippian Flett (MF) and Prophet (MP) formations; and Mississippian sandstones of the Mattson Formation (MM). In the northern part of the study area in the northern Liard Basin, Mattson Formation sandstones are described as modestly saline, porous, wet and tens of metres thick (Petrel Robertson Consulting Ltd., 2013). The formation is shallow in the Bovie Fault Zone where the water may be less saline and a net porous Mattson sandstone isopach map suggests enormous water reservoir potential there (Petrel Robertson Consulting Ltd., 2010).

4. AQUIFER IDENTIFICATION

Aquifers were identified from the compiled and interpreted surficial geology map data. All geological units with aquifer potential were identified and mapped (Figure 11). A total of 59,992 aquifer polygons were originally identified. After interpretation and merging of adjoining polygons, a total of 6418 aquifers were mapped comprising almost three hundred thousand hectares (292,178 ha). There are currently (as of March, 2018) 1130 aquifers mapped in BC using the provincial aquifer classification system. The median size of aquifers identified in this study is 0.46 km^2 whereas the median size of Quaternary aquifers in the BC database is 13.5 km^2 (median of 5.4 km^2). The main reason for this difference is the detailed scale of mapping used in this study (1:20,000 to 1:50,000) whereas Kreye et al. (1994) report that aquifers in the provincial system are delineated mainly at a scale of 1:50,000. A large proportion of the potential aquifer polygons identified in this study (>50%) were mapped at scale of 1:20,000 with an average polygon size of only 0.17 km^2. Many of these polygons could be generalized into larger map units (see recommendations).

Aquifer potential assessments were based on data provided by the original map author unit descriptions as well as the regional experience of the senior author of this report. Two broad categories of surficial aquifers were identified and mapped: alluvial aquifers and upland (mainly glaciofluvial) aquifers. Alluvial aquifers cover an average area of 99 ha whereas upland aquifers average 45 ha in size.

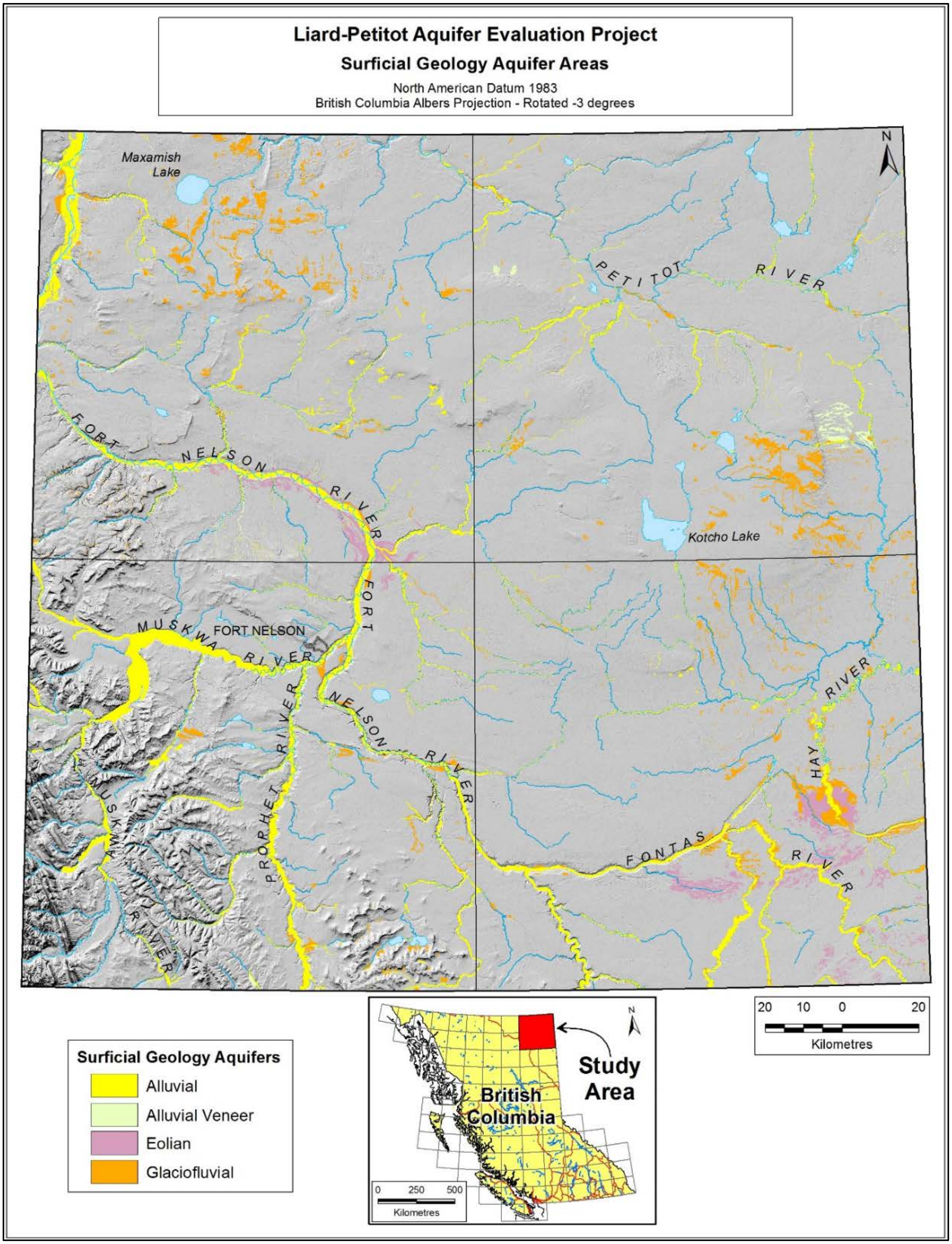

Figure 11. Aquifers in the study area mapped from surficial geology data.

4.1 Alluvial Aquifers

Alluvial aquifers are mainly Holocene in age and are associated with modern rivers and streams (channels, floodplains, terraces) and selected glacial meltwater channels. The aquifers were mapped on surficial geology and terrain maps mainly as alluvial floodplain (Ap), alluvial terrace (At) deposits and in a few cases as alluvial fans (Af). They were relatively easy to map in areas with lower quality (e.g. PEM) data by using a combination of vegetation/ecosystem maps, soil texture data and topographic data (e.g. see Figure 8).

Alluvial aquifer deposits are dominated by sands and gravels, up to tens of metres thick, and often are capped by silts and fine sands. The aquifer sediments generally thin towards the valley sides. They commonly are overlain by organic deposits that have accumulated on poorly drained overbank sediments, within floodplain lakes (e.g. oxbow lakes) or in other low-lying areas such as between scroll bars or within abandoned channels. Although commonly considered to be unconfined, these aquifers can be partially confined in some locations by relatively impermeable overbank silts and clays that are up to several metres thick, especially in large river valleys such as the Fort Nelson River valley.

The largest alluvial aquifer systems mapped in the region are associated with the major rivers, in particular, the Muskwa, Fort Nelson, Liard and Prophet rivers (Figure 11). Interestingly, other major rivers such as the Petitot, Sikanni Chief, Hay, Fontas and Kotcho rivers, do not support as large alluvial aquifers. Instead, these river valleys were largely cut by glacial meltwaters and they are characterized more commonly by typically large but isolated glaciofluvial terraces, kames and some eskers. Although alluvial aquifers certainly are present in these river valleys, glaciofluvial aquifers are more dominant. The rivers themselves are often small or misfit compared to the size of the valleys they occupy.

4.2 Upland Aquifers

Upland aquifers are mainly Late Pleistocene in age and typically include a wide variety of glaciofluvial deposits as well as coarse-grained beach and eolian deposits (e.g. Figure 11 and Figure 12). They are described as upland aquifers because they mainly occur in areas elevated above the main river and stream valleys. These aquifers include coarse-grained deposits mapped on surficial geology maps as glaciofluvial outwash plains (GFp), terraces (FGt), raised deltas (FGd), eskers (FGr) and kames (FGh). In addition, they include areas of thick sandy beach (sGL) and sand dune (sE) deposits.

These aquifers tend to occur as relatively subdued topographic features, generally of limited lateral extent. They often can be readily recognized on air photo stereo pairs and are well documented on surficial geology and terrain maps. However, they were difficult to map in areas with low quality data and required a dependence on soil texture data, where available, with some limited guidance provided by vegetation/ecosystem maps and topographic data. These included sites with gently sloping, deep, coarse-textured soils and a xeric to sub-xeric soil moisture regime based on PEM data (Forest Ecosystems Solutions Ltd., 2005). Most upland aquifers are isolated at surface but they may be hydraulically connected in the subsurface. They are typically relatively small features compared to alluvial aquifers with the main exception of outwash plains and terraces that can be quite large.

The largest glaciofluvial aquifer complex in the region is a large glaciofluvial delta on the Hay River that was first recognized and described by Levson et al. (2004) who found the delta to likely be the largest raised delta in the province, larger in size than the modern Fraser River delta. The delta was later mapped by Smith (2009) at a scale of 1:100,000 (Figure 12). The Hay River glaciofluvial delta is partially covered by eolian sandy veneers and sand dunes and surrounded by poorly drained glacial lake sediments (Figure 12). The delta was fed by the Hay River meltwater channel which in turn fed into the Ekwan, Kahntah and Fontas meltwater channels (Smith, 2009). All of these river systems are misfit streams that occupy relatively large meltwater channel valleys. The Hay River glaciofluvial delta supplies a large source of surficial sands in this region which occur as sandy veneers and thick sand dune deposits on the delta and in the surrounding areas.

The second largest source of upland aquifers are glaciofluvial terraces which typically occur as large features along the margins of, and in some cases within, most major meltwater channels in the region. A good example is shown in the lower right corner of Figure 12 where large glaciofluvial terraces flank the Hay River meltwater channel, especially on the south side of the channel. Other large glaciofluvial terrace aquifers occur periodically along the Ekwan, Fontas, upper and middle Fort Nelson, Klua, Middle Prophet, Sahdoanah and Petitot meltwater channel valleys (Figure 11 and Figure 13). In addition to these generally valley parallel glaciofluvial terraces, a number of large glaciofluvial terraces and outwash plains occur transverse to these major systems. These occur either where smaller tributary meltwater channels fed into the larger valleys or where earlier, topographically higher meltwater channels and outwash plains were cut-off by younger channels incising deeper valleys as regional base levels dropped. An excellent example of the latter is provided by a series of outwash plains and meltwater channels extending northwestward from the Fort Nelson River valley to the lower Prophet and Muskwa river valleys (Trommelen and Levson, 2008).

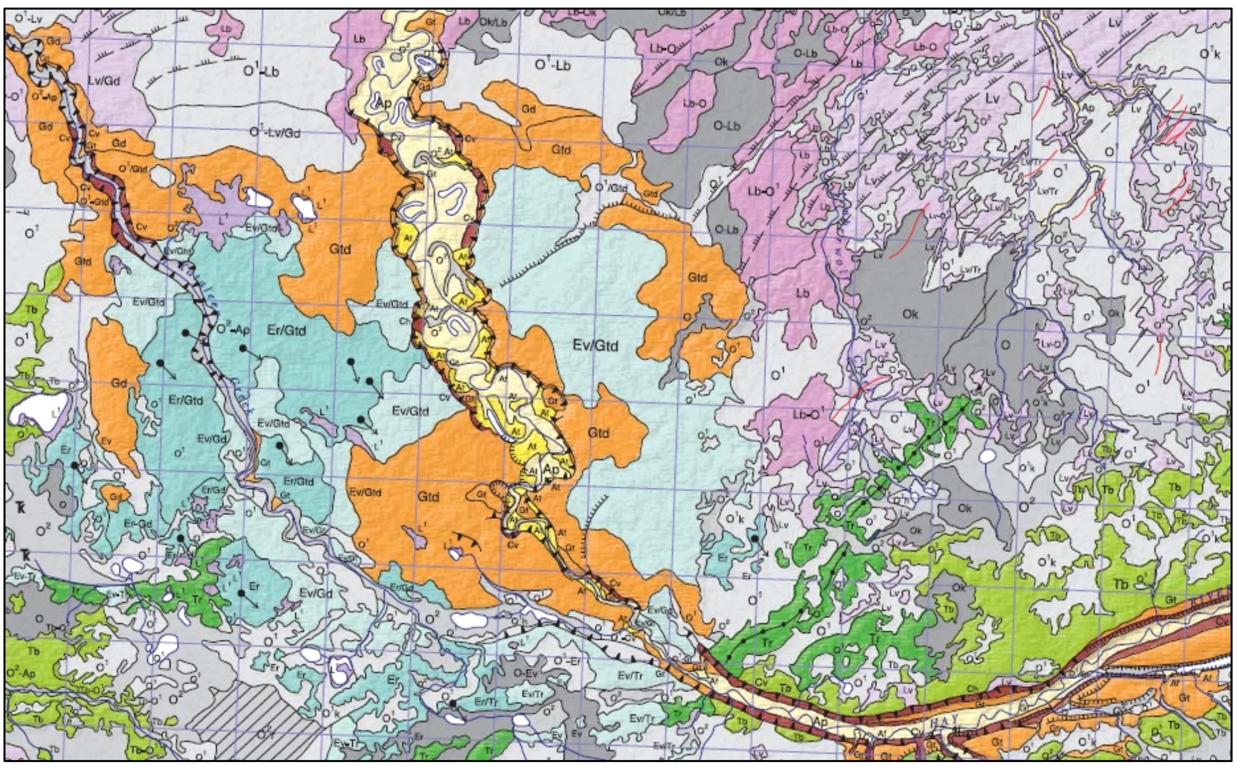

Figure 12. Hay River glaciofluvial delta (Gtd) partially covered by eolian sandy veneers (Ev/Gtd) and sand dunes (Er/Gtd) and surrounded by poorly drained glacial lake sediments (Lb, Lv, O-Lb, etc.). The delta was fed by the Hay River meltwater channel (lower right) now occupied by the misfit Hay River (Geology by Smith, 2009). Each map grid is four square kilometres.

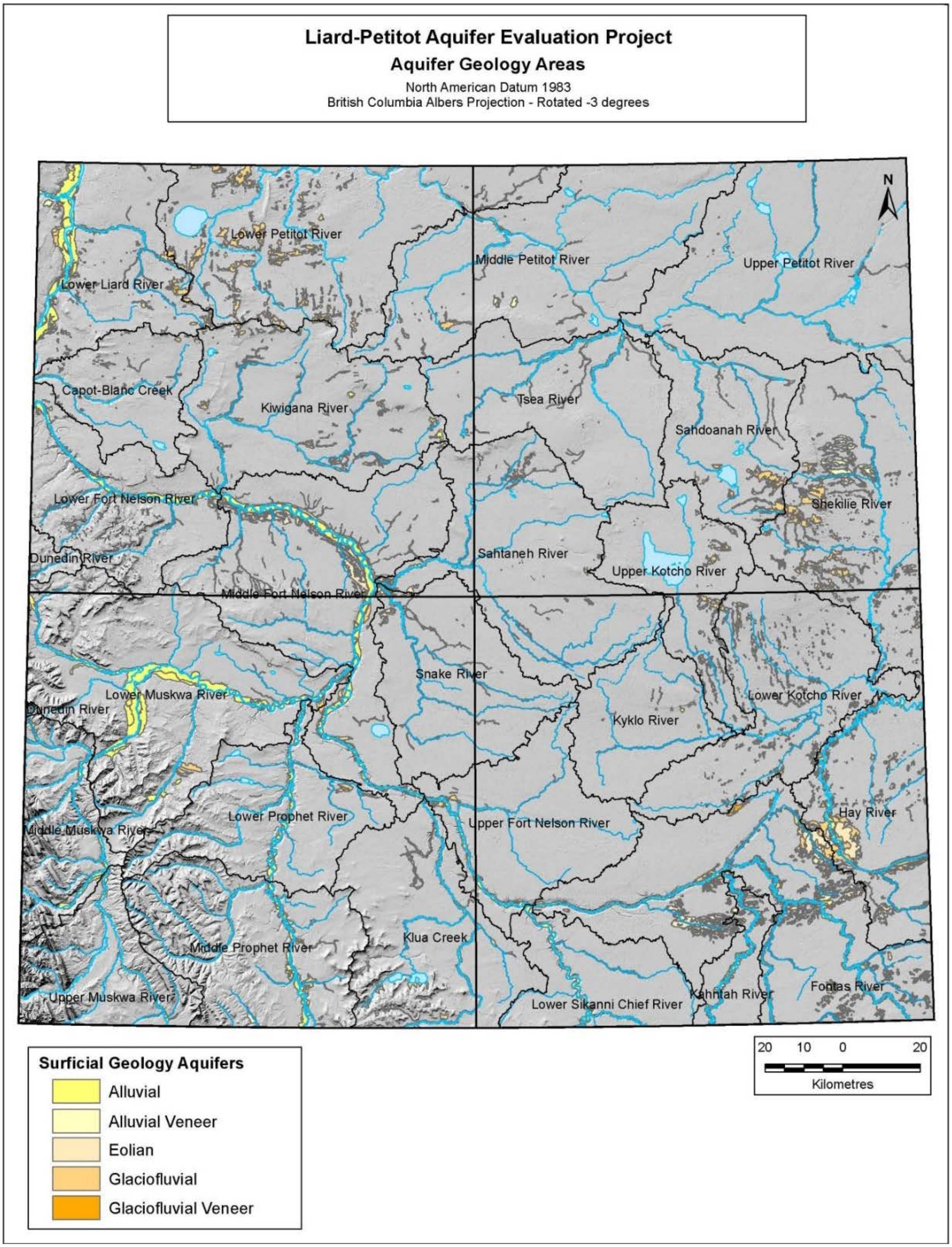

Figure 13. Mapped aquifers in the study area shown with drainage basin outlines.

The largest areas of mapped sand dunes in the study area occur in a large arcuate belt extending from south of the Hay River glaciofluvial delta southwestward across the Fontas and Kahntah river drainages (Figure 11 and Figure 13). Although upland aquifers are generally not large potential groundwater sources, in many areas they are likely important recharge zones for alluvial aquifers in the basin as well as some subsurface aquifers. Large parts of the study area are underlain by relatively impermeable glaciolacustrine sediments and clay-rich tills and as a result lakes, bogs and swamps are widespread in the region. The main opportunity for surface water to recharge the groundwater system is via coarse-grained surface deposits, largely defined by these upland aquifers. Certainly, not all coarse-grained surface deposits are hydraulically connected to the regional groundwater but the general lack of shallow water tables in these deposits suggests that in many areas they are acting as effective groundwater recharge zones.

Two relatively large clusters of upland aquifers occur in the Maxhamish Lake region and northeast of Kotcho Lake on NTS 94 O and P, respectively (Figure 11). These are areas of deep coarse-textured soils mapped on PEM data (Forest Ecosystems Solutions Ltd., 2005) and due to the poor quality of the original data there is low confidence in understanding these potential aquifer systems. Since the genesis of these features is unknown, they are included in the 'glaciofluvial' category as that is their most likely geological origin. The cluster northeast of Kotcho Lake is adjacent to a large number of upland aquifer polygons mapped by Bednarski (2008c) on NTS 94O/7 as alluvial veneers and described as sheets of slope-wash. They occur on gentle slopes on the east side of the Kotcho Upland and, although it is possible that some of the mapped PEM polygons have a similar origin, this is unlikely as most of the PEM polygons occur on the Kotcho Upland not on the slopes adjacent to it. The origin of the large cluster of coarse-grained soils in the Maxhamish Lake area is unknown but likely many of these features may be elevated till deposits rather than glaciofluvial deposits.

4.3 Aquifer Distribution within Drainage Basins

Mapped aquifers in the study area are shown by drainage basin in Figure 13, using basin boundaries defined by the BC Oil and Gas Commission. A total of 28 basins of approximately equal size occur within the study area (Figure 13). The most extensive aquifers occur in the Lower Muskwa River, Middle Fort Nelson River, Lower Liard River, Hay River and Fontas River drainage basins. As described above, coarse-grained soils mapped on PEM data are extensive near Kotcho and Maxhamish lakes in the Sahdoanah River, Shekilie River and Lower Petitot River drainage basins. However, the PEM data is of poor quality and, based on experience in the region, it is inferred that many of these coarse-grained soils are likely till and not glaciofluvial in origin. Nevertheless they may comprise significant recharge zones and, as a consequence, these areas are included in the aquifer map.

The areal extent of all aquifers including the extent of alluvial aquifers, upland aquifers and non-aquifer areas was determined in the GIS for each of the 28 drainage basins. Since the original surficial mapping in the region is of high quality and was compiled at detailed scales, aquifer area calculations are likely well within acceptable limits of error, especially considering that the final analysis is conducted at the drainage basin level. In fact, the data quality is sufficiently high that individual aquifers or groups of aquifers could be analyzed separately in future work, although such an analysis of all aquifers in the region would be extremely time consuming.

A statistical summary of drainage basin and aquifer characteristics is provided in Table 1. For each drainage basin, the basin area (in km^2) and aquifer area (orange bars) and the percent of aquifers in each basin (green bars) are shown on the left side of the table. The eight basins with the greatest total area of surficial aquifers include the Fontas, Lower Muskwa, Middle Fort Nelson, Lower Liard, Hay, Shekilie, Lower Petitot and Kiwigana river basins supporting 410, 276, 265, 205, 200, 194, 182 and 101 km^2 of aquifers, respectively. All other basins support less than 100 km^2 of surficial aquifers. The basins with the highest proportion of aquifer area, as a percent of drainage basin area, are the Kahntah, Fontas, Hay and Lower Liard river basins supporting 17, 13, 13 and 12 percent, respectively. In all remaining basins the surficial aquifer areas cover less than 10% of the basin. In total, surficial aquifers cover only 5.7% of the entire study area. This strongly contrasts with previous assessments that have assumed 100% aquifer coverage in their analysis.

A comparison of alluvial versus upland aquifers is shown on the right side of Table 1. In total, alluvial aquifers comprise 1676 km^2 while upland aquifers comprise 1247 km^2 (about 57% and 43%, respectively, of all aquifers in the study area). In almost every case, the proportion of alluvial to upland aquifers is much higher (averaging 7.7 times higher), highlighting the relative importance of alluvial aquifers. In addition, the area of upland aquifers is likely exaggerated as it locally includes coarse-grained soils, some of which are likely coarse tills, as well as some sandy eolian and beach soils that are likely too thin to host significant aquifers. Coarse-grained soils are identified in the database as “GF?” to distinguish them from glaciofluvial units identified on surficial geology maps.

5. AQUIFER CHARACTERIZATION

Aquifers in British Columbia generally fall into two prime groups and six types (Wei et al. 2009). Primarily, all aquifers are either in unconsolidated sand and gravel or in bedrock. In the interior of the province, unconsolidated sand and gravel aquifers include:

1. Unconfined fluvial/alluvial aquifers where the potential of hydraulic connectivity with a river exists [Note: In detailed mapping, type 1 aquifers would be sub-divided by stream order and include glaciofluvial terraces with potential hydraulic connectivity to a river].
2. Unconfined deltaic aquifers
3. Unconfined alluvial fan or colluvial aquifers
4. Aquifers of glacial or pre-glacial origin:
    a. Unconfined glaciofluvial outwash or ice-contact aquifers
    b. Confined aquifers of glacial or pre-glacial origin

Bedrock Aquifers include:

5. Sedimentary rock aquifers
    a. Fractured sedimentary rock aquifers; or
    b. Karstic aquifers
6. Crystalline rock aquifers
    a. Flat-lying volcanic flow aquifers;
    b. Fractured igneous intrusive, metamorphic, fractured volcanic, or metavolcanic aquifers

Aquifers types identified in the Liard-Petitot area include types: 1, 4a, 4b and 5a. Types 2 and 3 aquifers do exist in the area but are not found in well logs so they are discussed here together with aquifer type 1.

Table 1: Summary of drainage basin and surficial aquifer characteristics for the Liard-Petitot region, northeast B.C.

		Surficial aquifers		Alluvial vs Upland surficial aquifers		
Basin name	**Area of basin (km2)**	**Area of surficial aquifers in basin (km2)**	**Percent surficial aquifer by basin**	**Area of alluvial surficial aquifer in basin (km2)**	**Area of upland surficial aquifer in basin (km2)**	**Proportion of alluvial to upland aquifers #:1**
Capot-Blanc Creek	966.6	16.8	1.7%	9.6	7.2	1.3
Dunedin River	130.8	2.6	2.0%	0.9	1.7	0.5
Fontas River	3112.7	410.2	13.2%	148.3	261.9	0.6
Hay River	1529.6	200.2	13.1%	61.4	138.9	0.4
Kahntah River	440.3	73.0	16.6%	48.4	24.7	2.0
Kiwigana River	2222.2	101.5	4.6%	66.5	35.0	1.9
Klua Creek	1944.3	84.7	4.4%	58.4	26.4	2.2
Kyklo River	1113.7	14.7	1.3%	13.7	1.0	13.5
Lower Fort Nelson River	1537.3	75.2	4.9%	58.2	17.1	3.4
Lower Kotcho River	2055.2	71.3	3.5%	11.6	59.6	0.2
Lower Liard River	1695.5	204.6	12.1%	150.0	54.6	2.7
Lower Muskwa River	3191.9	276.2	8.7%	259.0	17.2	15.1
Lower Petitot River	2896.6	182.5	6.3%	9.9	172.7	0.1
Lower Prophet River	1573.6	81.5	5.2%	72.8	8.7	8.3
Lower Sikanni Chief River	1064.5	50.9	4.8%	50.3	0.6	85.2
Middle Fort Nelson River	3054.8	265.4	8.7%	164.0	101.4	1.6
Middle Muskwa River	995.6	54.7	5.5%	54.7	0.0	no upland aquifers
Middle Petitot River	2882.7	48.5	1.7%	31.7	16.9	1.9
Middle Prophet River	2010.0	96.6	4.8%	86.4	10.3	8.4
Sahdoanah River	1390.0	76.2	5.5%	25.8	50.4	0.5
Sahtaneh River	2370.4	72.0	3.0%	42.3	29.8	1.4
Shekilie River	2339.1	194.0	8.3%	62.3	131.7	0.5
Snake River	1701.1	59.6	3.5%	37.3	22.3	1.7
Tsea River	1991.2	55.3	2.8%	53.0	2.3	23.4
Upper Fort Nelson River	1636.9	51.5	3.1%	42.1	9.3	4.5
Upper Kotcho River	1201.2	38.1	3.2%	4.7	33.3	0.1
Upper Muskwa River	1156.2	23.2	2.0%	23.2	0.0	no upland aquifers
Upper Petitot River	3012.2	41.3	1.4%	29.5	11.8	2.5
All basins	**51216.0**	**2922.5**	**5.7%**	**1675.8**	**1246.7**	
Percent of study area		5.7%		3.3%	2.4%	

Mapped aquifers defined by surficial geology units in the area mainly include: Type 1, unconfined alluvial (fluvial) aquifers where the potential of hydraulic connectivity with a river exists; and type 4a, mainly unconfined, upland, glaciofluvial outwash or ice-contact aquifers. Table 2 shows a break-down of the percentages and areas of surficial aquifers in the region. Alluvial aquifers (type 1) cover 1675 km^2 (57.3% of all mapped aquifers and 3,2% of the study area) and upland aquifers (type 4a) cover 1247 km^2 (42.7% of mapped aquifers and 2.5% of the study area). In total, 6418 aquifers were mapped comprising almost 3 billion square metres (292,178 ha or 2,922 km^2) but only 5.7% of the total study region (5,121,701 ha or 51,217 km^2).

Note: In the land use disturbance portion of the analysis (Sections 7 to 9) reference is made to alluvial aquifers and upland aquifers. Alluvial aquifers are equivalent in classification mainly to type 1 aquifers, but also locally include types 2 and 3, and upland aquifers are mainly equivalent to type 4a aquifers.

Table 2: Surficial aquifers by type, area and percentage of both aquifer area and study area.

Surface Aquifer Type	Number of Polygons	Area (Hectares)	Area (Square Kilometres)	% of Mapped Aquifers	% of Study Area
1	1,897	167,508.55	1,675	57.3	3.3
4a	4,521	124,669.75	1,247	42.7	2.4
Aquifers	6,418	292,178.29	2,922	100.0	5.7
Study Area	-	5,121,701.02	51,217	-	-

5.1 Type 1: Unconfined Fluvial Aquifers

Generally, aquifers of this type consist of Holocene/modern alluvial (fluvial) floodplains and terraces within, or with potential to connect with, the modern river (geological map units include: A, Ab, Aj, Ap, At, Atp and Av). Unconfined deltaic (Ad) and alluvial fan (Af) deposits (type 2 and 3 aquifers, respectively) are also included here with alluvial aquifers. They are most commonly composed of sands and gravels overlain by silt, fine to coarse sand and organics, and underlain by till or glaciolacustrine clays (Trommelen and Levson, 2008). The composite surficial aquifer map of the Liard-Petitot area shows a minimum of 57.3% of all mapped surface aquifers fall into this category. Unconfined fluvial aquifers are described in detail in the Fort Nelson River valley at the Highway 77 bridge crossing (Appendix A.1); at aquifer #1041, on the Fort Nelson River, east of Muskwa (outlined on Figure 14 and described by Kohut, 2013 – Appendix A.2) and just south of Fort Nelson on the Muskwa River (well # 13659, Figure 14 and Figure 15).

One well in the unconfined fluvial aquifer on the Muskwa River (well tag number 13659) is located in the middle of the Muskwa River valley, on the active flood plain terrace (mapped as At). The well log for well tag number 13659 shows 25’ of silt over 16’ of sand and gravel over a minimum of 2’ of till. The water table is at 19’ below surface but the aquifer exists in 19’ of sand and gravel between 24’ and the till at 43’ and yields 75 Imperial gallons per minute (IGPM[1]).

[1] United States or Imperial units were not always differentiated in well log notes; if recorded, Imperial Gallons (IG) or United States liquid gallons (USG) per minute are specified. One IG is approximately equal to 1.2 USG (i.e. it is approximately 17% larger than a USG). If not recorded, yield is simply listed as gallons per minute (GPM).

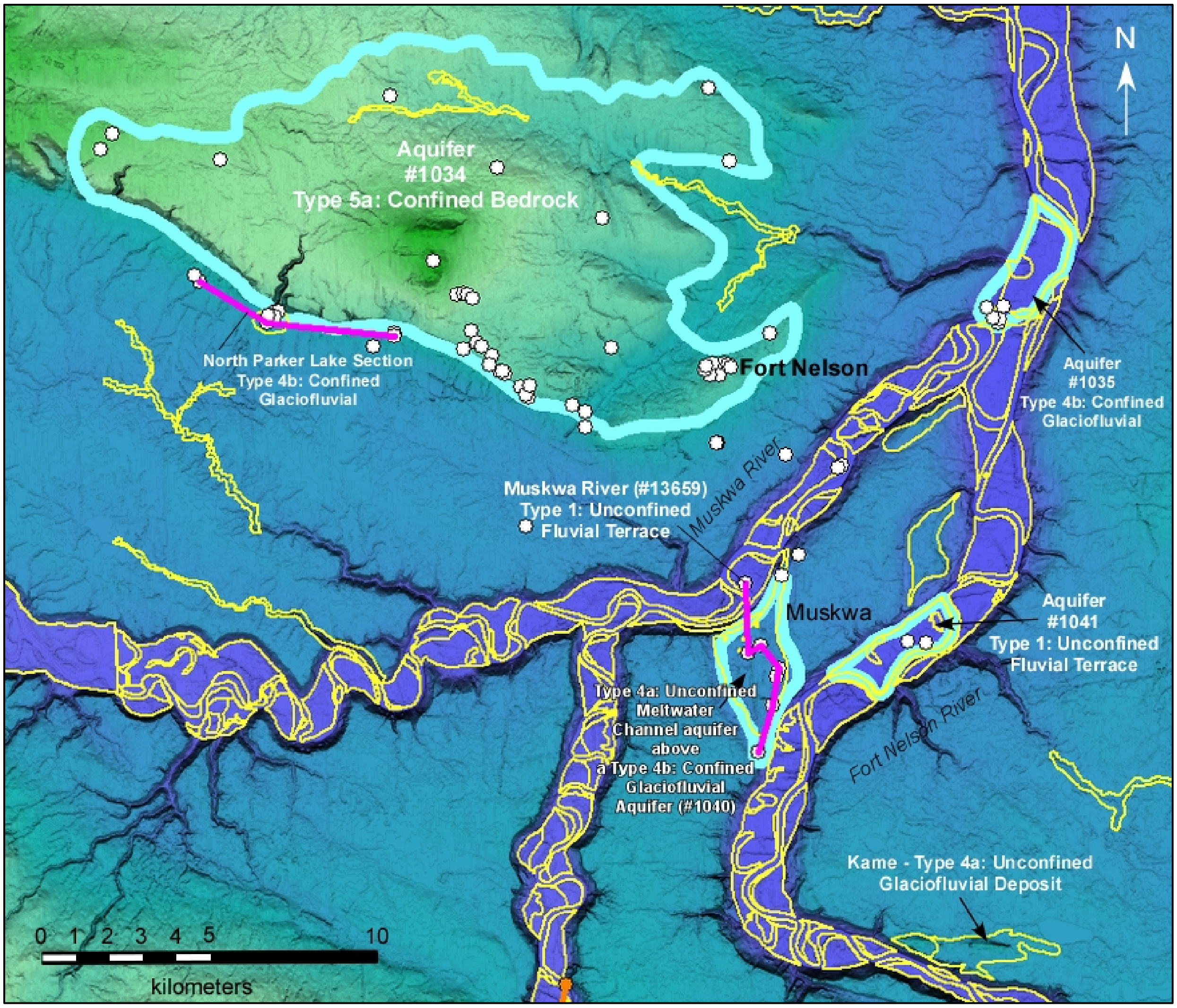

Figure 14. Fort Nelson area aquifers outlined in blue and showing mapped surficial aquifers in yellow. Magenta lines are cross section locations and white dots are water well locations.

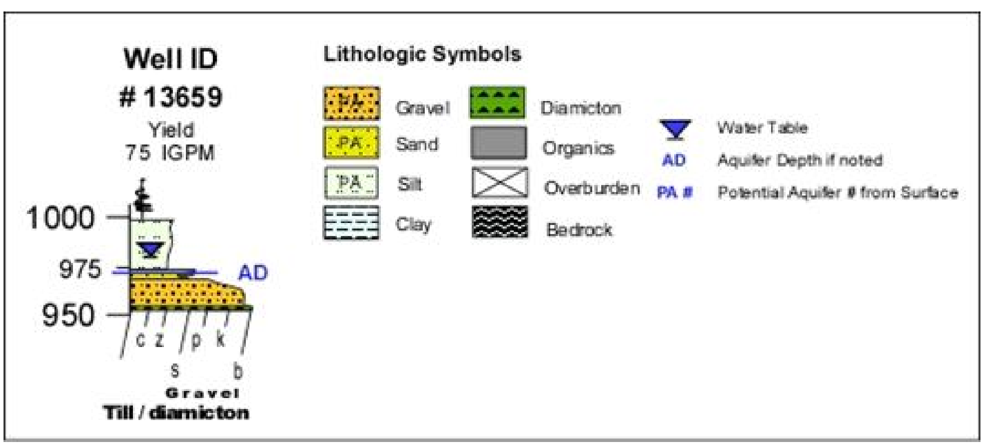

Figure 15. Example of a type 1 unconfined fluvial aquifer on the Muskwa River at the north end of the Muskwa section (see Figure 19 for location). The pattern of stratigraphy, silt over sand and gravel over till, is common in the alluvial terraces (At) of the area.

5.2 Type 4: Aquifers of Glacial or Pre-Glacial Origin

Aquifers of this type exist in two varieties in the Liard-Petitot area: type 4a, unconfined alluvial upland, glaciofluvial outwash or ice-contact aquifers; and type 4b, confined aquifers of glacial or pre-glacial origin.

5.2.1 Type 4a Aquifer - Example 1:

Unconfined to partially confined glaciofluvial outwash or ice-contact aquifers including glaciofluvial terraces, deltas, fans, eskers and kames are common in the Liard-Petitot area and comprise 42.7% of surficial aquifers and 2.5% of the study area. Geological map units in categorized as type 4a include: FG, FGa, FGb, FGf, FGh, FGir, FGj, FGt, FGu, FGv, G, Gf, Gi, Gih, Gir, Gt, Gtd, Gw, GF?, GFir, GFi, GFk, GFt, GFtb, GFtk and gFG. Also included in this category are coarse-grained glaciofluvial delta deposits (Gtd, gFGd, Gd) and eolian sands (E, Ea, Eb, Er, Ev) because these are coarse-grained sediments that commonly overlie or occur in direct association with outwash deposits. Type 4a aquifers are unconfined, elevated, sand and gravel deposits, generally found well above modern river valley levels. They are typically located near active river valleys but most commonly found in association with glaciofluvial outwash channels. A good example of this type of surficial aquifer is found at well site # 102721 (Figure 16), located approximately 230 feet above the modern Prophet River within a mapped surficial aquifer labelled as a gravelly, glaciofluvial delta. It consists of a minimum of 64 feet of fining-up sand with a water table at 32 feet below surface and yields 15 USGPM.

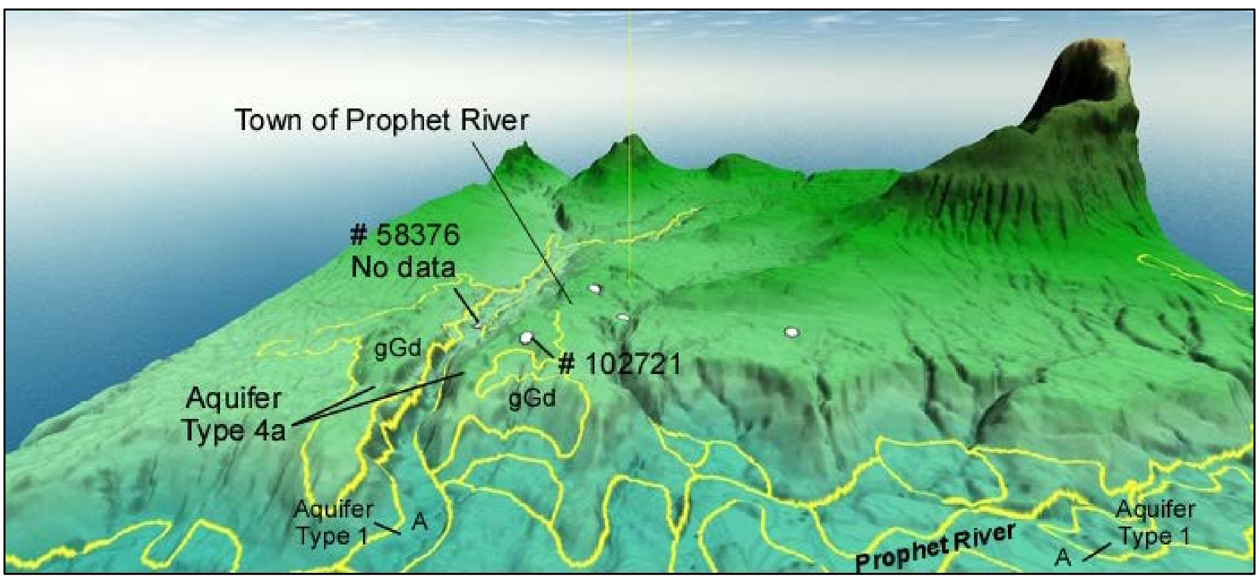

Figure 16. Example of a perched, glaciofluvial delta (type 4a aquifer) above the modern Prophet River examples of type 1 alluvial (A) aquifers in the lower valleys. View looking east over Prophet River (7x vertical exaggeration).

5.2.2 Type 4a Aquifer - Example 2:

Unconfined glaciofluvial outwash or ice-contact aquifers (Late-Wisconsinan, post-glacial deposits; Trommelen and Levson, 2008, Huntley et al. 2017) are exemplified by eskers, kames and meltwater channels (geological map units include: Gi, Gih, Gir, GFir, GFi, GFk, GFtk FGk and Gh). These aquifers are similar to those mapped and drilled at Elleh River kame, about 40 km southeast of Fort Nelson (Figure 17). The kame and associated meltwater channel at Elleh River contains wells 102574 and 102572 (Figure 18). The kame is above the modern Elleh River and about 500 feet above the nearest reach of the modern Fort Nelson River. It consists of 70 feet to more than 125 feet of sandy gravel, and yields from 10 to 25 USGPM, with a water table within 30 to 40 feet of surface. LiDAR imagery suggests that this unconfined aquifer probably extends along the meltwater-channel bottom, up-stream and to the east. Evidence from well sites on either side of the channel upstream, suggest that the aquifer may carry on up the channel but likely pinches out or goes underground at either side of the channel.

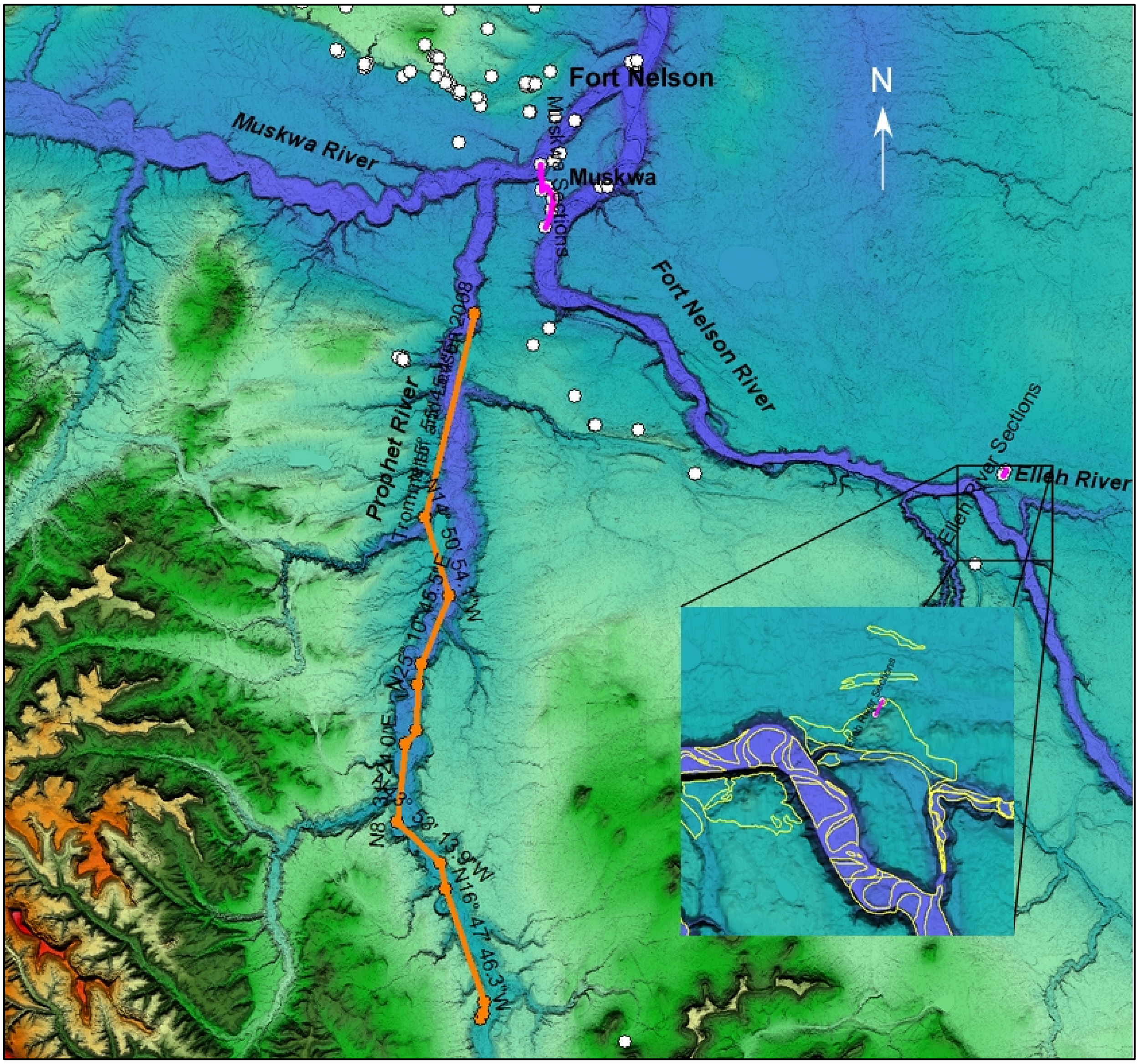

Figure 17. Location of the Elleh River kame and meltwater channel (aquifer type 4a). The magenta line shows the locations of cross-sections at Elleh River and Muskwa, the yellow lines in the inset map are of the mapped surficial aquifers and the orange line shows the location of the Prophet River cross-section (Trommelen and Levson, 2008).

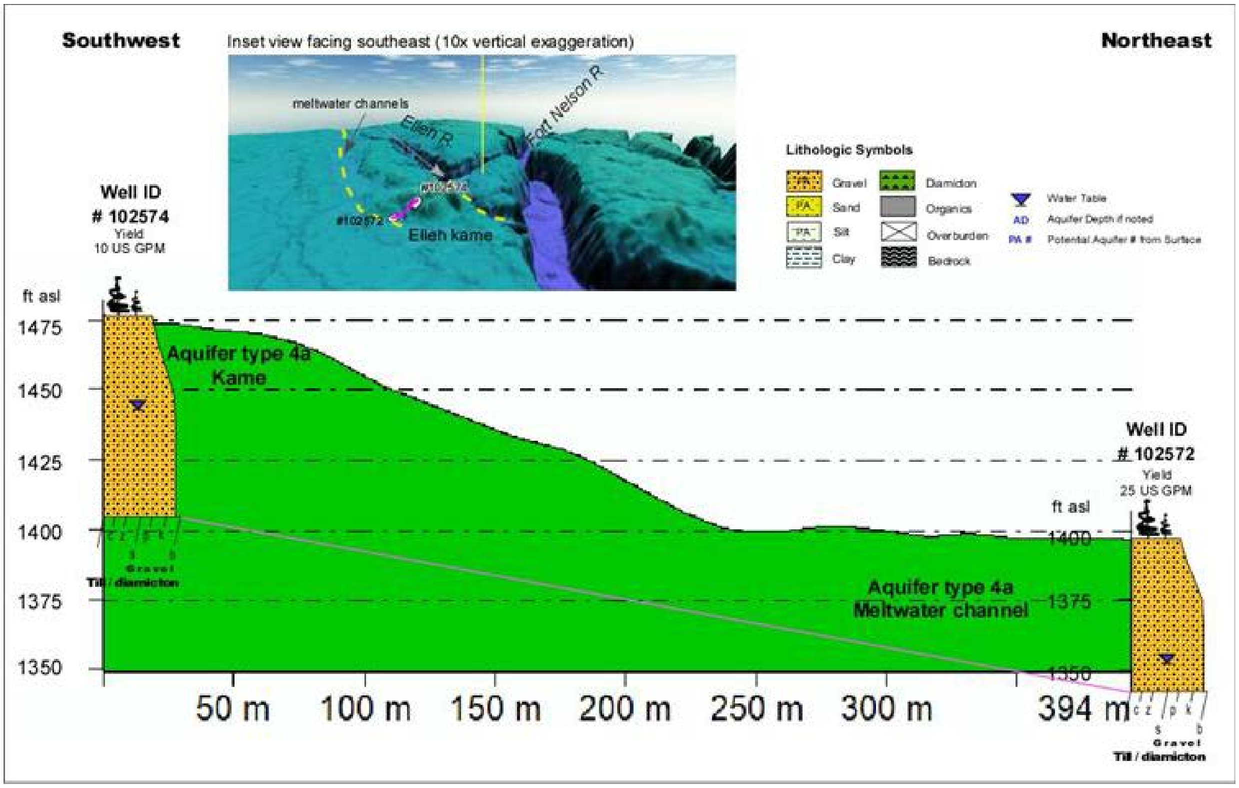

Figure 18. The Elleh River kame and meltwater channel type 4a aquifers. The well logs show more than 50 feet of gravel with a water table approximately 30 to 40 feet in depth. The green background does not represent diamicton but the slope profile as derived by Global Mapper 16™.

5.2.3 *Type 4a Aquifer - Example 3:*

Unconfined glaciofluvial outwash or meltwater channels (geological map units include: FGt, FGp, Gp, Gt, Gtd, GFt, GFtb), such as those on the upper plateau at Muskwa (Figure 14) or the unmapped channel containing well #102572 at Elleh River (Figure 18), are abandoned glacial river channels which once cut through the uplands during deglaciation and either ran dry or were captured by modern rivers. Though not completely mapped at the scale of this project, they are relatively common through the study area.

The meltwater channel identified at Muskwa (Figure 19), labelled as potential aquifer PA #1 (i.e. top of well #s 24443, 104413, 45435 and 104413), is one of a number of meltwater channels in the Muskwa area. They are characterized by relatively thick (45 feet to 50 feet), interbedded sands and gravels, which occur either directly on blue clay, up to 170 feet thick, or over lying up to 350 feet of till in the south. The aquifer at well #24443 is 45 feet thick, with a water table about 26 feet below surface and yields 94 GPM[1]. This aquifer may extend east and west but the wells to the south of well #24443 are dry. Meltwater channels are good targets for further groundwater exploration.

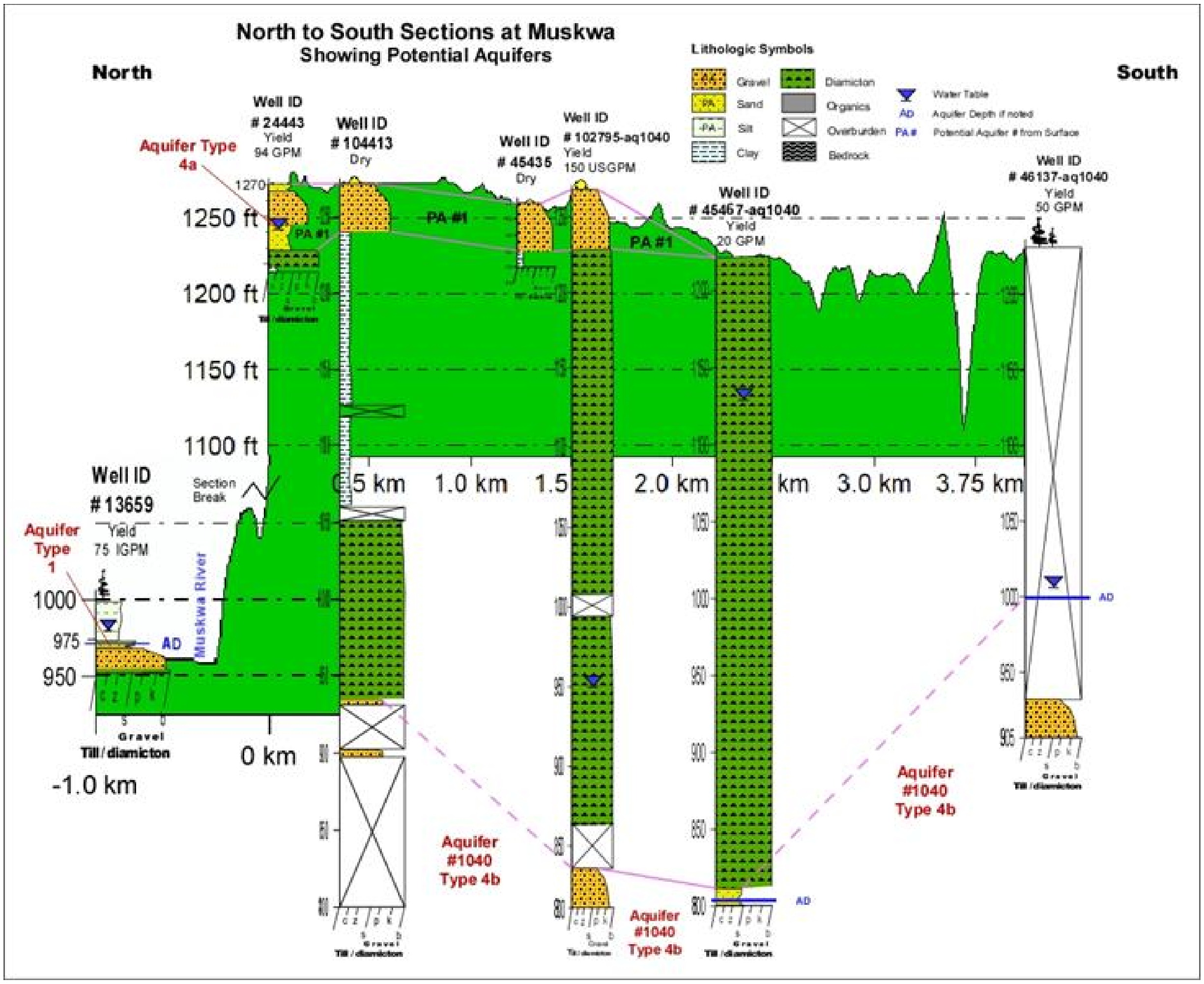

Figure 19. Muskwa cross-section showing three of the four types of aquifers in the area (type 1 at the Muskwa River, type 4a on the upper plateau and type 4b at depth.

5.3 Type 4b: Confined Aquifers of Glacial or Pre-Glacial Origin

Type 4b aquifers in the Liard-Petitot area consist primarily of pre-Late Wisconsinan fluvial and glaciofluvial (advance stage) sands and gravels and/or pre-Late Wisconsinan, montane fluvial gravels (Trommelen and Levson, 2008; Huntley et al. 2017) (Figure 20, unit's A through C). These pre-Late Wisconsinan fluvial and glaciofluvial aquifers are well described by Kohut (2013) as aquifers #1040 and #1035 (Appendix A.3 and A.4) and in the lower units of the Fort Nelson River, Highway 77 Bridge crossing (Appendix A.1). Aquifer #1040, below the meltwater channels at Muskwa (Figure 13), is also shown in cross-section in the lower well logs of well #s 104413, 102795, 45467 and 46137 (Figure 19 above) and Kohut (2013) describes it as consisting of glaciofluvial, sand and gravel beneath glaciolacustrine clays and till.

Detailed descriptions of pre-glacial sediments, as well as glacial and post-glacial sediments are described by Huntley et al. (2017) along the Fort Nelson and Petitot Rivers in map sheet 94O (Appendix A.5); and along the Prophet River valley in map sheet 94J by Trommelen and Levson (2008) (Appendix A.6). These descriptions, derived from detailed section work, include clast analysis and radiocarbon dating to determine source areas and sediment age. They are summarized in the composite stratigraphy on Figure 20 with their associated aquifer types (Wei, et al., 2009).

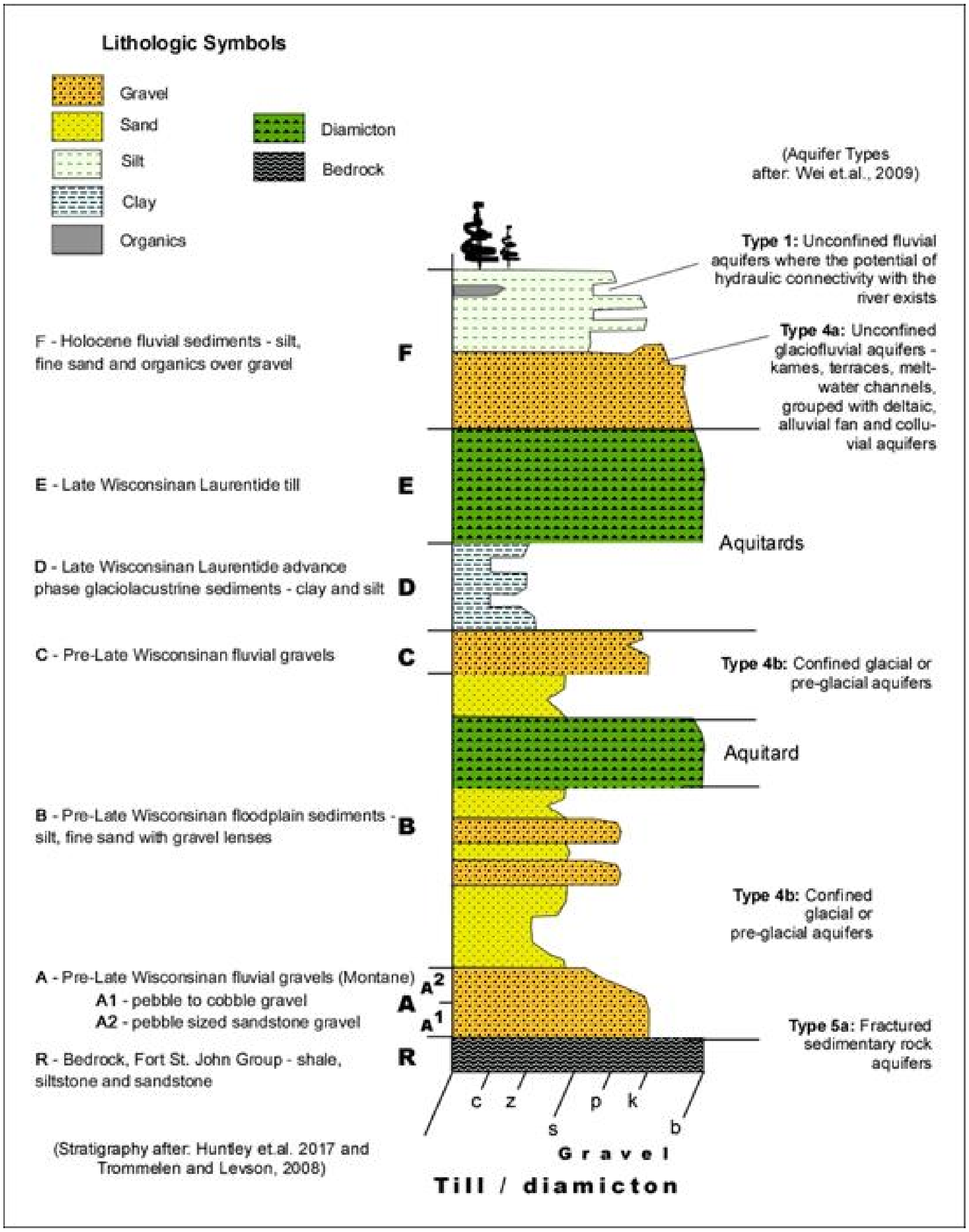

Figure 20. Composite stratigraphic section of the Liard-Petitot area showing aquifer types.

In general, type 4b, confined, pre-Late Wisconsinan fluvial and glaciofluvial aquifers in the area consist of interbedded silt, sand and lenticular gravels with lesser units of stratified diamicton, from 7 to 66 feet thick, which reside below the advance phase, glaciolacustrine clay and Late Wisconsinan till. They are generally deep aquifers, between 330 and 445 feet below surface (at 800 and 1000 feet above sea level (asl)), and the water table is commonly logged at over 300 feet above the producing aquifer (e.g. Figure 19, well #45467), with water yield ranges from 20 to 150 GPM.

Pre-Late Wisconsinan fluvial (Montane) and floodplain sediments (interbedded silt to cobble gravel sediments) such as noted by Trommelen and Levson (2008) and Huntley et al. (2017), may be discernable in the western project area but are not distinguishable in the well core data and thus could not be differentiated in this study.

A type 4b aquifer, north of Parker Lake (about 10 km west of Fort Nelson along highway 97), produced from 2 to 100 USGPM from a stratified till. If the quality of the water from bedrock aquifer #1034 is less than desirable for drinking, it may be worthwhile exploring the type 4b aquifers north of Parker Lake or the type 1, 4a and 4b aquifers at Muskwa. Similar type 4b aquifers were identified in the Western Plateau of NTS map sheet 94P and have potential to exist in other upland areas.

5.4 Aquifer Type 5a: Aquifers in Fractured Sedimentary Bedrock

Type 5a aquifers are most common in the upland areas of the study area and are well described by Kohut (2013) at aquifer #1034, located in the highland area north of Fort Nelson (Figure 14 and Appendix A.5). Aquifer #1034 is a confined aquifer between 75 to 470 feet below surface in fractured sedimentary bedrock. Low permeability clays and tills with minor sands and gravels from 8 to 212 feet thick, overly the aquifer formation, which is in the Cretaceous mudstone, siltstone, shale, minor sandstone and fine-grained clastic sedimentary rock of the Fort St. John or Smokey Group (Cui et al., 2017). Based on 34 to 38 water-well records, the water table ranges from 11.6 to 146 feet below surface, averaging 46.9 feet in depth and the aquifer produces from 0.25 to 60 USGPM, averaging 4.2 USGPM, (Kohut, 2013). It has a low vulnerability due to the low permeability of the overlying clays and tills and the low, domestic well density (Kohut, 2013).

Other examples of confined bedrock aquifers can be found in the uplands of the study area, including in the western upland of NTS map sheet 94O, on an upland meltwater terrace. Two wells penetrate the aquifer at this site (well tag numbers 112766 and 112768) and are characterized by about 85 feet of sand over sandstone, siltstone and mudstone bedrock, with a water table between 175 and 200 feet below surface. A water yield was not reported for well #12766, however, well #112768 produced 330 USGPM from an aquifer in the bedrock at 372 feet below surface (Figure 21).

5.5 Summary of Aquifer Characterization

Aquifers in the Liard-Petitot area consist of surficial and sub-surface types. Surficial aquifers are generally typed as unconfined alluvial aquifers and upland/glaciofluvial aquifers, mainly types 1 and 4a, respectively, following the classification of Wei et al. (2009). Of all the mapped surficial aquifers in the study area (6418 aquifers comprising 292,178 ha), alluvial aquifers (mainly type 1) comprise 57.3% and upland aquifers (mainly type 4a) comprise 42.7%. A total of 208 water well records were obtained for the area; 27% (56 wells) are in surficial aquifers and 33% are in bedrock aquifers (68 wells). The remaining wells are in unknown aquifer types (32%, 66 wells) or were dry (9%, 18 wells). Sub-surface aquifers are classified as either confined glacial, pre-glacial aquifers (type 4b) or confined, fractured sedimentary bedrock aquifers (type 5a) after Wei et al. (2009). A total of 40.4% of the wells are either dry or did not have aquifer information (Table 3).

Table 3: Water wells by type and percentage of all wells (Wei et al., 2009).

Aquifer Type	Count	Percent of all Wells
Type 1	5	2.4%
Type 4a	13	6.3%
Type 4b	38	18.3%
Type 5a	68	32.7%
Dry Wells	18	8.7%
Type Unknown	66	31.7%
Total # of wells	208	-

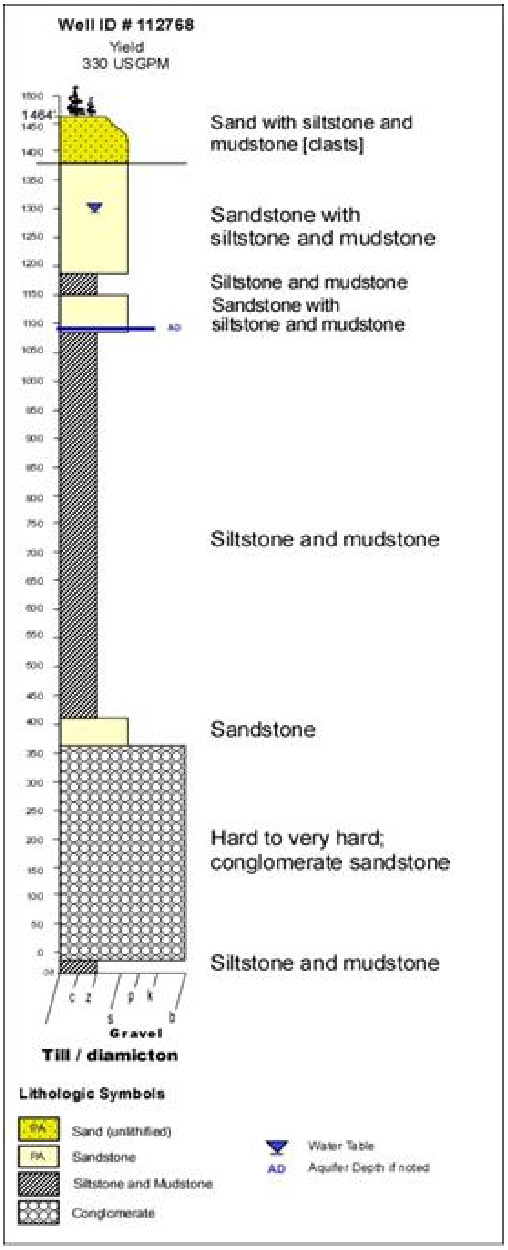

Figure 21. Confined aquifer in fractured sedimentary bedrock (type 5a). Example from western upland area in map sheet 94O, 16 km east of Nelson Forks.

The distribution and productivity of wells in the Liard-Petitot study area are illustrated in Figure 22. Notably, water well logs are relatively sparse in the area but some of them are quite productive (e.g. yields of more than 75 GPM). The general characteristics of aquifers in the Liard-Petitot area are as follows:

- Type 1, unconfined alluvial aquifers (yellow circles on Figure 22) are concentrated along the modern rivers, as would be expected. They commonly consist of Holocene/modern alluvial (fluvial) floodplains and terraces within, or with potential to connect with, the modern river. They are generally composed of 40 to 99 feet or more of silt, fine to coarse sand and gravel, underlain by till or glaciolacustrine clays. The water tables range between 17 and 19 feet below surface and yields range from 75 to 150 GPM.

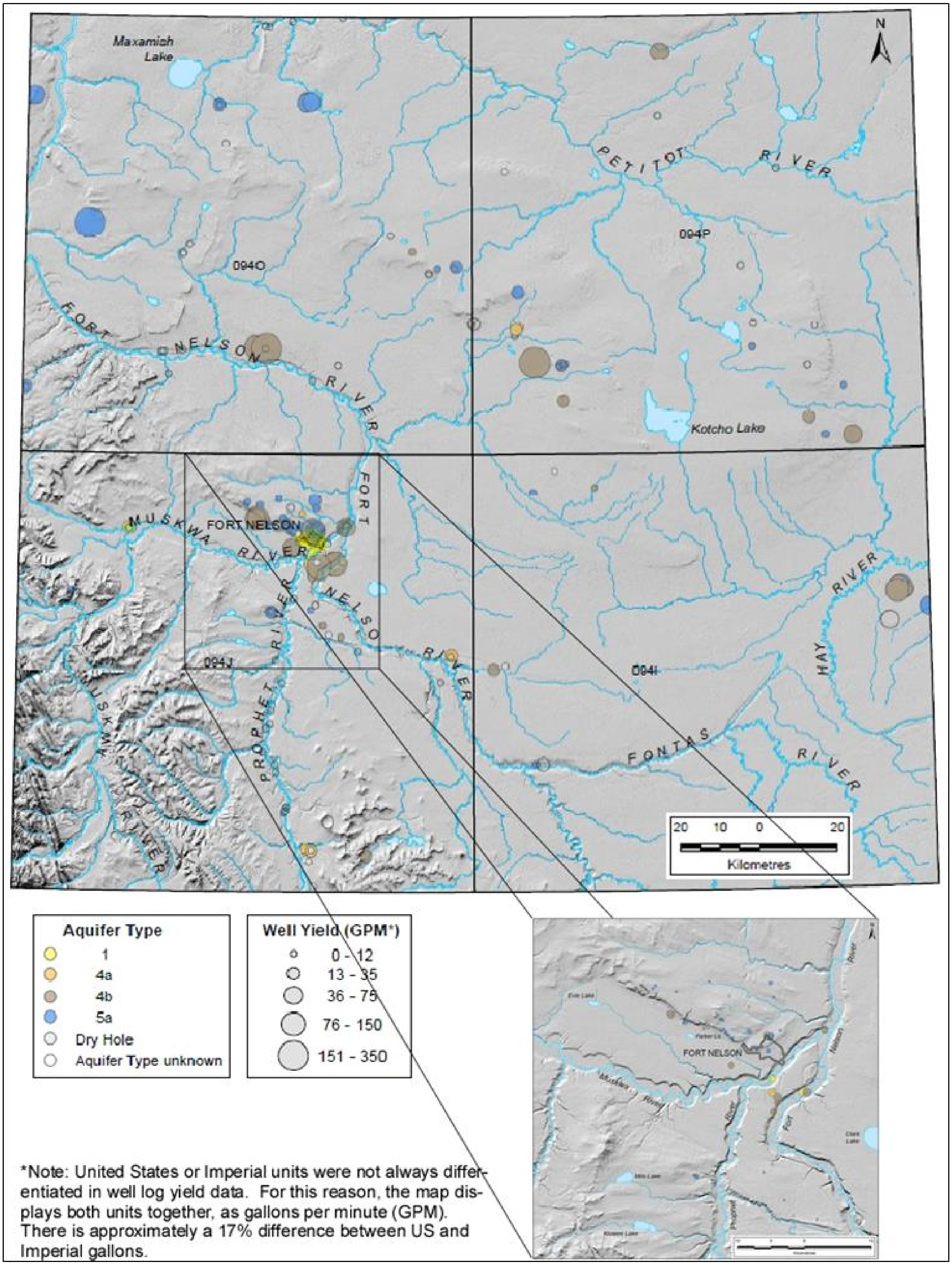

Figure 22. Distribution of aquifer types and yield in the Liard-Petitot area.

- Type 4a, unconfined glaciofluvial aquifers (orange circles on Figure 22) are primarily concentrated in or near the lower valleys associated with glaciofluvial terraces, kames and meltwater channels. Type 4a aquifers consist of glaciofluvial outwash and ice-contact sediments at surface. They are generally characterized by 45 feet to more than 125 feet (averaging 71 feet) of sand or interbedded sand and gravel. Where underlying sediments are noted, they are either thick deposits of blue clay (up to 170 feet thick) or till (up to 350 feet thick). The water table in these unconfined, glaciofluvial aquifers is normally about 30 feet below surface, with water yields averaging 36 GPM.
- Type 4b aquifers, confined aquifers of glacial or pre-glacial origin (brown circles on Figure 22), are common in the mid-slope to lower valleys. They are comprised of pre-Late Wisconsinan fluvial and glaciofluvial interbedded sand and lenticular gravels with lesser units of silt or stratified diamicton. They are generally deep aquifers; some are as little as 39 feet below surface but generally occur between 330 and 445 feet below surface. These aquifers are commonly confined by overlying, advance phase, glaciolacustrine clay and Late Wisconsinan till and overlie either lower layers of till or bedrock. The aquifers range in thickness from 2 to 203 feet thick, averaging 57 feet, with water tables averaging 115 feet below surface and commonly logged at over 300 feet above the producing aquifer. The average water yield of a type 4b aquifer is 64 USGPM but they range between 2 to more than 150 GPM.
- Type 5a confined fractured sedimentary bedrock aquifers (blue circles on Figure 22), dominate the upland plateaus of the study area. These aquifers generally consist of Cretaceous mudstone, siltstone, shale, minor sandstone and fine-grained clastic sedimentary bedrock of the Fort St. John or Smokey Groups and are found anywhere from 75 to 470 feet below surface. Low permeable clays and tills, with minor sands and gravels, from 8 to 212 feet thick, commonly overlie these aquifers. The water tables range from 11.6 to 146 feet below surface, with an average depth of 46.9 feet, just north of Fort Nelson but nearer 200 feet in depth in the Petitot area. Confined bedrock aquifers in the region produce from 0.25 to 60 USGPM, averaging 4.2 USGPM but can produce up to 330 USGPM in some areas (Figure 22).

6. ASSESSMENT OF LAND USE ACTIVITY

All major land use activities in the study area were assessed and mapped in as much detail as possible using the most recent and highest quality data available. Mapped land use activities include:

- roads (highways, petroleum development roads, forestry roads), trails, railroads, airstrips
- seismic lines (2D & 3D), gas pipelines, oil pipelines, gas wells, oil wells, petroleum facilities (compressor stations, gas processing plants, battery sites, dehydrator sites, flare sites, industrial camps, etc.), petroleum camps
- forestry cut blocks, agricultural areas, power lines, municipalities, sand and gravel pits, burns
- water well sites, water withdrawal sites, groundwater injection and disposal wells
- provincial and federal parks, First Nation reserves

All land use activities were evaluated and assigned to one of three broad categories based on their potential impact on aquifer quality and quantity in the region:

6.1 Category 1 Disturbance

Land use activities that result in disturbance but where some surface vegetation is retained or quickly reclaimed are considered category one disturbances. The risk of contamination of the groundwater by these activities is considered to be relatively low (compared to categories 2 and 3). The most common disturbance in these areas is the removal of trees and tall shrubs. Mineral soil is typically only exposed at these sites for relatively short periods of time, if at all. Example activities assigned to category 1 include: forestry cut blocks, trails, seismic lines, gas pipelines, clear-cuts and electric transmission lines.

6.2 Category 2 Disturbance

Land use activities that result in disturbance of the surface vegetation and where there is more potential for contamination of the groundwater than in category 1, are considered category 2 disturbances. The most common disturbance in these areas is the removal of most or all vegetation. Mineral soil may be exposed at these sites for relatively long periods of time but eventual reclamation of vegetation is expected. Example activities assigned to category 2 include: well sites, oil pipelines, agricultural areas (mainly hay crops) and burns (most fires in the area do not expose large areas of mineral soil).

6.3 Category 3 Disturbance

Land use activities that result in long term exposure of mineral soil potential and have a reasonably high potential for aquifer contamination are considered category 3 disturbances. Vegetation is entirely removed from these sites and there is a low probability of reclamation. Example activities assigned to category 3 include: roads, railroads, municipal developments, towns, airstrips, sand and gravel pits, petroleum facilities (compressor stations, gas processing plants, battery sites, dehydrator sites, flare sites), industrial camps and petroleum camps.

Weighting functions of 1, 1.5 and 2 are applied to the three disturbance categories as the potential for disturbance in category 2 is assumed to be approximately 1.5 times greater than category 1 based on the increased removal of vegetation, longer exposure of mineral soil and higher potential of oil spill, agricultural or other contamination. Likewise, disturbance in category 3 is likely to be approximately twice as high as category 1 based on the total removal of vegetation, long-term exposure of soil and increased potential for industrial contamination. This assumption can be modified in the analysis if different weighting functions are considered more appropriate by different users or for different purposes.

As with aquifer mapping, land use activities were evaluated separately within each drainage basin by areal extent.

7. ASSESSMENT OF LAND USE ACTIVITIES ON GROUNDWATER QUALITY

Assessments of the potential impact of land use activities on groundwater quality were based on both the density and type of land disturbances within each of the 28 drainage basins using the three categories described above. In addition, a separate assessment of potential impacts on groundwater quantity were made for each drainage basin (see Section 8). Land use activities were normalized against aquifer area within each basin as well as against the entire drainage basin area as described below.

A basic analysis of land use disturbances potentially affecting groundwater quality can be conducted simply by calculating the total amount of disturbed area as a percent of the total area within each basin. This metric was calculated for land use activities within each of the 3 levels of disturbance (categories 1, 2 and 3) and multiplied by the weighting factors of 1, 1.5 and 2, respectively, to characterize a weighted disturbance level within each basin.

In a second, slightly more complex analysis, another set of weighting functions were applied based on aquifer type (see below - 60% on alluvial aquifers; 30% on upland aquifers; 10% on non-aquifer or aquitard areas). Alluvial aquifers are weighted highest because they are especially prolific aquifers in the region and supply much of the groundwater that is in use both currently and likely in the future. Alluvial aquifers are also weighted highest because land use disturbance directly on these aquifers is much more likely to affect them than is disturbance on upland aquifers that may or may not be hydraulically connected with the alluvial aquifers. Although upland aquifers are less important than alluvial aquifers as water sources in the region, they have a significant role as potential recharge areas. Lastly, disturbance in non-aquifer areas is ranked lowest but not ignored because disturbances in these areas may affect adjacent aquifers via runoff.

The following formula was used to calculate an index of disturbance relating to groundwater quality effects:

Index of basin surface disturbance = 0.6 Alluvial [(L1 x 1) + (L2 x 1.5) + (L3 x 2)] + 0.3 Upland [(L1 x 1) + (L2 x 1.5) + (L3 x 2)] + 0.1 Aquitard [(L1 x 1) + (L2 x 1.5) + (L3 x 2)]

where:

- Alluvial = area of surficial alluvial aquifers, Upland = area of surficial upland aquifers, and Aquitard = areas outside of surficial aquifers; altogether these are general hydrogeologic types. Relative weightings of 0.6, 0.3 and 0.1 are given to each of these. Thus, for example, disturbance on alluvial aquifers is six times more important than aquitard areas. Note: when calculating only for aquifer areas, the constant for aquitards was set to 0.
- L1, L2 and L3 are land use disturbance categories where the value is the area of a given category as described in the preceding section. The three disturbance categories (L1, L2 and L3) are given weightings of 1, 1.5 and 2, respectively. Thus, for example, land use disturbance category L3 is twice as important for groundwater quality as is land use disturbance category type L1.

The index of disturbance relating to groundwater quality effects was calculated for each of the 28 basins as a proportion of the entire basin area (Table 4, left side) and as a proportion of just the aquifer area (Table 4, right side). A normalized index was generated by dividing each index by the highest index value for the population, multiplied by 100. For example, the highest index of the 28 basins has a normalized index value of 100. A value half that size would have a normalized index value of 50.

The normalized index of disturbance relating to water quality effects as a proportion of the entire basin area is provided in the first column on the left side of Table 4. The drainage basins with the most surface disturbance are the Lower Prophet, Middle Fort Nelson, Lower Fort Nelson, Lower Liard, Upper Muskwa and Lower Muskwa river basins with indices of 100, 74, 70, 67, 63 and 62, respectively. All other drainage basins have a normalized surface disturbance index of less than 50.

The normalized index of disturbance relating to water quality effects as a proportion of aquifer area within each basin is provided in the first column on the right side of Table 4. The most disturbed basins as a proportion of aquifer area are the Lower Fort Nelson, Middle Fort Nelson, Lower Prophet, Lower Muskwa, Lower Liard, Upper Fort Nelson and Lower Sikanni Chief river basins with indices of 100, 77, 66, 61, 59, 59 and 57, respectively. All other drainage basins have a normalized surface disturbance index of less than 35.

Table 4: Rankings of aquifer disturbance in study area basins as a proportion of basin area (left side) and as a proportion of aquifer area (right side). The rankings are normalized by dividing each index by the highest index value for the population, multiplied by 100. Thus, a value of 100 represents the highest indexed value.

	Using basin-wide data				**Using aquifer-area data** (ignores surface disturbance outside of aquifers)			
Basin name	**Normalized index of proportion of basin surface disturbed**	**Normalized index of well density**	**Total index of land disturbance and well density** (uses basin-wide data)*	**Rank**	**Normalized index of proportion of aquifer disturbed**	**Normalized index of well density**	**Total index of land disturbance and well density** (uses land data within surficial aquifer areas and basin-wide wells)*	**Rank**
Capot-Blanc Creek	13.0	3.8	13.4	23	7.8	3.8	8.2	17
Dunedin River	3.9	3.8	4.3	28	1.3	3.8	1.7	27
Fontas River	22.0	3.8	22.4	14	17.0	3.8	17.4	12
Hay River	46.7	32.2	49.9	7	4.5	32.2	7.7	19
Kahntah River	11.6	0.0	11.6	25	5.1	0.0	5.1	25
Kiwigana River	16.3	13.8	17.7	18	8.2	13.8	9.6	15
Klua Creek	7.4	1.9	7.6	27	7.0	1.9	7.2	20
Kyklo River	16.1	0.4	16.2	22	17.2	0.4	17.2	13
Lower Fort Nelson River	69.9	3.8	70.2	4	100.0	3.8	100.4	1
Lower Kotcho River	22.2	0.0	22.2	15	8.0	0.0	8.0	18
Lower Liard River	67.2	1.9	67.4	5	59.3	1.9	59.5	6
Lower Muskwa River	62.2	100.0	72.2	3	60.6	100.0	70.6	3
Lower Petitot River	8.0	13.6	9.3	26	4.2	13.6	5.5	22
Lower Prophet River	100.0	15.7	101.6	1	66.0	15.7	67.6	4
Lower Sikanni Chief River	22.2	0.0	22.2	16	56.7	0.0	56.7	7
Middle Fort Nelson River	73.8	67.7	80.5	2	76.6	67.7	83.3	2
Middle Muskwa River	19.5	5.8	20.1	17	4.7	5.8	5.2	24
Middle Petitot River	16.0	5.8	16.6	21	17.1	5.8	17.7	11
Middle Prophet River	39.4	17.4	41.2	11	23.5	17.4	25.2	9
Sahdoanah River	28.8	9.8	29.7	13	8.3	9.8	9.3	16
Sahtaneh River	30.2	44.5	34.6	12	34.8	44.5	39.2	8
Shekilie River	42.5	11.5	43.6	10	22.1	11.5	23.3	10
Snake River	11.7	0.2	11.7	24	5.3	0.2	5.3	23
Tsea River	15.8	8.2	16.6	20	5.1	8.2	5.9	21
Upper Fort Nelson River	48.2	9.6	49.2	8	58.9	9.6	59.9	5
Upper Kotcho River	46.8	0.0	46.8	9	11.1	0.0	11.1	14
Upper Muskwa River	63.4	0.0	63.4	6	0.1	0.0	0.1	28
Upper Petitot River	16.9	2.0	17.1	19	3.1	2.0	3.3	26

Note: Weighting for surface land use = 1. Weighting for wells = 0.1

All land use disturbances in each of the various data sets are recorded by areal extent. Wherever possible, the most up to date and accurate land use information are utilized. In many cases accurate data providing the actual areal extent of the various land use activities were acquired. For example, actual area data were obtained for individual forestry cut blocks, municipal boundaries, aboriginal lands, parks, power line right of ways, burned areas, air strips, industrial camps, sand and gravel pits and a variety of oil and gas facility types including battery sites, campsites, dehydrator sites, flare sites and gas processing plants. The best quality data available was acquired including high quality field survey data for compressor sites, dehydrator sites, drill sites / well sites, electric power lines, flare sites, gas and oil pipelines, gas processing plants and industrial camps.

In some cases, survey data could not be directly used because some data sets were not complete or out of date. For example, there are far more oil and gas well sites in the study area (10080 sites) than there are well sites with area measurements in the Tantalis Crown Land data (3918 sites), so an average well site area (1.622 ha) was determined using the Tantalis well site data (2070 sites with surveyed data) and applied to the complete well site data set. Thus, both the most accurate and most up to date information was utilized in the analysis.

Likewise, for roads, an average width of 11.911 m (obtained from 301 road segment width measurements) and an average width of 7.378 m for pipelines (obtained from 2578 pipelines including 2170 surveyed lines) were used. For a few point features (e.g. sump locations) and line features (e.g. trails) accurate area data were not available so reasonable estimates of the areal extents of these features were applied. All data used in the calculations are provided in the excel project files in and could easily be updated if better information becomes available.

Potential effects on groundwater quality for all alluvial aquifers, upland aquifers and non-aquifer areas are evaluated within each basin as well as for the entire area of each basin.

8. ASSESSMENT OF LAND USE ACTIVITIES ON GROUNDWATER QUANTITY

Groundwater consumption data were compiled to assess potential land use disturbances affecting groundwater quantity. These data do not include surface water withdrawals as these occur primarily from dugouts, ponds and lakes and there is little evidence that these features have significant hydraulic connections to aquifers in the region. Most ponds and lakes in the region overlie relatively impermeable glacial lake sediments and clay-rich tills. For example, a number of sand and gravel pits adjacent to lakes, ponds, bogs and swamps are completely dry to depths well below the surface water level, clearly indicating that they are not hydraulically connected.

A straight forward approach to evaluating effects of land use activities on groundwater quantity is to simply determine the total number of groundwater wells in each basin as a percent of the total number of wells in the study area. Included in the data are water wells in the WELLS database, other water wells compiled for this study (Anderson Drilling wells), and active water wells used by the petroleum industry (designated by the Oil and Gas Commission as active wells with water as the bore fluid type). The latter include groundwater withdrawal, injection and disposal sites and a number of water wells of unknown (unreported) purpose. Many of these industrial wells are likely in saline formations well below the base of fresh groundwater, but that information was not supplied in the data file. However, it is considered unlikely that withdrawal or injection of water into these deep formations would have significant effects on fresh groundwater quantity so only a 5% weighting has been applied to these wells compared to the ENV and Anderson wells. Thus, the ENV and Anderson wells have 20 times more weight than active OGC water wells.

The following formula was used to calculate an index of disturbance relating to water quantity effects:

Index of well density = 1.0 (count of ENV and Anderson water wells) + 0.05 (count of OGC water wells)

where:

- ENV wells are water wells from the B.C. WELLS database and Anderson wells are water wells added from this study. The "count" is the number of wells within a given basin.
- OGC water wells are active oil and gas wells with "water" indicated as the bore fluid type
- 1.0 and 0.05 are relative weightings given to each.

This index was calculated for each of the 28 basins. The normalized index for well density was calculated using the same method as for the Index of basin surface disturbance.

The results of this analysis are shown in Table 4. The normalized index of well density (relating to water quantity effects) as a proportion of the entire basin area is provided in the second column on both the left and right sides of Table 4. Only one set of indices was calculated as all wells in the entire study area were used (not just wells directly overlying mapped aquifers). The most effected basins are the Lower Muskwa, Middle Fort Nelson, Sahtaneh and Hay river basins with indices of 100, 68, 44, and 32, respectively. All other drainage basins have a normalized well density index of less than 20 and most are less than 10.

9. ASSESSMENT OF PRIORITIES FOR FUTURE MAPPING AND CHARACTERIZATION

After assessing the effects of various land use activities on groundwater quality and quantity using the methods described above, the final step of the analysis was to identify priority areas for future work through the ranking of all drainage basins for the combined effects on groundwater quality and quantity (Table 4). As described above, a simple and straight forward approach is utilized that is easily understood by a variety of users and also easily replicated or revised. The same weighting functions are used: 60% for alluvial aquifers, 30% for upland aquifers and 10% for all other areas (aquitards) in the drainage basin. It should be noted that, although weighting functions have been somewhat arbitrarily assigned, they can easily be altered or revised in the spreadsheets. The reasoning for the weighting functions, as is discussed in Section 6 above, is that disturbance directly on an aquifer is likely to result in a much greater effect on the aquifer than is disturbance somewhere else in the drainage basin. Alluvial aquifers are weighted twice as high as upland aquifers simply because they are more prolific and important aquifers in the region. Non-aquifer areas are not ignored because disturbances in these areas may affect adjacent aquifers via runoff.

Land use disturbance is ranked within aquifers (calculated as a percent of the total aquifer area in each basin) and within the entire basin (calculated as a percent of the total basin area) for each of the 28 basins to make two final maps: a basin disturbance map (Figure 23) and an aquifer disturbance map (Figure 24).

All 28 drainage basins in the study area were ranked from highest to lowest disturbance for both groundwater quality and quantity. Since these two types of impact are relatively distinct, the two data sets were not initially combined into a single ranking. As a last step in the evaluation, however, a composite standing was calculated simply by assigning weighting factors to each data set. A weighting of 1.0 was used for disturbances of the land surface relating to water quality, the primary focus of the analysis, and a weighting of 0.1 for the effects of well density on groundwater quantity.

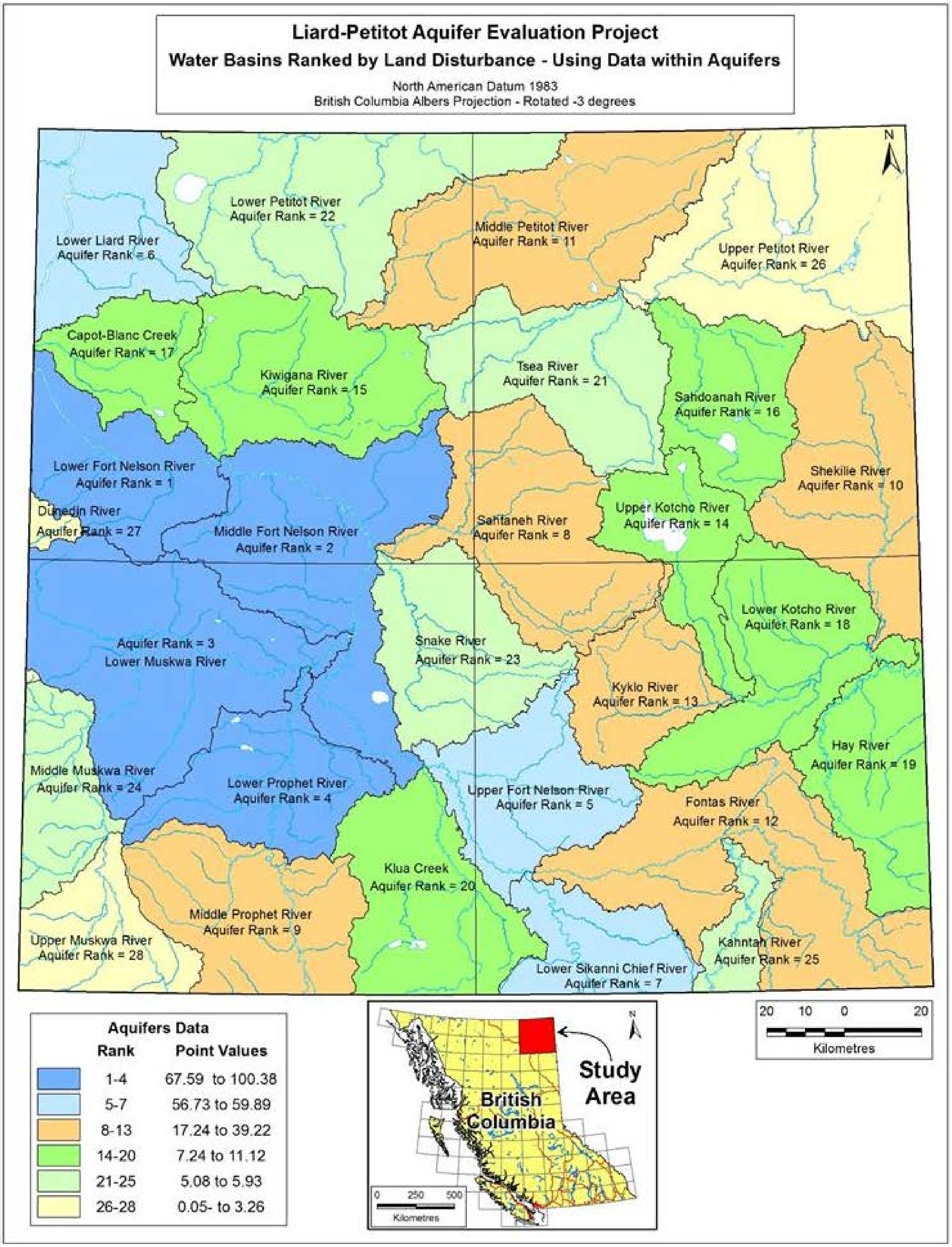

Figure 23. Total index of land disturbance and well density as a proportion of the entire basin area.

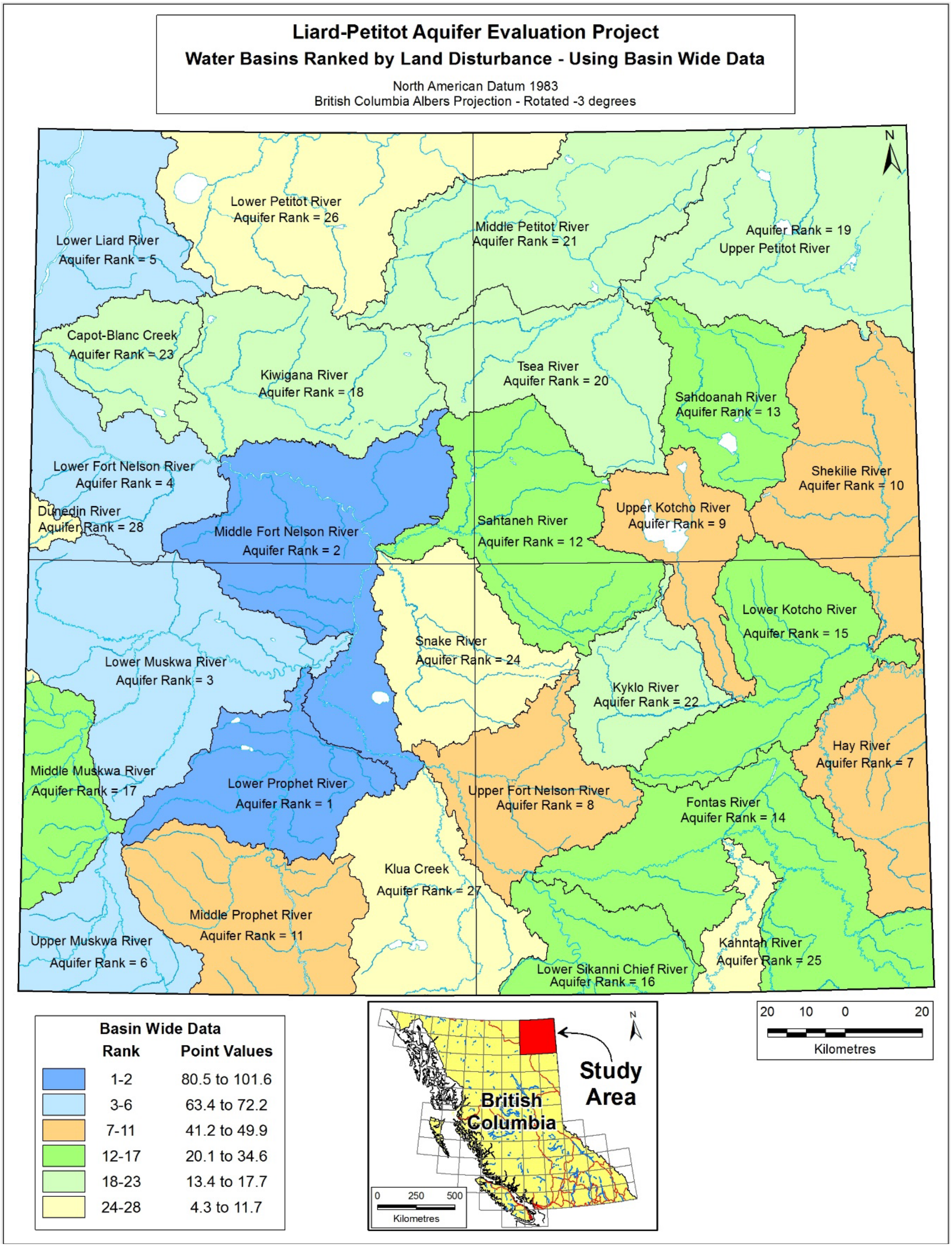

Figure 24. The total index of land disturbance and well density as a proportion of the aquifer area.

The following formula was used to calculate a total index of land disturbance and well density:

Total index of land disturbance and well density = 1.0 (normalized index of basin surface disturbed) + 0.1 (normalized index of well density)

It was not necessary to normalize this total index as the calculated values were simply ranked from highest to lowest for each of the 28 drainage basins (Table 4). The total index of land disturbance and well density as a proportion of the entire basin area is provided in the third column on the left side of Table 4 (blue bars). The basin ranking is shown in the fourth column highlighted with colours. The top six basins (red and orange colours) are the Lower Prophet (1), Middle Fort Nelson (2), Lower Muskwa (3), Lower Fort Nelson (4), Lower Liard (5) and Upper Muskwa (6) river basins (Figure 23). The total index for each of these basins 101.6, 80.5, 72.2, 70.2, 67.4 and 63.4, respectively. All other basins have a combined index of less than 50. In terms of priority ranking for future investigation, all these basins are ranked as high priority. Medium priority basins include the Hay, Upper Fort Nelson, Upper Kotcho, Shekilie, Middle Prophet, Sahtaneh and Sahdoanah river basins with total index rankings of 49.9, 49.2, 46.8, 43.6, 41.2, 34.6 and 29.7, respectively. All other basins have a composite ranking of less than 25 and are considered low priority.

The total index of land disturbance and well density as a proportion of the aquifer area in each basin is provided in the third column on the right side of Table 4 (blue bars). The basin ranking is shown in the fourth column highlighted with colours. The top seven (high priority) basins (red and orange colours) are the Lower Fort Nelson (1), Middle Fort Nelson (2), Lower Muskwa (3), Lower Prophet (4), Upper Fort Nelson (5), Lower Liard (6) and Lower Sikanni Chief (7) river basins (Figure 24). The total index for each of these basins is 100.4, 83.3, 70.6, 67.6, 59.9, 59.5 and 56.7, respectively. Medium priority basins include the Sahtaneh, Middle Prophet, Shekilie, Middle Petitot, Fontas, Kyklo and Upper Kotcho river basins with total indices of 39.2, 25.2, 23.3, 17.7, 17.4, 17.2 and 11.1, respectively. All other basins have a combined index of less than 10 and are considered low priority for future work.

Interestingly, the results are similar for the two different approaches of evaluating disturbance (using basin-wide data versus aquifers-only data). The main differences are illustrated by a comparison of the highest ranked basins. Four basins rank in the top four in both methods. The Lower Fort Nelson, Middle Fort Nelson, Lower Muskwa and Lower Prophet drainage basins are ranked as the top four priority basins in both types of rankings. This confirms the priority ranking of these basins and indicates that both the basins as a whole and the aquifers within the basins are all highly disturbed. The Lower Liard River basin also shows up on both high priority lists and ranks 5 and 6. The high priority Upper Fort Nelson and Lower Sikanni Chief River basins are ranked as 5 and 7, respectively, on the aquifer-only analysis but ranked 8 and 16, respectively, on the basin-wide analysis. This indicates that aquifers within these basins are much more disturbed than are the basins as a whole. The only significant anomaly in the high priority rankings is the Upper Muskwa River basin which ranks third in the basin-wide analysis but is last in the aquifer-only data. This indicates that although that basin has been significantly impacted by land use activities, aquifers in the basin have not been directly affected to any great extent.

Some land use activities can affect both groundwater quality and groundwater quantity. For example, land use activities that result in a decrease in surface infiltration rates within recharge zones (such as vegetation removal and soil compaction) have a negative impact on groundwater recharge. However, determining the magnitude of such impacts in a regional scale analysis would require detailed knowledge of the various methods employed in each type of land use activity (e.g. different methods of seismic line construction) and the relative impacts of each method on infiltration. In addition, detailed information on other factors such as surface soil texture in any one area would be required to assess aspects such as ground compaction and changes in permeability. Although it is difficult to directly account for these combined impacts, this study does intrinsically address these aspects simply by applying a heavy weighting on disturbance within the surface aquifers themselves and not on the entire region.

9.1 Comparison of Results with Previous Studies

The Province of British Columbia (2017) recently completed an excellent analysis to prioritize water monitoring in all of British Columbia northeast of the continental divide using a disturbance-sensitivity based approach. Data for the analysis had previously been compiled by Johnson (2015) in Part 2 of the report. Since the report covered a much larger part of northeast B.C. than this study (from south of Dawson Creek, north to the Yukon/NWT border and west well into the Rocky Mountains), the two reports are not directly comparable. However, the Province report did provide summary maps of priority monitoring areas by drainage basin (their figures 4 and 5) that can easily be compared to the basin wide analysis (Figure 24). The Province of British Columbia (2017) priority basins for surface water quality monitoring were centered on the communities of Fort St. John, Dawson Creek, Tumbler Ridge, Chetwynd and Fort Nelson. In the current study area, these high priority basins include the Middle Fort Nelson, Lower Muskwa, Kyklo and Sahtaneh basins (ranked, 5, 13, 16 and 29, respectively, out of 69 basins). In this study, the first two of these basins are also ranked as high priority (ranks 2 and 3) but the last two are ranked much lower priority (ranks 12 and 22, out of 28 basins).

The Province of British Columbia (2017) also ranked priority areas for groundwater monitoring of quality, using combined rankings of groundwater vulnerability and demand, by 1:50,000 scale map sheets (their figure 11). Although not directly comparable, this ranking is perhaps most similar to the basin-wide results presented here (Figure 24). The map sheets ranked highest by the Province (their tier 1) in the present study area are again centred on the Fort Nelson townsite (map sheets 94J/15 and 94J/10 ranked 15 and 24, out of 219). These two sheets occur mainly within the Middle Fort Nelson and Lower Muskwa drainage areas, ranked as priority 2 and 3 by basin in this study (Figure 24). The next two highest ranked map sheets are 94J/2 and 94P/4 (their tier 2, ranked as 45 and 48.5 out of 219 map sheets). These map sheets occur in relatively low ranked basins in this study (Middle Sahtaneh and Middle Prophet, ranked 8 and 9 out of 28). Likewise, several tier 3 ranked map sheets occur in relatively low priority basins in this study (including the lower and Middle Petitot, Tsea River, upper Kotcho and Hay River basins).

In summary, the results from this study are similar to those of the Province of B.C. (2017) for two basins (Middle Fort Nelson and Lower Muskwa). However, the highest ranked basin (Lower Prophet River) and other high priority basins (Lower Fort Nelson, Lower Liard and Upper Muskwa River) in this study were not identified as priorities in the provincial study. These different results are attributed mainly to the different methodologies used in the two studies. The groundwater quality weighting system used in the Province of B.C. study weighs 14% on future development, 7% equally on 10 different types of current disturbance and 16% on groundwater vulnerability (DRASTIC). In addition, they base their analysis on entire 1:50:000 map sheet areas whereas the analysis used here is based mainly on disturbance of individual aquifer units and source area polygons and to lesser extent on non-aquifer areas.

Another study of shallow groundwater intrinsic vulnerability in northeast B.C. was completed by Holding and Allen (2015). They used the DRASTIC approach and their results showed that the only area of high vulnerability in the present study area was a narrow strip along the Liard River valley (their Figure 12). This dramatically different result is attributed to the different approaches used. The DRASTIC approach requires seven input parameters: depth to water, recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity. Unfortunately, most of these parameters are not well understood in northeast B.C. and data are lacking. As a result, use of the DRASTIC approach in this area requires reliance on relatively low-resolution information, rough estimates for parameter inputs and generalized model assumptions. For example, the classification of aquifer media in the study area was based on very low-resolution (1:5 million scale) surficial geology maps and required the assumption that potential aquifers are present in all subsurface materials. As a result, in the entire area, high permeability aquifer media (glaciofluvial sands and gravels) were only mapped along the Liard River. Likewise, since only five pumping test results (4 in bedrock and 1 in till) were available for their entire study area, hydraulic conductivity parameters were based on estimated values for the aquifer media. As a result, only the Liard River valley showed high hydraulic conductivity, as expected since it was derived from the generalized aquifer media map. Interestingly, hydraulic conductivity estimates were orders of magnitude lower than the actual pump test data. In the current study area, their input data shows shallow water tables only along the Fort Nelson and Liard river floodplains, which they incorrectly report as areas of exposed bedrock (their Figure 3). Only a single recharge ranking and mainly low-confidence soil media rankings are used for almost the entire area covered by the current study. For impact of vadose zone ratings, no distinctions were made for different types of bedrock. In summary, it is concluded that this type of approach is not applicable to the current study area and, although interesting, cannot be compared in any meaningful way to the results presented here.

9.2 Cumulative Effects

Cumulative effects are integrated into the analysis presented here through the inclusion of overlapping land use activities in the calculations of disturbed areas. This approach adds all land use impacts even if they overlie one another. As a result, in some aquifers the total percent of disturbed area actually exceeds 100% of the aquifer area. This indicates that there is more area of disturbance than area of surficial aquifer. The rationale for retaining overlapping disturbances is simply that each subsequent disturbance adds another layer of potential effects. For example, each time a seismic line is re-used it gets brushed out and becomes progressively more disturbed. Likewise, a road on an old clear-cut adds more disturbance in addition to the original effects from logging. Thus, the area of a forestry cut block, as well as the areas of overlapping land use activities such as roads or seismic lines, are accumulated in the analysis, despite the overlap. Although this approach may result in an over estimation of cumulative effects, there is no reasonable way to calculate the actual cumulative effects with such a large regional data set. In addition, since all drainage areas are assessed equally, the overall relative effect of differences between drainage basins is likely to be small.

9.3 Additional Comments

In response to two questions posed by the reviewers regarding First Nation consultation and potential effects of permafrost, the following comments are provided.

1. First Nations were not consulted as part of this project as consultation was not identified as a contract component given the limited project scope, time-frame and budget. Any possible future consultation with First Nations and other potential users of this report is welcomed. Since the data and analyses are quite technical in nature, consultation should include a briefing by someone well trained in geological mapping (especially in surficial geology applications) and GIS analysis. In addition, written comments and questions are welcomed at any time from all users of the data provided for this project.
2. Permafrost was indirectly included in this analysis because most surficial geology mapping projects in northern Canada include information on permafrost features where observed. Such features include those that provide direct evidence of permafrost such as patterned ground, ice-wedge polygons and depth to permafrost (if measured) and, more importantly, indirect evidence such as the distribution of peat palsas and peat bogs where permafrost is likely

present. Since all the original surficial geology mapping data has been captured, all direct and indirect observations on permafrost are available in the data files (Appendices).

An important effect of permafrost, of course, is that it reduces subsurface permeability to near zero and inhibits groundwater infiltration below the permafrost. In areas of discontinuous permafrost such as the study area, these effects are strongly controlled by the thickness, extent and distribution of permafrost. However, since direct measurements of these factors are rare, most permafrost mapping programs rely on the identification of landform features like those mentioned above. In particular, thick peat deposits are well known to insulate the subsurface and enhance the preservation of permafrost. In the approach to aquifer mapping and analysis used in this study, peat areas are categorized as aquitards, regardless of whether or not they contain permafrost. As a consequence, the addition of any available permafrost map data (some recent unpublished mapping has been completed but was not available for this study) is unlikely to significantly change the results of the analysis. However, an assessment of the new permafrost map data is recommended, especially with regards to the identification of permafrost in any areas not covered by peat.

10. SELECTION OF DRILLING AND/OR PUMPING TEST SITES

At the request of the contract manager, three potential sites for drilling and/or pumping tests were selected. All three sites are in high priority basins and have potential for both shallow and buried aquifers. The first two sites are in alluvial aquifers. One is on the lower Muskwa River aquifer upstream of Fort Nelson townsite and the other is on the lower Fort Nelson River alluvial aquifer above the confluence with the Liard River. The third proposed site is located on an upland glaciofluvial aquifer located between the Fort Nelson and Muskwa River valleys. The proposed sites are all located near road access and have a high probability of encountering one or more potential aquifer units.

10.1 Proposed Site 1

The first site is located in the number 1 priority basin (ranked by aquifer area, Figure 24, and ranked # 4 using basin-wide data, Figure 23), along the lower Fort Nelson River about 1.8 km downstream of the Highway 77 crossing (Figure 25). The site is located at UTM coordinates of approximately 10V 484100E and 6565060N. The groundwater table was reported, in geotechnical borehole 83-01 on the south side of the highway bridge crossing, to be at a depth of 22 feet, near the top of a sand and gravel aquifer underlying about 18 feet of floodplain silts (Appendix A, Figure A1). On the north side of the bridge at borehole 83-06, the groundwater table was reported at 24 feet in a clay with sand layers. In borehole 2 near the south end of the bridge, artesian pressure and/or gas was reported in a sandy gravel unit from 96 to 100 feet depth buried under an alluvial sand and gravel unit extending from near the surface to about 83 m depth and about 13 feet of hard clay. The proposed drill site is located downstream of the bridge-crossing, approximately in the centre of the lower Fort Nelson River alluvial aquifer. Access is provided along an unnamed road that passes through a gravel pit on the north side of the valley and extends to the modern river edge. The access road joins with Highway 77 about 2.5 km north of the highway bridge (Figure 25). An alternate option to this site is located on the south side of the river where there is also access directly off Highway 77 (Figure 25).

Figure 25. Location of proposed drill site 1.

10.2 Proposed Site 2

A second proposed site is within the Lower Muskwa River basin, ranked as number 3, using both aquifer only (Figure 24) and basin-wide (Figure 23) data. Access to site 2 is provided via the old Nelson-Mainline Road off Highway 97. The site is located at UTM coordinates 10V 518370E 6514890N in the lower Muskwa alluvial aquifer upstream of Fort Nelson (Figure 26) and upstream of potential land use impacts from the townsite area. The proposed site is located about 0.7 kilometres northeast of well #13659 shown on Figure 19. That well was drilled through 30 feet of overbank silts coarsening-down into fine sands, that overlie 11 feet of gravel and sand with a reported yield of 75 IGM and static water level of 19 feet. The aquifer overlies gravelly clay from 41 feet to 43.2 feet. Two other wells drilled in this same aquifer are located about 1 km downstream of the Highway 97 bridge, about 3.5 km northeast of proposed drill site 2. The first well (#71091) was drilled to a depth of 475 feet through alluvial sands and gravels (0-33 ft) overlying mainly stony clays (probably till), clays and silts with no reported well yield. The second well (#75469) was drilled through 22 feet of overbank silts and sands into coarse alluvial gravels and sands to a depth of 60 feet with no reported well yield. Wells in alluvial aquifers of this type in the region are known to produce 150 GPM or more in shallow gravels. For example, well #18325 and #18500 near the BC Rail bridge crossing over the Fort Nelson River aquifer both have reported well yields of 150 GPM from coarse alluvial gravels at only 36-52 feet depths overlying blue clay. The alluvial aquifer along the Fort Nelson River near the BC Rail bridge provides an alternate option to site 2.

Figure 26. Location of proposed drill site 2.

10.3 Proposed Site 3

The third proposed site is located on an upland glaciofluvial aquifer in the Muskwa area. Several wells have penetrated this glaciofluvial unit (Figure 19). The site is located at UTM coordinates 10V 517935E 6512245N and accessed from Highway 97 via an access road off the Chopstick Factory Road (Figure 27). The proposed site is located close to two wells (#24443 and #36435 that produced yields of 94 GPM and 114 USGPM, respectively). These wells possibly could be used to monitor water levels during pumping tests. Well #24443 was drilled through coarse gravel (5-27 ft) and fine sands (27-52 ft) into blue clay (52-53 ft) with the static water level at 26 feet. Nearby well #36435 was drilled through silt and silty gravel (0-25 ft), sands and pebbly gravels (25-42 ft) and clay silt (42-52 ft). Another producing well in the area (#102795) is located about 1 km southeast of the proposed site, just east of the Alaska Highway. The well log is shown in Figure 19 and shows coarse glaciofluvial gravels (0-37 ft), compact clay and gravel (likely till, 37-406 ft), fine sand (406-433 ft) over gravels and sands (433-455 ft). The buried aquifer produced a well yield of 150 GPM with a static water level of 330 feet. Another well about 0.5 km farther south (#45467, Figure 19) yielded 20-30 GPM in a buried sand at 425 feet depth with a static water level of 100 feet. One last well in the area (#46137) along the Fort Nelson valley edge produced 50-60 GPM reportedly at 225 feet, although the well was drilled to a depth of 325 feet into a basal gravel (Figure 19, 321-325 ft) and had a static water level of 220 feet. An alternate option for Site 3 is to drill a well into one of these deeply buried aquifer targets near any of the wells described above.

Figure 27. Location of proposed drill site 3.

11. RECOMMENDED FUTURE WORK

1. Due to the large number of aquifers mapped as part of this project, it is recommended that grouping of aquifer clusters would provide a more manageable data set for future analysis. Aquifers could be grouped on the basis of their geology and hydrogeology as well as proximity. For example, many alluvial aquifers on opposite sides of modern rivers could be grouped together and mapped as a single alluvial aquifer. Such aquifers are geologically similar and almost certainly hydraulically connected.
2. The main data gaps identified in this study occur in areas where only poor-quality data exist. These areas include parts of the northeast quadrants of NTS map areas 94/I and 94/O, part of the southwest quadrant of 94/0 and parts of six 1:50,000 map sheets on 94/P (1, 2, 3, 6, 14 and 15). Although complete surficial geology mapping projects ultimately should be conducted in these areas, this is unlikely in the near future. Thus, it is recommended that aquifer-specific mapping be conducted in these areas to identify surficial geology units that have good potential to host aquifers. Aquifer maps could readily be produced using air photo and satellite data interpretation combined with use of geophysical logs and other subsurface data sets. Mapping could be prioritized on the basis of basin rankings determined in this study (Section 9).
3. Detailed scale (e.g. 1:20,000 or 1:50,000) surficial geology and aquifer maps should be published by the Province of B.C. using provincial terrain mapping standards for all priority drainage basin areas from the data compiled during this project. In addition to surficial geology map units, these maps would include surface features and landforms important for aquifer delineation including:
    a. meltwater channels that are common through the study area and are good targets for further mapping and groundwater exploration
    b. landforms such as eskers and kames that likely host groundwater resources in many areas

4. Subsurface aquifer mapping is also recommended in priority basins identified in this study (Section 9) by integrating depth-interval data and interpretation of downhole geophysical logs. As a first step to better identify deeply buried aquifers in the region, bedrock topography and overburden thickness maps for the entire study area (94I, J, O and P) could be created using the methods of Levson et al. (1994, 2004) and Hicken et al. (2008). Data for subsurface aquifer mapping would include:
    a. the extensive oil and gas gamma log data base for the region
    b. existing water well data and other well data not acquired during this study - e.g. missing US Army Engineer well logs from the 1950's drilled to depths of 159, 442 and 215 m (521, 1451 and 706 ft, respectively) in the Fort Nelson airport area,
    c. geotechnical data from sources who did not respond to the requests for data due to time or other constraints
    d. industry geophysical data to help map paleo-valleys and bedrock topography where possible.

12. CONCLUSION

Priorities for future mapping and aquifer characterization have been completed for the entire study region. The analysis emphasizes the potential effects of various land use activities on groundwater quality. The effects of surface activities are weighted depending on the type of disturbance and on the hydrogeological setting where the disturbance occurs (i.e. on alluvial aquifers, upland aquifers or other areas in the basin). The analysis also includes an assessment of groundwater quantity based on water well density. All results are normalized to allow a direct comparison of 28 different drainage basins in the study area. Basin indices for both groundwater quality and quantity were determined and combined to form a total index of disturbance for each basin. The final indices are ranked using two slightly different approaches: one evaluates basin-wide effects of surface disturbances and the other emphasizes effects only on mapped aquifers. Basins are ranked from 1 to 28 and separated into high, medium and low priority categories based on natural breaks in the data indices. Interestingly, both approaches result in very similar high priority rankings. The basin-wide ranking indicates that the highest priority areas include the Lower Prophet, Middle Fort Nelson, Lower Muskwa, Lower Fort Nelson, Lower Liard and Upper Muskwa river basins, with total indices of 101.6, 80.5, 72.2, 70.2, 67.4 and 63.4, respectively. On an aquifer-only basis, the highest priority areas for future work are the Lower Fort Nelson, Middle Fort Nelson, Lower Muskwa, Lower Prophet, Upper Fort Nelson, Lower Liard and Lower Sikanni Chief river basins, with total indices of 100.4, 83.3, 70.6, 67.6, 59.9, 59.5 and 56.7, respectively.

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APPENDIX A. WATER WELL AND AQUIFER DESCRIPTIONS

A.1 Aquifer Type 1 (Unconfined) Alluvial and Type 4b (Confined) Glaciofluvial Aquifers

Fort Nelson River aquifers [at the Highway 77 Bridge crossing the Fort Nelson River]

One of the best subsurface representations of the Fort Nelson River aquifer is provided by a series of geotechnical boreholes drilled by the Ministry of Transportation and Highways at the bridge on Highway 77 (map sheet 94O). Cross-sections of the area (Figure A1) indicate that the Fort Nelson River aquifer is unconfined and underlies the river but thickens towards the southeast to more than 30 m (99 ft) where it is overlain by about 5.5 m (18 ft) of silts. The aquifer is dominated by sandy gravels and gravelly sands with minor silty sands. The gravels and sands are mainly well sorted (poorly graded) indicating that this is likely a highly productive aquifer. The water table was reported in the aquifer at 22 ft on the SE bank and at 24 ft on the NW bank. Progressive thickening of the sands and gravels towards the southeast suggests that a substantial part of the aquifer extends well beyond the edge of the river bank and likely underlies all of the adjacent floodplain (Figure A2).

A secondary potential aquifer is indicated at the northwest end of the section at a depth of 21-31 m (70-102 ft) and is overlain by a thick sequence of clays and silts, probably of glaciolacustrine origin. This probable confined aquifer is described as a dense silty sand and it thins under the river to less than 3 m at a depth of 12.8-15.2 m (42-50 ft).

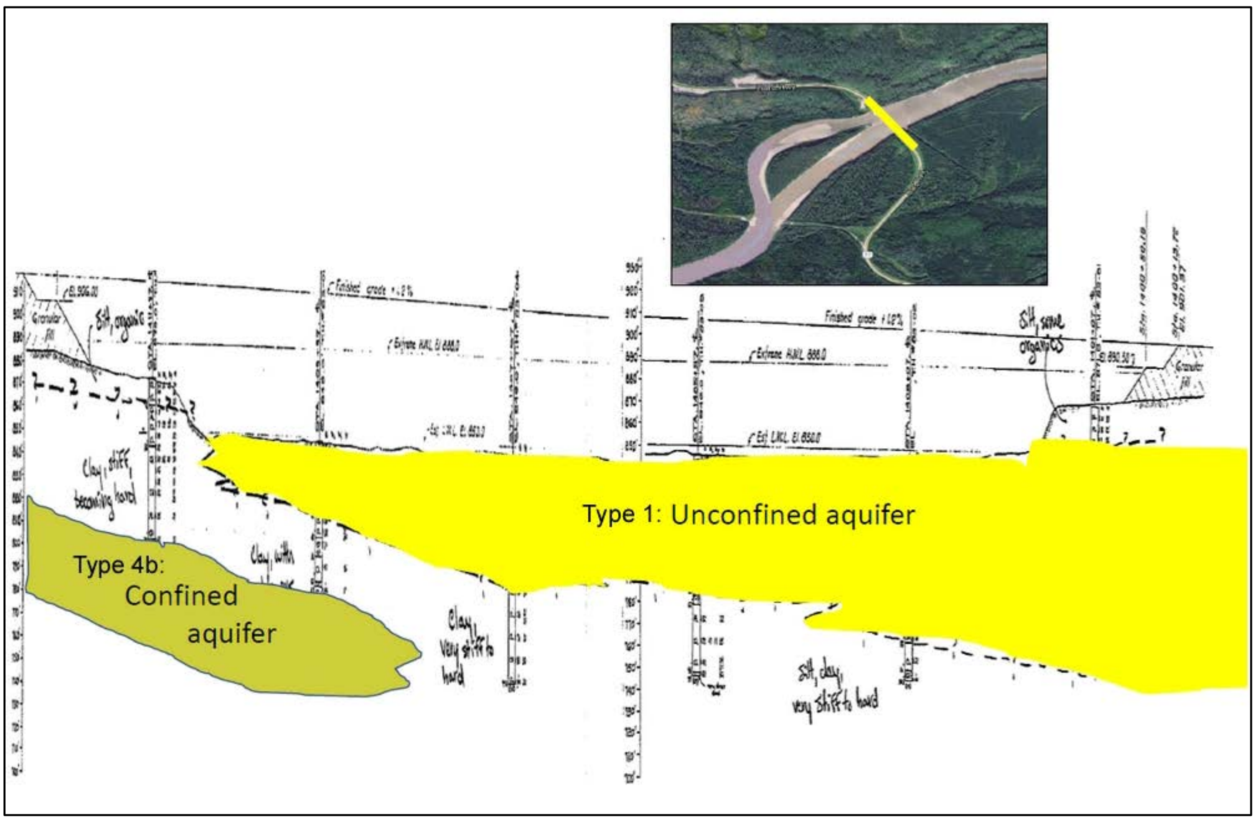

Figure A1: Simplified cross-section of the Fort Nelson River aquifer at the Highway 77 bridge crossing based on geotechnical data (source: BC Ministry of Transportation and Highways). The northwest bank of the river channel is shown at the left and the SE bank is on the right.

Figure A2: Air photo view of the Fort Nelson River Bridge crossing on Highway 77. Note the broad floodplain area south of the bridge likely underlain by sands and gravels of the Fort Nelson River aquifer.

A.2 Aquifer Classification Work Sheet for Aquifer 1041 - Type 1, Unconfined Alluvial (Modified from Kohut 2013 to remove duplicate data):

DATE: October 22, 2013

AQUIFER MAPPER: A. P. Kohut

AQUIFER REFERENCE NUMBER: 1041

DESCRIPTIVE LOCATION OF AQUIFER: North side of Fort Nelson River, 7km SE of Fort Nelson.

NTS MAP SHEET: 94J10 and J15

BCGS MAP SHEET: 94J077, 078

CLASSIFICATION: III A RANKING: 9

Aquifer Size: 3.3 km^2

Aquifer Boundaries: The aquifer boundary has been delineated using spatially limited water well record information, area of development, river boundary and topography.

Aquifer Sub-type: 1b; aquifers found along rivers of moderate stream order with the potential to be hydraulically influenced by the river.

Aquifer Priority Rating for Observation Wells: 22.1

Geologic Formation (overlying materials): Primarily coarse sand and fine gravel.

Geologic Formation (aquifer): Likely fluvial gravel and sands

Confined/Partially Confined/Unconfined: Unconfined

Vulnerability: High. Although one well reported 1.22 m (4 ft) of sandy clay deposits at surface, this aquifer is considered highly vulnerable.

Productivity: High. Reported yields for only 2 wells were 9.463 L/s (150 gpm) each.

Depth to Water: Depth for the 2 wells were 5.18 and 5.49 metres (17 and 18 ft) respectively.

Direction of Groundwater Flow: Not determined.

Recharge: Precipitation, snowmelt and local surface water runoff in relevant seasons and infiltration from the Fort Nelson River.

Domestic Well Density: Low < 1/ km^2

Type of Water Use: Commercial and Industrial

Reliance on Source: Not known

Conflicts between Users: None reported in well records

Quantity Concerns: none reported

Quality Concerns: none reported

Comments: Even though only 2 wells, on file with the Ministry, have been constructed in this aquifer, this aquifer was classified because of its high productivity and its proximity to the Fort Nelson River. The geometric mean depth of water wells in this aquifer is 19.90 metres (65.3 feet). The median depth of wells is 20.42 metres (67.0 feet) and the range of well depths is from 15.85 to 24.99 metres (52 to 82 feet).

References:

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AQUIFER CLASSIFICATION AND RANKING

AQUIFER LOCATION: North side of Fort Nelson River, 7km SE of Fort Nelson.

AQUIFER REFERENCE NUMBER: 1041

AQUIFER SUB-TYPE: 1b; aquifers found along rivers of moderate stream order with the potential to be hydraulically influenced by the river.

AQUIFER PIORITY RATING FOR OBSERVATION WELLS: 22.1

CLASSIFICATION: III A **RANKING VALUE: 9**

Classification Component:

Level of Development: Light, *Low* level of demand in relationship to *high* level of aquifer productivity and water availability.

Level of Vulnerability: High, *High* level of vulnerability to surface contamination

Ranking Component:	Ranking Value
Productivity:	3
Vulnerability:	3
Size:	1
Demand*:	1
Type of Use:	1
Quality Concerns:	0
Quantity Concerns:	0
Total:	**9**

** Demand has been assessed subjectively. Demand is based on domestic well density as well as general knowledge of well use and land use in the area. Demand assumes that the reported well capacity is the amount of water used, which can be misleading. The reported well capacity is often higher than actual use.*

Number of water wells available for aquifer delineation = 2

Statistical Summary of Well Data for Aquifer # 1041

	Well Depth		Depth to Water		Depth to Bedrock		Reported Est. Well Yield		Est. Thickness of Confining Materials	
Number of Wells	2	2	2	2	0	0	2	2	1	1
	m	ft	m	ft	m	ft	L/s	USgpm	m	ft
Minimum	15.85	52	5.18	17			9.463	150	1.22	4
Maximum	24.99	82	5.49	18			9.463	150	1.22	4
Median	20.42	67.0	5.33	17.5			9.463	150.0	1.22	4.0
Arithmetic Mean	20.42	67.0	5.33	17.5			9.463	150.0	1.22	4.0
Geometric Mean	19.90	65.3	5.33	17.5			9.463	150.0	1.22	4.0

A.3 Aquifer Classification Work Sheet for Aquifer 1040 - Type 4b, Confined Glacial and Pre-Glacial Aquifer

DATE: October 22, 2013

AQUIFER MAPPER: A. P. Kohut

AQUIFER REFERENCE NUMBER: 1040

DESCRIPTIVE LOCATION OF AQUIFER: Industrial area 6 km south of Fort Nelson.

NTS MAP SHEET: 94J15

BCGS MAP SHEET: 94J077

CLASSIFICATION: **III C** **RANKING: 11**

Aquifer Size: 5.6 km^2

Aquifer Boundaries: The aquifer boundary has been delineated using spatially limited water well record information and based on the area of development. There are 3 other wells identified in a map diagram found in Hall (1971) that provided enough data to extend the boundary of this aquifer. There was not however, any data on well yield or depth to water. These wells could be added to the WELLs database.

Aquifer Sub-type: 4b; confined sand and gravel aquifer underneath glaciolacustrine clays and some tills.

Aquifer Priority Rating for Observation Wells: 26.4

Geologic Formation (overlying materials): Clay, silty clays, tills

Geologic Formation (aquifer): Glaciofluvial gravels and sands

Confined/Partially Confined/Unconfined: Confined

Vulnerability: Low. Extensive, low permeability clays, silty clays and tills overlie this unconsolidated aquifer. Confining sediments ranging in thickness from 112.47 to 124.97 metres (369 to 410 ft); with a geometric mean of 118.57 metres (389.0 ft).

Productivity: High. Reported yields range from 1.262 to 9.463 L/s (20 to 150 gpm); with a geometric mean of 3.350 L/s (53.1 gpm). Pump tests were reported for two wells. Specific capacity ranged from 4 to 7.4 US gal/ft of drawdown (13 to 24 US gal/ft of drawdown). T values were reported to range from 1.1×10^5 to 2.2×10^5 US gpd per ft width of aquifer (Erdman, 1971; Livingston, 1974).

Depth to Water: Ranges from 30.48 to 100.58 metres (100 to 330 ft); with a geometric mean of 59.01 metres (193.6 ft).

Direction of Groundwater Flow: Not determined.

Recharge: Precipitation, snowmelt and local surface water runoff in relevant seasons.

Domestic Well Density: Low < 1/ km^2

Type of Water Use: Domestic and commercial

Reliance on Source: This is likely the predominant drinking water supply where water quality is potable or treatable. There are some shallower productive (up to 7.3 L/s) aquifers (< 30 metres from ground surface) overlying this deeper confined aquifer

Conflicts between Users: None reported in well records

Quantity Concerns: One well, was completed in a minor aquifer and was reported to run dry after an 8-hr. pumping test. It was not known what the pumping rate was.

Quality Concerns: Water quality is a calcium magnesium bicarbonate type hard water but potable, though phosphate and TDS were close to the maximum recommended for drinking water. In a few wells, the presence of both methane and high Fe have also been reported. Being an industrial area with an extensive railway yard, the potential for contamination of the upper aquifer is also a possibility.

Comments: Both this aquifer and the upper aquifer have the potential to be further developed. The geometric mean depth of water wells in this aquifer is 121.19 metres (397.6 feet). The median depth of wells is 129.54 metres (425.0 feet) and the range of well depths is from 99.06 to 138.68 metres (325 to 455 feet). The statistics quoted for this aquifer are based on only 2 to 3 water-well records.

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AQUIFER CLASSIFICATION AND RANKING

AQUIFER LOCATION: Industrial area 6 km south of Fort Nelson.

AQUIFER REFERENCE NUMBER: 1040

AQUIFER SUB-TYPE: 4b; confined sand and gravel aquifer underneath glaciolacustrine clays and some tills.

AQUIFER PIORITY RATING FOR OBSERVATION WELLS: 26.4

CLASSIFICATION: III C **RANKING VALUE: 11**

Classification Component:

Level of Development: Light, *Low* level of demand in relationship to *moderate* level of aquifer productivity and water availability.

Level of Vulnerability: Low, *Low* level of vulnerability to surface contamination

Ranking Component:	Ranking Value
Productivity:	3
Vulnerability:	1
Size:	2
Demand*:	1
Type of Use:	3
Quality Concerns:	1
Quantity Concerns:	0
Total:	**11**

** Demand has been assessed subjectively. Demand is based on domestic well density as well as general knowledge of well use and land use in the area. Demand assumes that the reported well capacity is the amount of water used, which can be misleading. The reported well capacity is often higher than actual use.*

Number of water wells available for aquifer delineation = 3

Statistical Summary of Well Data for Aquifer # 1040

	Well Depth		Depth to Water		Depth to Bedrock		Reported Est. Well Yield		Est. Thickness of Confining Materials	
Number of Wells	3	3	3	3	0	0	3	3	2	2
	m	ft	m	ft	m	ft	L/s	USgpm	m	ft
Minimum	99.06	325	30.48	100			1.262	20	112.47	369
Maximum	138.68	455	100.58	330			9.463	150	124.97	410
Median	129.54	425.0	67.06	220.0			3.154	50.0	118.72	389.5
Arithmetic Mean	122.44	401.7	66.05	216.7			4.624	73.3	118.72	389.5
Geometric Mean	121.19	397.6	59.01	193.6			3.350	53.1	118.57	389.0

A.4 Aquifer Classification Work Sheet for Aquifer 1035 - Type 4b, Confined Glacialfluvial and Pre-Glacial Aquifers

DATE: October 12, 2013

AQUIFER MAPPER: A. P. Kohut

AQUIFER REFERENCE NUMBER: 1035

DESCRIPTIVE LOCATION OF AQUIFER: East side of Fort Nelson River, just north of confluence with the Muskwa River.

NTS MAP SHEET: 94J15

BCGS MAP SHEET: 94J088

CLASSIFICATION: III B RANKING: 10

Aquifer Size: 4.5 km^2

Aquifer Boundaries: The aquifer boundary has been delineated using spatially limited water well record information, topography and drainage features. The aquifer is bounded in part by the west bank of the Fort Nelson River. Assuming all the well locations are accurate, the aquifer currently extends under the river.

Aquifer Sub-type: 4b; confined sand and gravel aquifer underneath till, in between till layers, or underlying glaciolacustrine deposits, or other confining low permeability deposits.

Aquifer Priority Rating for Observation Wells: 29.9

Geologic Formation (overlying materials): Silts, tills, clay and silty clays

Geologic Formation (aquifer): Likely fluvial and some glaciofluvial sands, gravel and sands and gravel.

Confined/Partially Confined/Unconfined: Confined

Vulnerability: Moderate. Normally this aquifer would be defined as low vulnerability based on the lithology reported in the well logs. Low permeable silts, clays and tills overlie this unconsolidated aquifer; ranging in thickness from 5.49 to 68.58 metres (18 to 225 ft); with a geometric mean of 11.73

metres (38.5 ft). However, it appears that 3 of the wells completed in this aquifer are shown located within the Muskwa River channel or possibly on an island. It is not known if, any or all, of the previous 5.49 to 9.14 metres (18 to 30 ft) of confining materials in these wells have been removed? It is also not known if these 3 wells were properly abandoned before being inundated or whether they have been floodproofed? It is recommended that the vulnerability designation remains moderate until these questions have been addressed by ground truthing.

Productivity: Moderate. Reported yields range from 2.208 to 3.785 L/s (35 to 60 gpm); with a geometric mean of 2.870 L/s (45.5 gpm). Larger diameter wells could see the aquifer productivity designation changed to high.

Depth to Water: Ranges from 7.92 to 20.42 metres (26 to 67 ft); with a geometric mean of 10.70 metres (35.1 ft).

Direction of Groundwater Flow: Not determined, likely downgradient towards the northeast.

Recharge: Precipitation, snowmelt, local surface water runoff and recharge from the Fort Nelson and Muskwa rivers.

Domestic Well Density: Low, approx. 1 well/km^2

Type of Water Use: Domestic and commercial

Reliance on Source: Likely the predominant drinking water supply where water quality is potable or treatable.

Conflicts between Users: None reported in well records

Quantity Concerns: None reported.

Quality Concerns: No documented quality concerns have been found by the mapper. However, as 3 of the 5 wells constructed in this aquifer appear now to be underwater or situated on an island, it is possible that these wells have been abandoned or floodproofed.

Comments: The geometric mean depth of water wells in this aquifer is 22.77 metres (74.7 feet). The median depth of wells is 18.29 metres (60.0 feet) and the range of well depths is from 10.67 to 72.54 metres (35 to 238 feet). The statistics quoted for this aquifer are based on 3 to 5 water-well records.

References:

Berardinucci, J. and K. Ronneseth. 2002. *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater*. Water, Air and Climate Change Branch. BC Ministry of Water, Land and Air Protection. Victoria, B.C., 54 pp.

Ministry of Environment. 2013. *Fort Nelson Groundwater Investigation Data*. NTS File # 38000 - 40/094J/15-04. Victoria, British Columbia.

Thomas, J.F.J. 1959. *A Survey of Water Quality at Camp Muskwa, Fort Nelson, BC.* Mines Branch Investigations Report IR60-41. Ministry of Environment, NTS File # 38000 - 40/094J/15-01. 27p.

AQUIFER CLASSIFICATION AND RANKING

AQUIFER LOCATION: East side of Fort Nelson River, just north of confluence with the Muskwa River.

AQUIFER REFERENCE NUMBER: 1035

AQUIFER SUB-TYPE: 4b, confined sand and gravel aquifer underneath till, in between till layers, or underlying glaciolacustrine deposits.

AQUIFER PIORITY RATING FOR OBSERVATION WELLS: 29.9

CLASSIFICATION: III B **RANKING VALUE: 10**

Classification Component:

Level of Development: Light, *Low* level of demand in relationship to *moderate* level of aquifer productivity and water availability.

Level of Vulnerability: Moderate: *Moderate* level of vulnerability to surface contamination

Ranking Component:	Ranking Value
Productivity:	2
Vulnerability:	2
Size:	1
Demand*:	1
Type of Use:	2
Quality Concerns:	2
Quantity Concerns:	0
Total:	**10**

** Demand has been assessed subjectively. Demand is based on domestic well density as well as general knowledge of well use and land use in the area. Demand assumes that the reported well capacity is the amount of water used, which can be misleading. The reported well capacity is often higher than actual use.*

Number of water wells available for aquifer delineation = 5

Statistical Summary of Well Data for Aquifer # 1035

	Well Depth		Depth to Water		Depth to Bedrock		Reported Est. Well Yield		Est. Thickness of Confining Materials	
Number of Wells	5	5	4	4	0	0	3	3	4	4
	m	ft	m	ft	m	ft	L/s	USgpm	m	ft
Minimum	10.67	35	7.92	26			2.208	35	5.49	18
Maximum	72.54	238	20.42	67			3.785	60	68.58	225
Median	18.29	60.0	8.99	29.5			2.839	45.0	7.32	24.0
Arithmetic Mean	28.71	94.2	11.61	38.1			2.946	46.7	22.19	72.8
Geometric Mean	22.77	74.7	10.70	35.1			2.870	45.5	11.73	38.5

A.5 Stratigraphic Descriptions by Huntley et al. (2017) for Map Sheet 940

One of the few subsurface representations north of Fort Nelson (map sheet 94O), was produced by Huntley et al. (2017). This work consists of a series of section descriptions along the Petitot and Fort Nelson Rivers (Figure A3 to Figure A6), which primarily represent the stratigraphy of this area consisting of Late Wisconsinan, Laurentide till directly over bedrock (shale, siltstone and sandstone of the Fort St. John Group), followed by 3 to 260 feet of post-glacial, interbedded, silt, sand and gravel, topped with thin, discontinuous eolian fine sand and silt. The one exception to this sequence is found in Emile Creek (HRB044), where the Late Wisconsinan Laurentide till is underlain by Late Wisconsinan or pre-Late Wisconsinan glaciofluvial and glaciolacustrine sediment, similar to the upper four units of Trommelen and Levson (2008) (Figure A7).

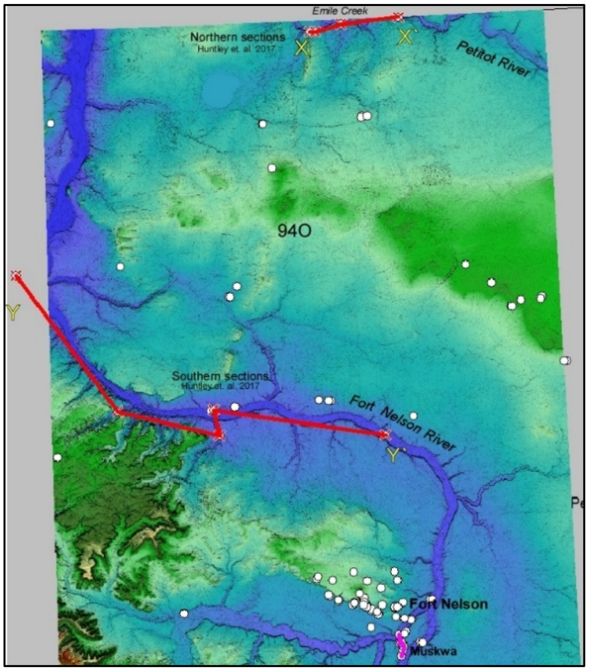

Figure A3: Location of northern and southern 94O Quaternary sections by Huntley et al. (2017).

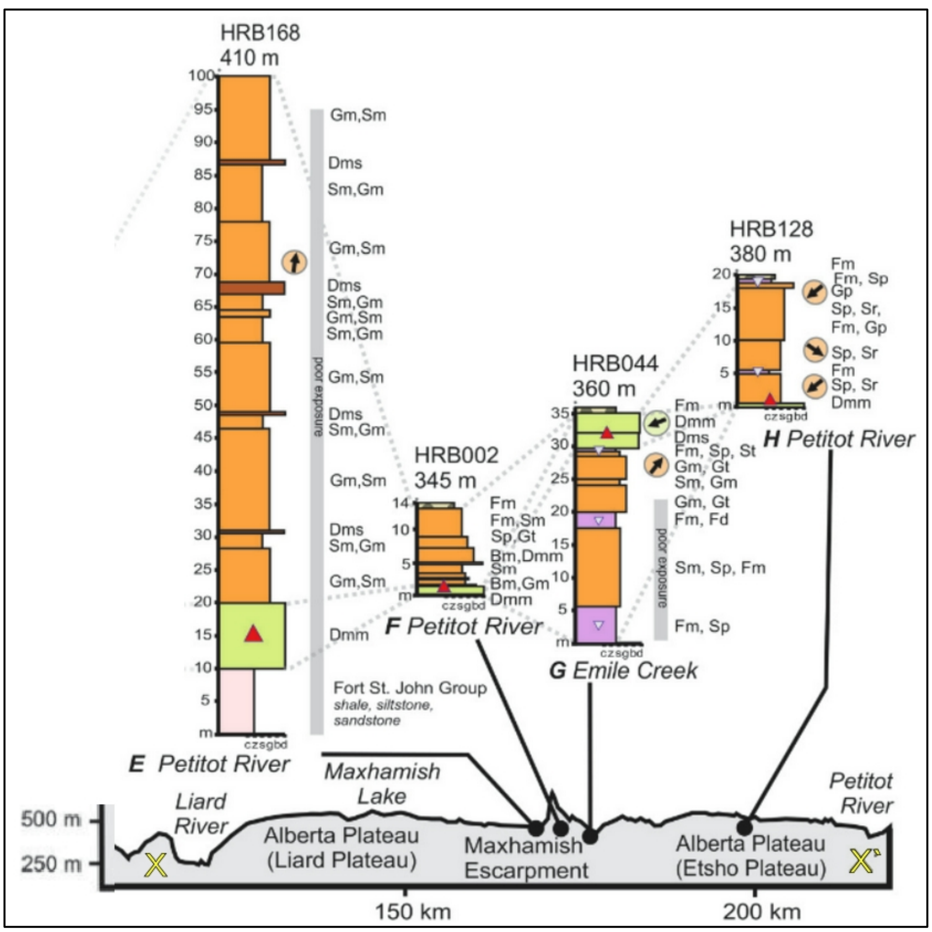

Figure A4: Quaternary stratigraphy of the northern half of 94O (Huntley et al., 2017).

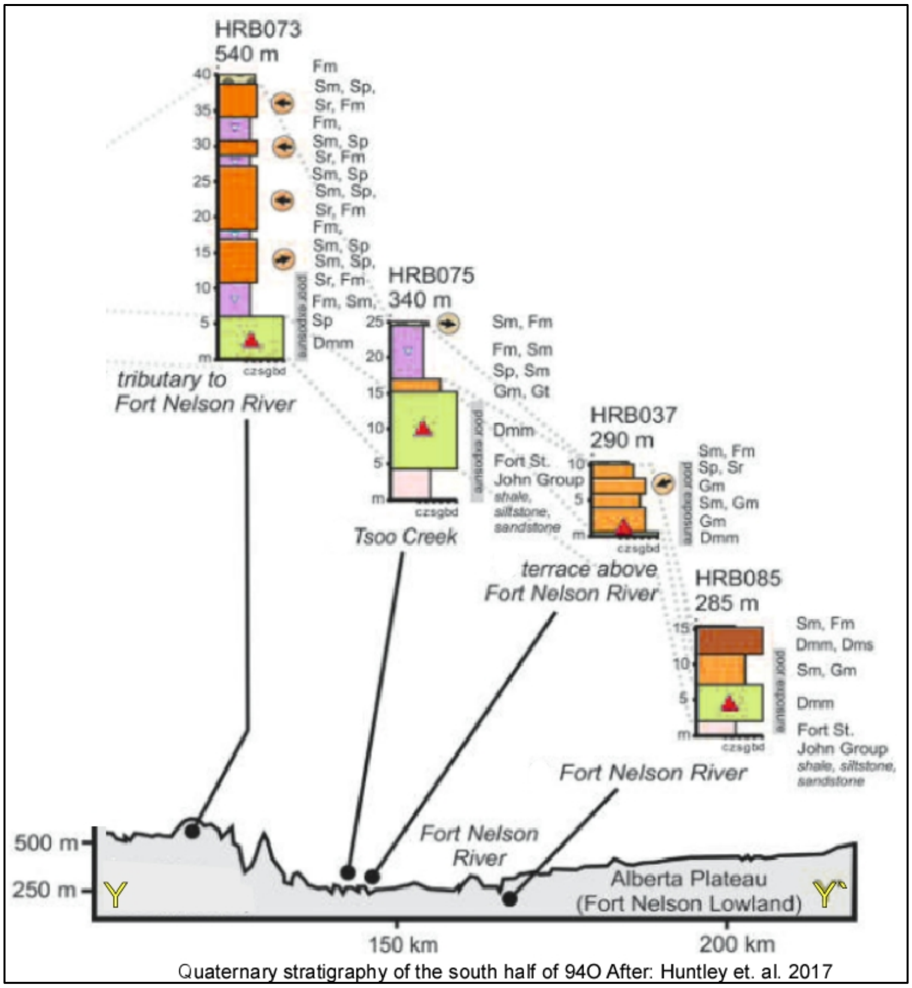

Figure A5: Quaternary stratigraphy of the southern half of 94O (Huntley et al., 2017).

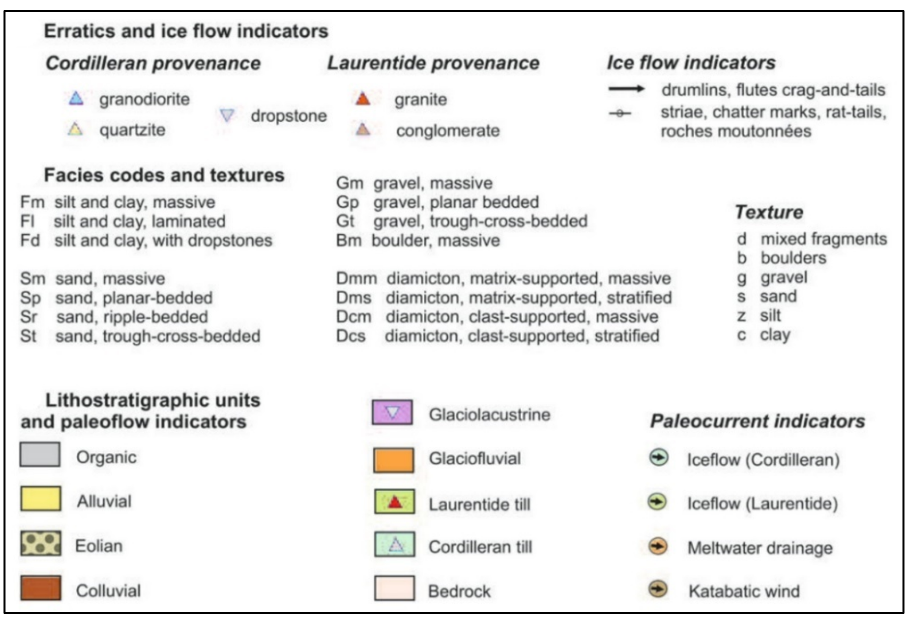

Figure A6: Legend for the Quaternary stratigraphic work in 94O (Huntley et al., 2017).

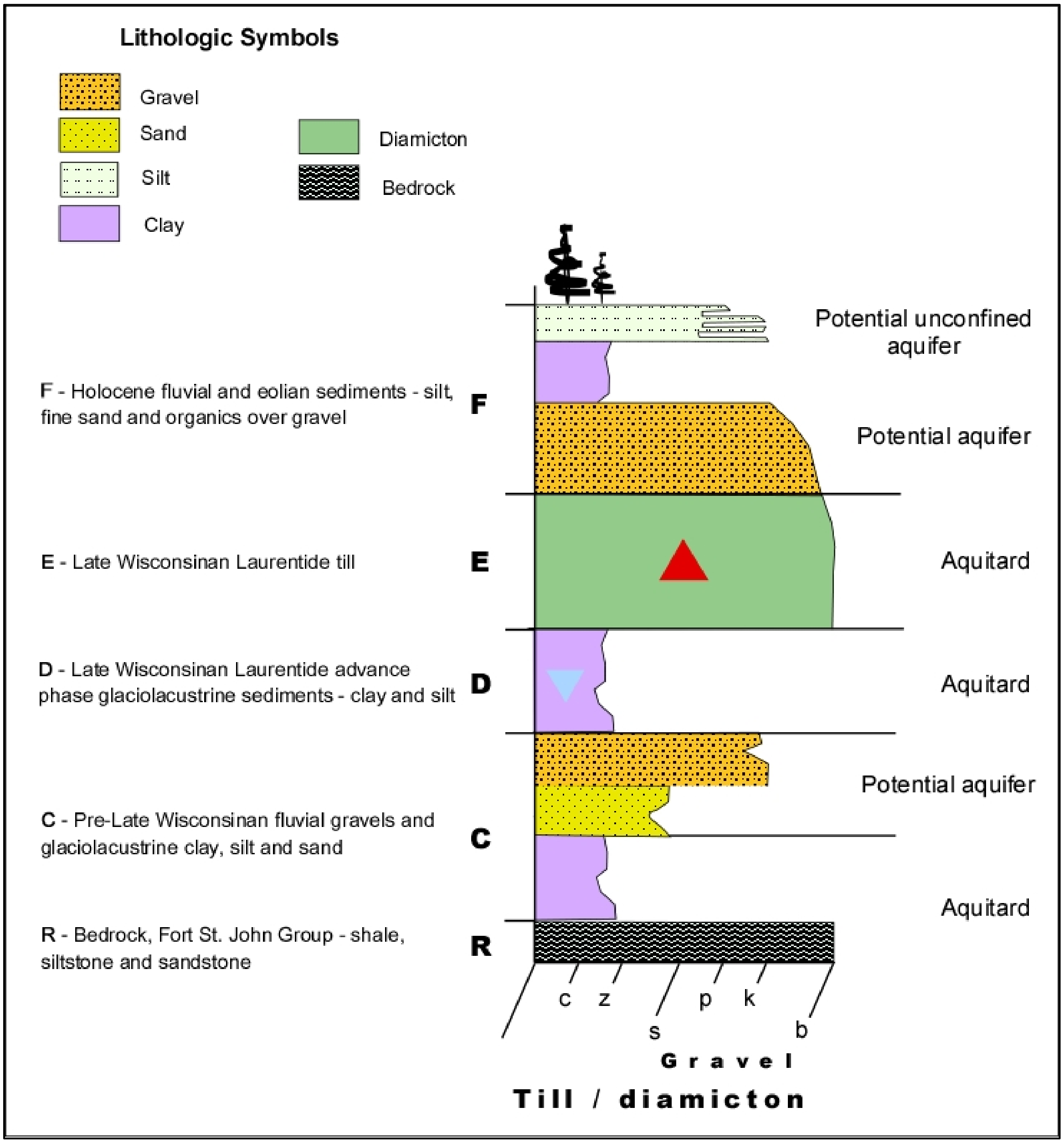

Figure A7: Composite stratigraphic section for Map Sheet 94O (After Huntley et al. 2017).

References in Section A.5

BC Wells database, November 18, 2017. https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp

Huntley, D.H., Hickin, A.S., Lian, O.B., 2017. The pattern and style of deglaciation at the Late Wisconsinan Laurentide and Cordilleran ice sheet limits in northeastern British Columbia.

A.6 Prophet River Stratigraphy by Trommelen and Levson (2008)

Based on the Quaternary section descriptions of Trommelen (2006) and Trommelen and Levson (2008), conducted along the Prophet River about 20 km southwest of Fort Nelson (Figure A8), a relatively simple Quaternary stratigraphy has been identified for the Prophet River and potentially all of the Fort Nelson Lowlands. The section work starts approximately 10 km south of the confluence of the Prophet and Muskwa Rivers and extends southward some 58 kilometers along the Prophet River valley to within 20 km of the southern edge of the project area (94J). The 13 sections combine to create the dated and correlated cross section drawn from south to north in Figure A9.

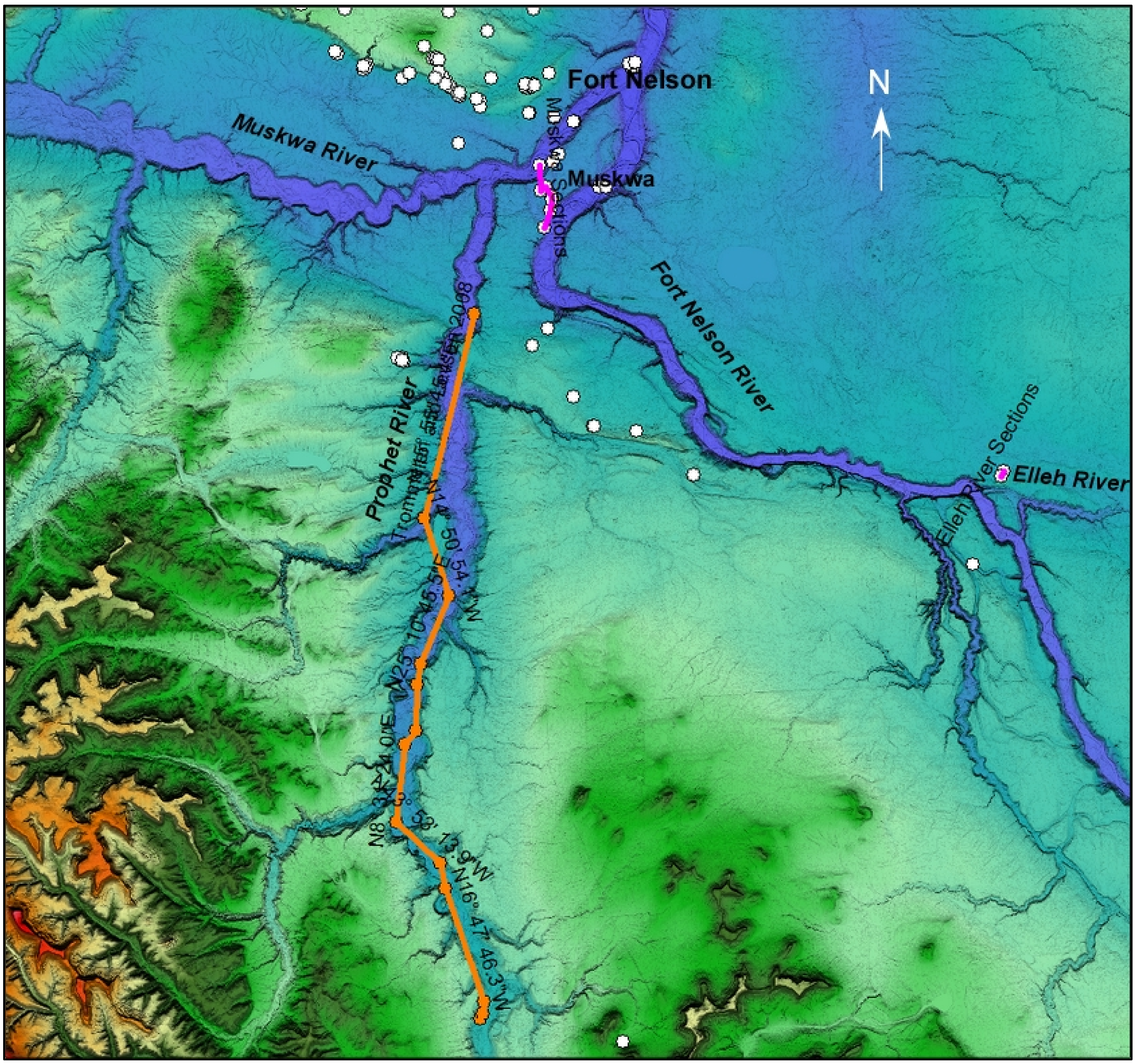

Figure A8: Location of the Prophet River sections.

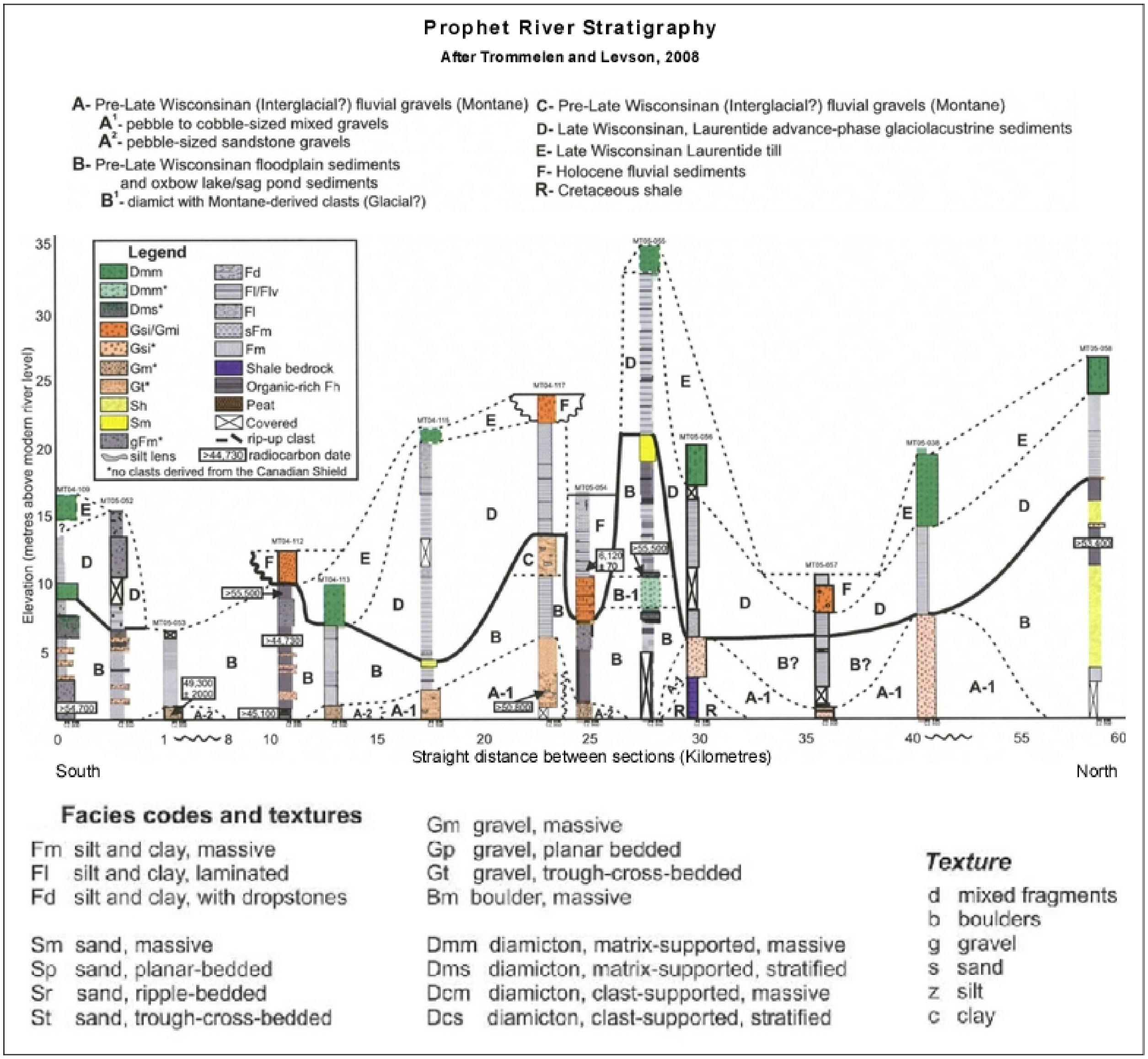

Figure A9: Prophet River sections after Trommelen and Levson (2008).

Though insufficient well data exists to link various aquifers to stratigraphic units, the composite stratigraphy (Figure A.10) for the valley gives some idea of the potential aquifers in the study area.

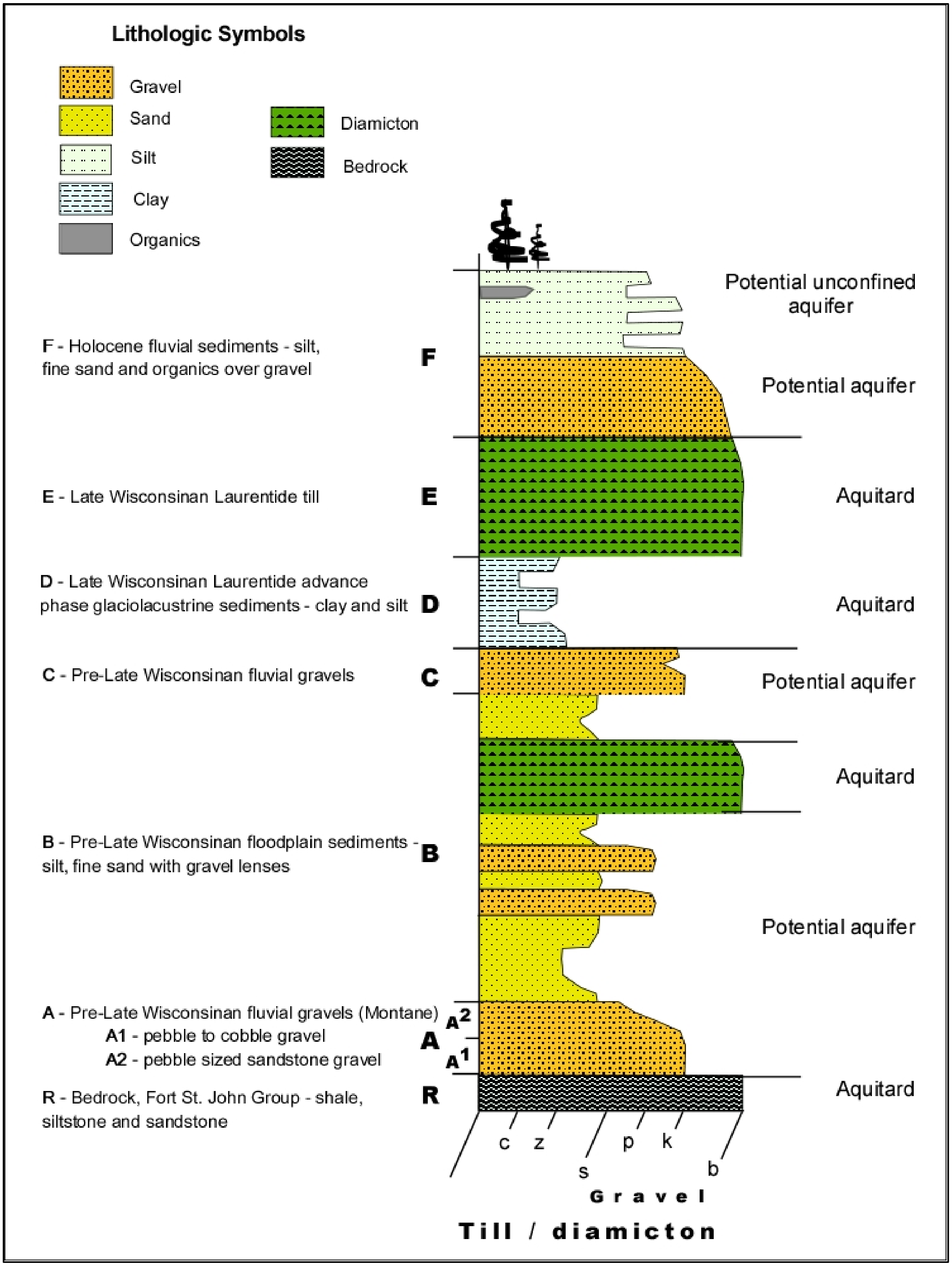

Figure A10: Composite stratigraphic section of the Prophet River valley showing potential aquifers (After Trommelen and Levson, 2008).

A.7 Aquifer Classification Work Sheet for Aquifer 1034 - Type 5a, Confined Sedimentary Bedrock Aquifer

DATE: October 11, 2013

AQUIFER MAPPER: A. P. Kohut

AQUIFER REFERENCE NUMBER: 1034

DESCRIPTIVE LOCATION OF AQUIFER: Highland area north of Fort Nelson.

NTS MAP SHEET: 94J14 and J15

BCGS MAP SHEET: 94J085, 086, 087, 096 and 94J087

CLASSIFICATION: III C **RANKING: 9**

Aquifer Size: 130 km^2

Aquifer Boundaries: The aquifer boundary has been delineated using spatially limited water well record information, topography and drainage features.

Aquifer Sub-type: 5a; fractured sedimentary rock aquifers, primarily found in association with old sedimentary basins.

Aquifer Priority Rating for Observation Wells: 30.9

Geologic Formation (overlying materials): Tills, clay with gravel (likely till), lacustrine clays, silts and minor sands and gravels

Geologic Formation (aquifer): Cretaceous mudstone, siltstone, shale, minor sandstone (reported in drill logs) fine-grained clastic sedimentary rocks of the Fort St. John Group or Smokey Group

Confined/Partially Confined/Unconfined: Confined

Vulnerability: Low. Low permeability clays and tills overlie this bedrock aquifer; ranging in thickness from 2.44 to 64.62 metres (8 to 212 ft); with a geometric mean of 8.60 metres (28.2 ft). Only one well record (NE area of aquifer) reported 1.52 m (5 ft) of low permeability materials over the aquifer.

Productivity: Low. Reported yields range from 0.158 to 3.785 L/s (0.25 to 60 gpm); with a geometric mean of 0.265 L/s (4.2 gpm).

Depth to Water: Ranges from 3.54 to 44.50 metres (11.6 to 146 ft); with a geometric mean of 14.30 metres (46.9 ft).

Direction of Groundwater Flow: Not determined. Likely reflects the general topography.

Recharge: Precipitation, snowmelt and local surface water runoff in relevant seasons.

Domestic Well Density: Low (3.4 wells /km^2)

Type of Water Use: Domestic

Reliance on Source: Likely the predominant drinking water supply where water quality is potable or treatable.

Conflicts between Users: None reported in well records

Quantity Concerns: A few wells were reported dry for the depths the wells were constructed.

Quality Concerns: Some well records reported high iron (up to 10 mg/l) and a sulphur smell. TDS was reported over 1000 mg/L in a few of the well records. One well reported the water to be unsuitable as a drinking water source.

Comments: The geometric mean depth of water wells in this aquifer is 57.18 metres (187.6 feet). The median depth of wells is 57.15 metres (187.5 feet) and the range of well depths is from 22.86 to 143.26 metres (75 to 470 feet).

The statistics quoted for this aquifer are based on 34 to 38 water-well records.

In the 1950's, east of aquifer 1034 at the airport, 3 wells were drilled by the US Army Engineers (Ministry of Environment, 2013), to depths of 158.80, 442.26 and 215.19 m (521, 1451 and 706 ft). These wells are not in the province's WELLs database and their exact location is not known.

Unconsolidated materials are fairly thick in this area. Bedrock was encountered at 219.46 m (720 ft) in the deeper borehole. This is likely a paleovalley as rounded pebbles were identified at depth overlying the bedrock. The first hole encountered gas (primarily methane) and was abandoned. The second well encountered a lot of gas in sandstone at 307.85 m (1010 ft). Aquifers in both the 2nd and 3rd wells were found and developed at 192.02 and 201.17 m (630 and 660 ft) respectively. If the location of these wells can be identified, then possibly a deeper aquifer could be developed in this area.

There is also evidence of shallower sand and gravel deposits above, within and underling the lacustrine clays and tills found in the valley on both sides of the river. During the 1950s there were hundreds of seismic survey shot holes drilled in the region to depths of 46 m (average 18 m) where the stratigraphy was logged. If this data could be accessed and reviewed, it is possible smaller local aquifers could be identified and mapped.

Water quality is often noted as a concern. Thomas (1959) reported a water quality study by the army in 1959-60 at the Muskwa River army camp. In the camp well, Fe levels ranged from 35ppm to as high as 85ppm. It is not known if this camp well is on file in the WELLs database.

References:

Berardinucci, J. and K. Ronneseth. 2002. *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater*. Water, Air and Climate Change Branch. BC Ministry of Water, Land and Air Protection. Victoria, B.C., 54 pp.

Massey, N.W.D., MacIntyre, D.G., Okulitch, A.V., Desjardins, P.J., and R.T. Cooney. 2013. Digital Geology Map of British Columbia: Tile NO10 Northeast B.C., B.C. Ministry of Energy and Mines, GeoFile 2005-10. Geology coverage found at *BC Water Resources Atlas*, Ministry of Environment website: http://www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html

Ministry of Environment. 2013. *Fort Nelson Groundwater Investigation Data*. NTS File # 38000 - 40/094J/15-04. Victoria, British Columbia.

Thomas, J.F.J. 1959. *A Survey of Water Quality at Camp Muskwa, Fort Nelson, BC.* Mines Branch Investigations Report IR60-41. Ministry of Environment, NTS File # 38000 - 40/094J/15-01. 27p.

AQUIFER CLASSIFICATION AND RANKING

AQUIFER LOCATION: Highland area North of Fort Nelson.

AQUIFER REFERENCE NUMBER: 1034

AQUIFER SUB-TYPE: 5a; fractured sedimentary rock aquifers, primarily found in association with old sedimentary basins.

AQUIFER PIORITY RATING FOR OBSERVATION WELLS: 30.9

CLASSIFICATION: **III C** **RANKING VALUE:** **9**

Classification Component:

Level of Development: Light, *Low* level of demand in relationship to *low* level of aquifer productivity and water availability.

Level of Vulnerability: Low, *Low* level of vulnerability to surface contamination

Ranking Component:	Ranking Value
Productivity:	1
Vulnerability:	1
Size:	3
Demand*:	1
Type of Use:	2
Quality Concerns:	1
Quantity Concerns:	0
Total:	**9**

** Demand has been assessed subjectively. Demand is based on domestic well density as well as general knowledge of well use and land use in the area. Demand assumes that the reported well capacity is the amount of water used, which can be misleading. The reported well capacity is often higher than actual use.*

Number of water wells available for aquifer delineation = 38

Statistical Summary of Well Data for Aquifer # 1040

	Well Depth		Depth to Water		Depth to Bedrock		Reported Est. Well Yield		Est. Thickness of Confining Materials	
Number of Wells	38	38	35	35	34	34	37	37	35	35
	m	ft	m	ft	m	ft	L/s	USgpm	m	ft
Minimum	22.86	75	3.54	11.6	1.5	5	0.158	0.25	2.44	8
Maximum	143.26	470	44.50	146	71.9	236	3.785	60	64.62	212
Median	57.15	187.5	14.39	47.2	6.9	22.5	0.252	4.0	6.10	20.0
Arithmetic Mean	65.14	213.7	17.01	55.8	16.7	54.7	0.524	8.3	13.56	44.5
Geometric Mean	57.18	187.6	14.30	46.9	9.60	31.5	0.265	4.2	8.60	28.2

APPENDIX B. BEDROCK GEOLOGIC INFORMATION

This appendix is provided as a separate attachment in an Excel file format.