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Peace River Regional District Physical Hydrogeology Database & 3D Model

Prepared for:

Peace River Regional District and Treaty 8 Tribal Association

Prepared by:

GW Solutions Inc.

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GW Solutions Inc.
201 – 5180 Dublin Way, Nanaimo, BC, V9T 0H2
Tel. (250) 756-4538 gw@gwsolutions.ca

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A. Glossary

AQUIFER	An underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand) from which groundwater can be extracted using a water well. (See also confined aquifers and unconfined aquifers.). Aquifers can be interconnected to other aquifers and surface water and can be present at various depths.
AQUITARD	An aquitard is a zone in the ground or bedrock that restricts the flow of groundwater from one aquifer to another, or from the surface to the subsurface. Aquitards are usually comprised of silt, clay, or non-porous rock of low hydraulic conductivity.
AQUICLUDE	A zone in the subsurface that prevents the movement of groundwater. An aquiclude is synonymous with a material being impervious to the flow of water. A thick layer of clay is an aquiclude.
BEDROCK	Solid rock underlying surficial deposits such as soil, alluvium or other unconsolidated material.
CONFINED AQUIFER	A confined aquifer is a fully saturated layer of permeable material that has a "confining" layer of low permeability material (aquitard or aquiclude) above it. The low permeability confining layer causes the aquifer to be under pressure so that when the aquifer is penetrated by a well, the water will rise above the top of the aquifer.
FLUVIAL DEPOSITS	Units of granular particles (silt, sand and gravel) deposited by a river.
FRACTURED BEDROCK AQUIFER	In solid rock (i.e. bedrock), groundwater is stored in the fractures, joints, bedding planes and cavities of the rock mass. Despite the potential for having voids (known as porosity), a rock can only act as an aquifer if those voids are saturated and connected via conduits such as fractures.
GEOGRAPHIC INFORMATION SYSTEM (GIS)	A geographical information system (GIS) is a software system designed to capture, store, manipulate, analyze, manage, and present spatial or geographical data.

GEOVOLUMES	Three-dimensional (3D) representations of geological or hydrogeological features. These are interpolated in 3D modelling software.
GLACIO-FLUVIAL DEPOSITS	Deposits of granular material left by glacial meltwater streams.
GLACIOLACUSTRINE	Deposits of mostly fine-grained material (silt, clay), deposited under water in lakes resulting from the melting of glaciers. Thick, glaciolacustrine deposits in the Peace River region were formed by repeated inundation by large, ice-dammed meltwater lakes.
GROUNDWATER	Groundwater is water found in the soil or rock below the surface where the pores and openings are filled with water.
HYDRAULIC CONDUCTIVITY	Hydraulic conductivity defines the capacity of a medium to transmit water.
HYDRAULIC GRADIENT	The hydraulic gradient is represented by the slope of the water table or the piezometer surface.
HYDROGEOLOGICAL GROUP	The hydrogeological group (HGG) represents the two dominant groundwater flow regimes and aquifer types: 1) flow through porous media in surficial aquifers, and 2) flow through fractured media in bedrock aquifers.
HYDROGEOLOGICAL UNIT	Hydrogeological units (HGU) represent one or more Material Classes that have similar hydrogeological characteristics and behaviors. These units are created by aggregating materials based on our understanding of hydrogeology and by assigning named aquifers directly to the borehole intervals.
HYDROGEOLOGY	The science of groundwater.
IMPERMEABLE	Impervious to flow of fluids.

INTERMEDIATE ZONE	Zone in the subsurface from approximately 500 m to 2 km. It contains fluids (water and gas). In the intermediate zone, the groundwater becomes more saline with depth as it is increasingly isolated from recharge by precipitation. Also, it has resided for a long period of time within the aquifer rock and will have dissolved various salts and minerals within the rock.
MARINE DEPOSITS	Sand, silt, and clay materials deposited under a marine environment.
MATERIAL CLASS	Material Classes are soil or bedrock types that are used to define as objectively as possible the information provided by drillers logs. They are used as an intermediate step to group or correlate geological information at the location of one well or a group of wells in the same area in order to estimate the geometry of aquifers, aquitards, and aquicludes.
OVERBURDEN	The layer of granular and unconsolidated material including soil, silt, sand and gravel overlying bedrock, which has been either transported from elsewhere or formed in place. Also referred to as surficial deposits.
PERMEABILITY	The property describing the capacity of a medium to transmit a fluid.
PIEZOMETRIC LEVEL	The elevation reached by water in a non-pumping water well completed in a confined aquifer. It also corresponds to the water table in unconfined aquifers.
PIEZOMETRIC SURFACE	A piezometric surface is the theoretical water elevation of all points in a pressurized, or confined aquifer. The surface can be interpolated from piezometric level point data using computer algorithms and the resultant surface can be contoured. Hydraulic gradients can be inferred from the resultant piezometric contours.
POROSITY	The volume of voids in a rock, sediment or soil. Porosity can be expressed as the ratio of the volume of voids in the medium to its total volume.
SALINITY	Salinity describes the concentration of salts in water. For groundwater in the intermediate zone, it can range from brackish up to 200,000 mg/l or more (for reference seawater is about 35,000 mg/l).

SATURATED ZONE	The subsurface zone in which all voids are filled by groundwater.
SEDIMENTARY ROCKS	Rocks formed from consolidation of loose sediments such as clay, silt, sand, and gravel.
SHALE	A fine-grained sedimentary rock, formed by the consolidation of clay, silt, or mud.
SHALLOW GROUNDWATER	Shallow groundwater is groundwater accessed from shallow surficial or bedrock aquifers, typically up to 300 m deep. Shallow groundwater has typically travelled for short periods of times (years, decades) in the subsurface and typically contains low concentrations of salts and other elements (e.g., metals).
STATIC WATER LEVEL (or STATIC LEVEL)	The level of water in a well that is not being influenced by groundwater withdrawals (e.g., pumping). The distance to water in a well is measured with respect to some datum, usually the top of the well casing or ground level.
SURFACE WATER	Surface water is water that can be seen on land. It includes lakes, rivers, streams, creek, ponds, wetlands. It is usually freshwater.
SURFICIAL DEPOSITS	Soil deposits overlying bedrock and consisting of clay, silt, sand, and gravel.
TILL	Till consists of a mixture of clay, silt, sand, gravel and boulders. Till is associated with glacial deposits.
TOTAL DISSOLVED SOLIDS (TDS)	Concentration of total dissolved solids (TDS) in groundwater expressed in milligrams per litre (mg/L), is found by evaporating a measured volume of filtered water sample to dryness and weighing this dry solid residue.
TRANSMISSIVITY	Rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

UNCONFINED AQUIFER	The saturated portion of a permeable soil or fractured bedrock medium where the water table is at a lower elevation that the top of the medium.
UNCONSOLIDATED DEPOSITS	Soil deposits that have not been subject to the pressure of the ice from glacial eras.
WATERSHED	A Watershed is the area of land that, due to its topography, collects water from precipitation and drains into a receiving surface water body (a river, a lake, a foreshore). Every piece of land is part of a watershed.
WATER CYCLE	The water cycle (also called the hydrologic cycle) is the cycle by which water circulates between the earth's oceans, atmosphere and land, involving precipitation as rain and snow, drainage in streams and rivers to the ocean, infiltration in the ground and flow in the subsurface as groundwater, and return to the atmosphere by evaporation and transpiration. Water is in continuous movement on earth, even at great depth in the subsurface. Sometimes, it moves fast (e.g., river), sometimes extremely slowly (e.g. in clay), but it always moves.
WATER TABLE	The surface corresponding to the top of the zone where all the voids in an aquifer are saturated with groundwater. It applies to unconfined aquifers. The depth to water in a non-pumping well completed in an unconfined aquifer will be the depth to the water table.
WELL SCREEN	Part of a water well where groundwater from the aquifer enters the well. It provides mechanical stability by preventing fine particles from entering the well. It should also offer enough opened area to allow groundwater to flow as freely as possible into the well.
WELL YIELD	The rate of groundwater that can be produced by a well.

B. Background

GW Solutions was retained to build a water quality baseline for both surface water and groundwater. This project was funded by the Real State Foundation of British Columbia (REFBC), the Peace River Regional District (PRRD), the Treaty 8 Tribal Association (T8TA), and with in-kind participation of GW Solutions Inc., and Interraplan Inc.

1 Main objectives

One of the primary objectives of this work was to build a regional database for all physical hydrogeological data and water quality data across the PRRD. The database enables storage and retrieval of spatial information (e.g. well locations and water quality monitoring points) and time-series data (e.g. laboratory results over time). The physical hydrogeology component pertains to the wells, aquifers, groundwater elevation surfaces, hydrogeological units and 3D geological volumes throughout the region. The work starts with publicly available data sources of varying quality and vintage. These data must be processed, structured or otherwise standardized.

The second objective of this work was to create a visual reference for the groundwater system that lies out of sight, under our feet. As specialists working for the public, and the public good, we are challenged to translate the complexity of groundwater into visual representations that can be understood by all. To do this we use software tools to create physical conceptual models (i.e., three dimensional models that integrate data into visually compelling representations of the subsurface).

To achieve these objectives, we work in an iterative cycle from database to 3D model, back to database. By working with the data in 3D, geologic and groundwater patterns emerge that would otherwise not be apparent in 2D mapping, such as in a desktop GIS. These patterns allow us to correlate borehole intervals to distinctive hydrogeological units such as different aquifer types, significant aquitards or bedrock units. The hydrogeological units, or HGU's, are the fundamental building blocks of our conceptual models of hydrogeology because they allow us to model the three-dimensional architecture of the subsurface, and efficiently capture information required to populate the database. We can then export tables, imagery and GIS data from the models to populate the database (Figure 1).

The two objectives: 1) to build a database of the physical hydrogeology; and 2) to produce conceptual, 3D models, are mutually dependent.

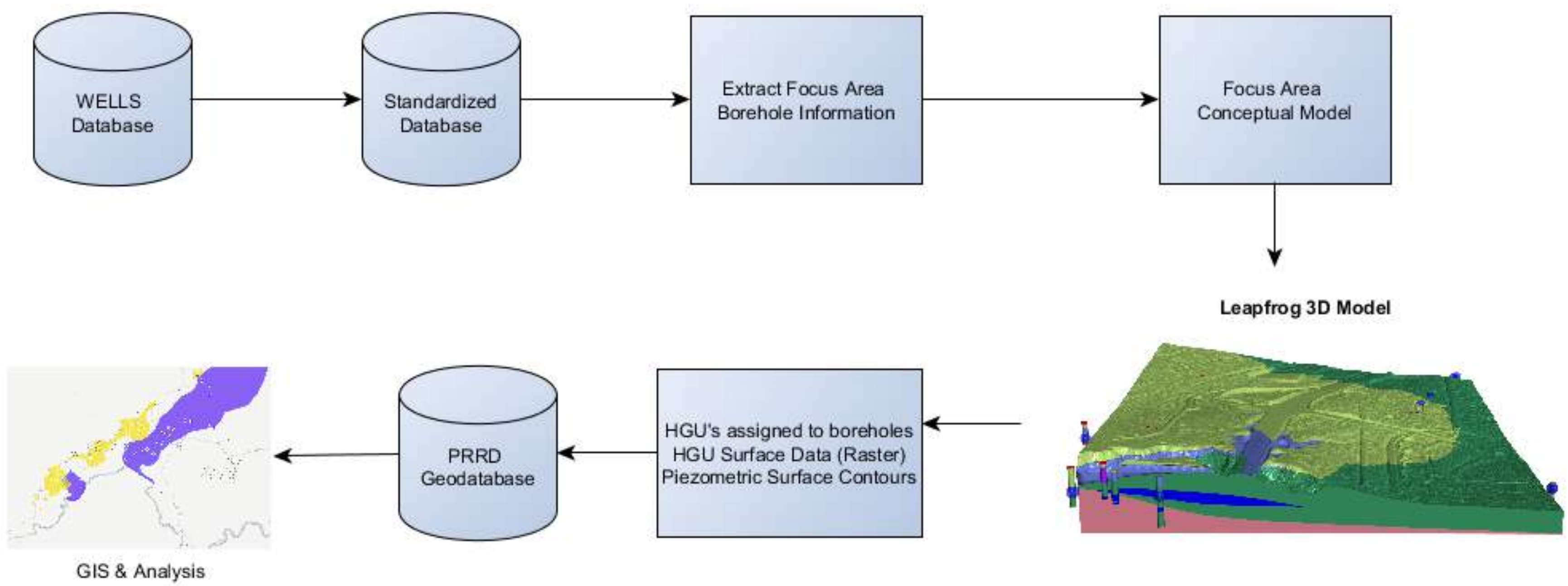


Figure 1. Data standardization and 3D modelling process flow diagram. HGU = Hydrogeological Units, the fundamental building blocks of a conceptual model of hydrogeology.

C. Data and Modelling Process

1 Methodology and Tools

Groundwater flows through three dimensional geological units and it is important for the specialist to interpret the data in 3D. GW Solutions has developed 3D hydrogeological models in order to facilitate the creation of a database of physical hydrogeology. Building a 3D conceptual model of groundwater requires integrating available water well data in context with topography, groundwater level data, and other GIS data (e.g. surficial geology mapping). The goal of the model is to derive the fundamental hydrogeological building blocks of aquifers, aquitards, and bedrock units. To achieve this, we use Leapfrog Hydro (ARANZ Geo Ltd 2016), a geological modelling and visualization software, in combination with a variety of database and Geographic Information System (GIS) tools. The models GW Solutions has developed for the PRRD can be updated as new information becomes available. Output from the models includes imagery, maps, data tables and 3D scenes that are geared towards specialists and non-specialists alike. In addition, access to 3D models is possible through use of the free Leapfrog model viewer software.

The primary database system used in this project is PostgreSQL, an open-source, relational database system (RDBMS) with full spatial (GIS) integration. Desktop GIS software used to display and analyze data stored in the database includes both proprietary software like ArcMap (ESRI 2016) and Leapfrog, and freely-available software such as QGIS (Creative Commons).

1.1 Information Sources

1.1.1 WELLS Database

Two publicly available, online resources are available from the British Columbia Ministry of Environment (BC MoE) that can be used to obtain well information in the province: the BC Water Resource Atlas and the WELLS Database. The BC Water Resource Atlas (BCWRA) is an online, map-based (GIS) tool. The WELLS Database is the provincial groundwater wells database and is the de facto repository for all subsurface and groundwater information obtained from water wells drilled in BC[1]. The Ministry data sources require a significant effort to clean up and re-structure before the they can be used for work at a regional or watershed scale. For this reason, we have opted to use our own standardized well database (See Section 1.2).

[1] Historically, submission of well reports has been voluntary.

1.1.2 Topography

A digital elevation model (DEM) of ground surface topography is a vital component of the model. Due to the regional scale of the work, we have used the 1:50,000 scale DEM available from Natural Resources Canada (NRCAN). The NRCAN DEM has an inherent horizontal and vertical accuracy and spatial resolution that is suitable for regional or "watershed" scale studies (approximately 10 to 100's of km^2 footprints). Local or site level investigations (i.e. less than 1 km^2 footprint) would require a DEM of a higher spatial resolution such as that obtained from Light Detection and Ranging (LiDAR) surveying tools.

1.1.3 Groundwater Depth

Maps of piezometric levels (i.e. elevation of the water table) were derived from the depths to groundwater recorded in the WELLS database. Although water levels were measured at different times (both in terms of season and year), they are nevertheless useful for estimating the hydraulic gradients at the "watershed-scale". Three broad classes of water levels were distinguished from the WELLS database based on the depth drilled and the aquifers encountered in the well.

1. shallow, typically dug wells less than 10 m deep, completed in unconfined, surficial aquifers;
2. deep, drilled wells, greater than 10 m deep completed in confined surficial aquifers; and
3. wells of varying depths drilled into fractured bedrock.

In addition, from 2011 to 2014, FLNRO collected over 300 groundwater samples from wells throughout the PRRD, and measured depths to groundwater in the wells. While these data provide much required additional data points to complete mapping of piezometric levels and gradients, without associated database ID's (i.e. Well Tag Number of Well Plate ID), it is difficult to link field data to the database. Despite efforts on the part of MoE to associate the sampled wells with Well Tag Numbers, many of the sampled wells could not be definitively linked to a database identifier.

1.1.4 Surficial Geology

A surficial geology map of glacial and post-glacial landforms and deposits was available from 1:250,000-scale digital Surficial Geology mapping compiled by Geoscience BC based on original hard copy maps from the Geological Survey of Canada GSC) (Hickin & Fournier 2011). Surficial deposits play a pivotal role in the dynamics of groundwater flow and storage. The depositional environment of the unconsolidated sediments enables us to infer probable hydraulic properties of the materials. For example, permeable sand and gravel is likely to occur in glaciofluvial and alluvial deposits whereas lower permeability silts and clays are more likely to occur in glaciolacustrine deposits or glacial tills. The relationship between surficial geology and material properties allows us to connect surface mapping to the subsurface intervals obtained from boreholes. For example, a glacial till unit mapped at the surface can be correlated with subsurface tills (e.g., “boulder clay”, or “hardpan” noted by drillers) to form an aquitard unit in the subsurface.

1.1.5 Bedrock Geology

The British Columbia Geological Survey (BCGS) has compiled provincial-scale bedrock geology mapping for the province with the latest update released in 2015 (Cui, Y., Miller, D., Nixon, G., and Nelson 2015) (Figure 2). The upper tier of bedrock strata in the region is dominated by Cretaceous clastic rocks (i.e. conglomerate, sandstone, siltstone, shale and mudstone).

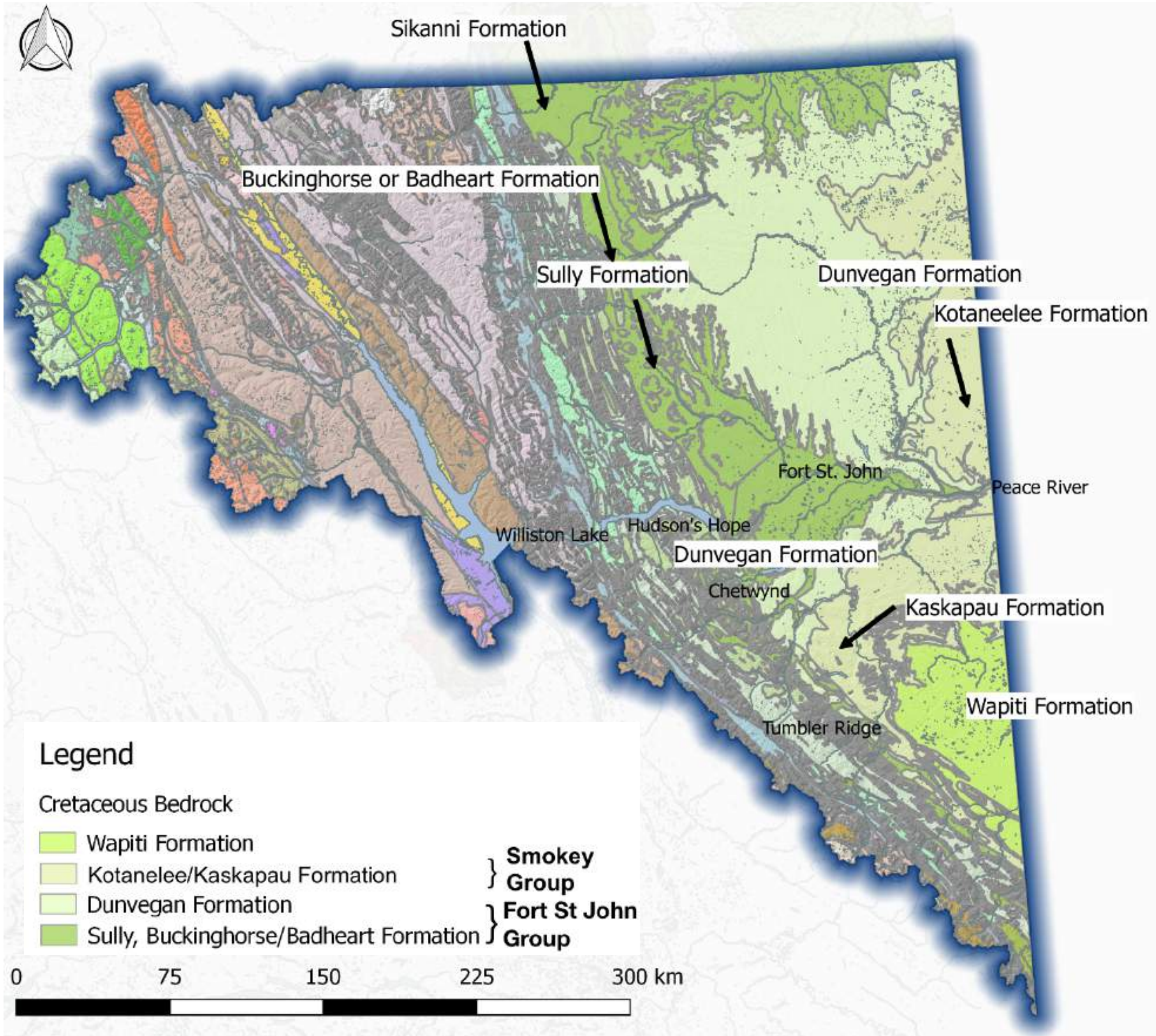


Figure 2. Peace River Regional District bedrock geology is characterized by upper Cretaceous clastic rocks of the Smokey and Fort St. John groups. The dominant, shallow bedrock aquifer systems in the region are comprised of sandstone and minor shales of the Dunvegan Formation. (modified from (Cui, Y., Miller, D., Nixon, G., and Nelson 2015))

1.1.6 Aquifers Mapping

The BC Ministry of Environment (MoE) maps aquifers in the province according to a well-established standard (Berandinucci & Ronneseth 2002). The end product of the MoE's aquifer mapping is a set of spatial polygons outlining areas where groundwater is used throughout the province. These outlines guided the 3D modelling process; however, the objective of model building required hydrogeological units to be assigned to individual borehole intervals, and therefore wells.

Lowen Hydrogeology outlines the main geologic units that are associated with surficial aquifers in the Peace River region (Lowen Hydrogeology 2011) (from youngest to oldest):

- Type 1: Shallow to near-surface sand and gravel deposits associated with modern alluvium along major creeks and rivers;
- Type 2: Shallow to intermediate depth glaciofluvial deposits formed by glacial melt waters at the end of the last glaciation;
- Type 3: Deeper glaciofluvial and fluvial interglacial sand and gravel units deposited during advance and retreat of ice sheets, including those deposited in pre-glacial and interglacial valleys;
- Type 4: Deep, pre-glacial sand and gravel deposits occurring in buried valleys.

Unlike surficial aquifers, the bedrock aquifers of the Peace River Regional District are much more regionally extensive. At a regional scale, the coarse clastic (i.e. sandstones and conglomerates) of the Bullhead Group, Dunvegan and Wapiti formations can be viewed as potential aquifers, whereas the marine shale units of the Fort St. John Group, Kaskapau, Puskwaskau and Kotaneelee formations can be viewed as aquitards or aquicludes.

However, (Riddell 2012) cautions that:

> *"Generalizations about [Peace River] aquifer characteristics at the formation scale, however, are not sufficiently accurate for groundwater exploration purposes because none of the Cretaceous formations is lithologically homogeneous. […] All of the coarse clastic formations contain shale members, and all of the shale formations contain continuous or lensoid coarse clastic members. In addition, fracture enhancement of porosity is seen in both shale and coarse clastic formations, producing local aquifers."*

1.2 WELLS Data Standardization

Despite it being the richest, if not the only source of information about the subsurface and groundwater conditions, the BC WELLS database is essentially unusable for regional-scale hydrogeology unless a significant amount of data mining and re-structuring is done.

The following assumptions and potential sources of error are inherent in the data:

- Until 2016 submission of water well drilling logs was voluntary in the province. Therefore, the number of water wells in the database is thought to underrepresent the actual number of wells drilled in the province;
- Wells in the database may no longer be in use;
- Horizontal (x-y) positional accuracy of wells is highly variable and not all wells are accurately located within a land parcel;
- Vertical (z) accuracy is dependent on x-y positional accuracy, since well elevations are obtained from the available digital elevation model (DEM) at a particular location. The level of accuracy of the DEM, in turn, will affect the vertical accuracy of wells points; and
- Well lithologies can only be as complete or accurate as the original driller's descriptions.

1.2.1 Material Classes

Water well drillers' recorded descriptions of the materials encountered during the drilling process remain an invaluable source of information about subsurface conditions, although these descriptions can be difficult to interpret. The aim of standardizing lithologies is to classify well drillers descriptions into terms relevant to groundwater. Standardized borehole logs are the foundation for making linkages between wells and the aquifers they draw from. Lithology records were processed to extract standard geological terms, called Material Classes, from original well driller's descriptions. The original well logs and descriptions are retained in the database for cross-referencing to the standardized lithologies.

Material Classes are soil or bedrock types that are used to define, as objectively as possible, the information provided by drillers logs. Material Classes are the smallest geological units, that can be extracted from drillers' descriptions, that we deem to be regionally consistent and relevant to groundwater. It is not possible to extract formal geological descriptions from the source data, and Material Classes are not intended to be used in lieu of a borehole log collected by a trained specialist. Rather, they are used as an intermediate step towards grouping borehole intervals according to likely hydraulic conductivity with respect to groundwater. There are twelve principal Material Classes for standardized lithologies (Table 1). Capitalized terms refer to the material presumed to be dominant in the description.

Table 1. Material Class descriptions in the standardized well lithology table.

Material class	Count
CLAY/gravel	142
CLAY/sand	312
GRAVEL/silt	224
SAND/clay	131
boulder/gravel	83
bedrock	4956
continued in adjacent table	

Material class	Count
clay	1670
sand/gravel	1266
sand/gravel/clay	157
silt	145
silt/clay	168
soil/organic	65
till	960

There are 11 Material Classes for surficial deposits and only one bedrock class. This is because water well drillers rarely record accurate descriptions of bedrock geology, since they are principally interested in finding water. When drilling through bedrock, drillers typically note the occurrence of groundwater-producing fractures. For this reason, the bedrock lithologies in boreholes have been lumped together in this study.

1.3 3D Modelling Process

The modelling process starts with the standardized wells database that includes key water well attributes: X-Y location, maximum depth, screened interval, static water level, and lithology intervals. The modelling process involves assessing the standardized lithologies from borehole records in relation to the following information (where available):

- depth to water at time of drilling;
- well completion/screened intervals;
- inferred hydraulic gradients;
- producing fractures;
- surficial geology; and
- depth to bedrock.

The average human eye can accurately differentiate a maximum of 12 colours (Figure 3). Since making geological correlations is a human-driven endeavor, we have distilled the geologic descriptions down to 12 Material Classes. This enables visual differentiation of the various strata represented in boreholes and enables the digitization of hydrogeological units in 3D modelling software.

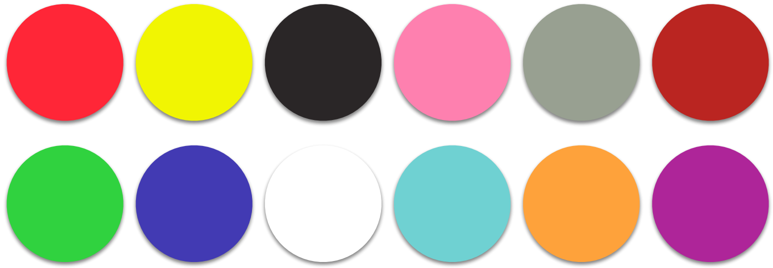


Figure 3. Rapid differentiation of hydrogeology is aided by following the general rule in cartography of using 12 colours or less.

Hydrogeological units are assigned directly to borehole intervals, and are given colour codes to allow for fast, visual identification and correlation between units. Each unit is colour-coded according its respective role in the groundwater regime: Blue colours represent higher permeability units and probable aquifers; greens represent lower permeability units and probable aquitards; and all bedrock is grouped together as pink-coloured units (Figure 4). The original driller's descriptions contain valuable information; however, so many unique descriptions exist that it is impossible for software to create a colour scheme that allows for visual identification of patterns and correlations between units (Figure 5).

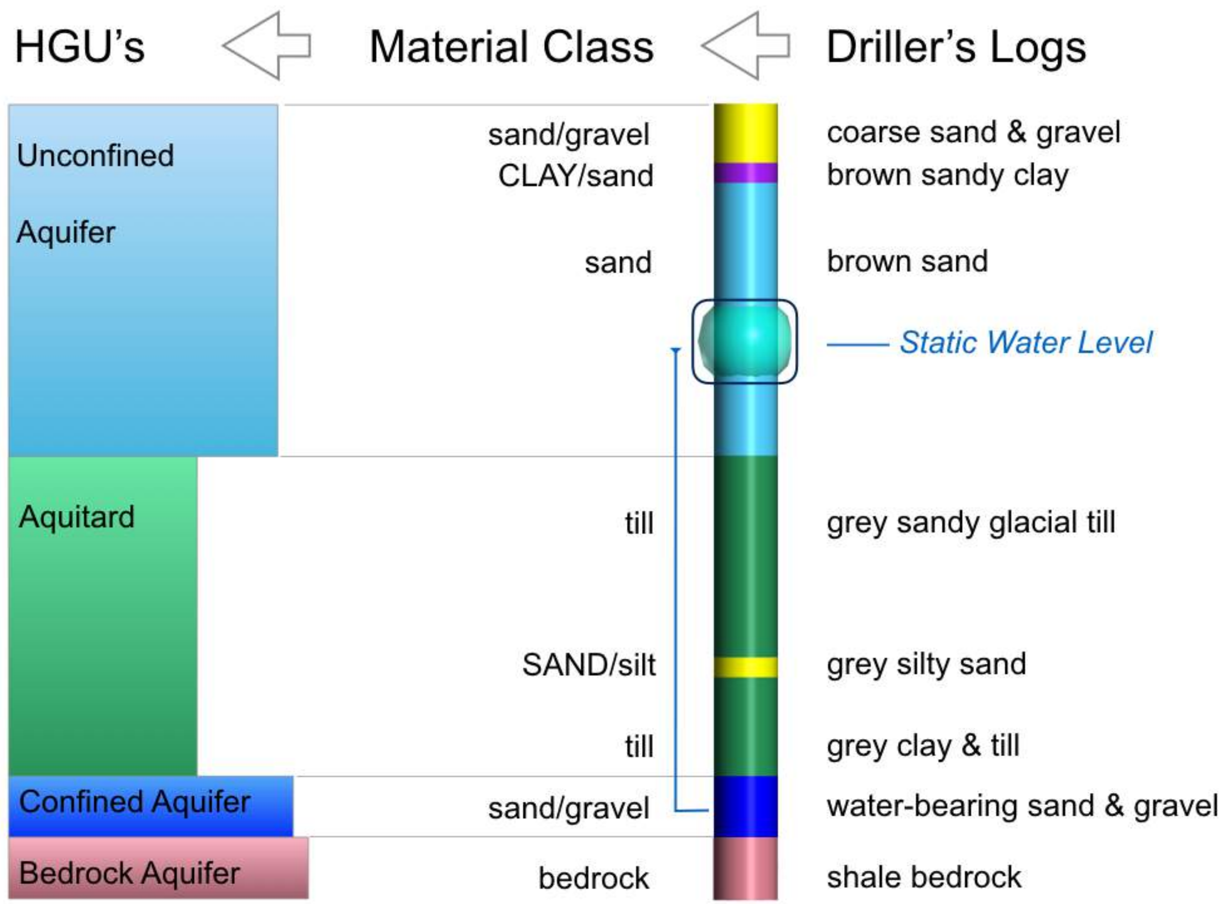


Figure 4. The process of taking driller's logs through a standardization process, and then through the 3D modelling stage

- LIGHT BLUE represents semi-confined or unconfined aquifers;
- DARK BLUE represents confined aquifers;
- GREEN represents low permeability units that are likely aquitards;
- YELLOW represents permeable material that are likely dry or unsaturated;
- PURPLE represents semi-permeable material;
- PINK represents bedrock.

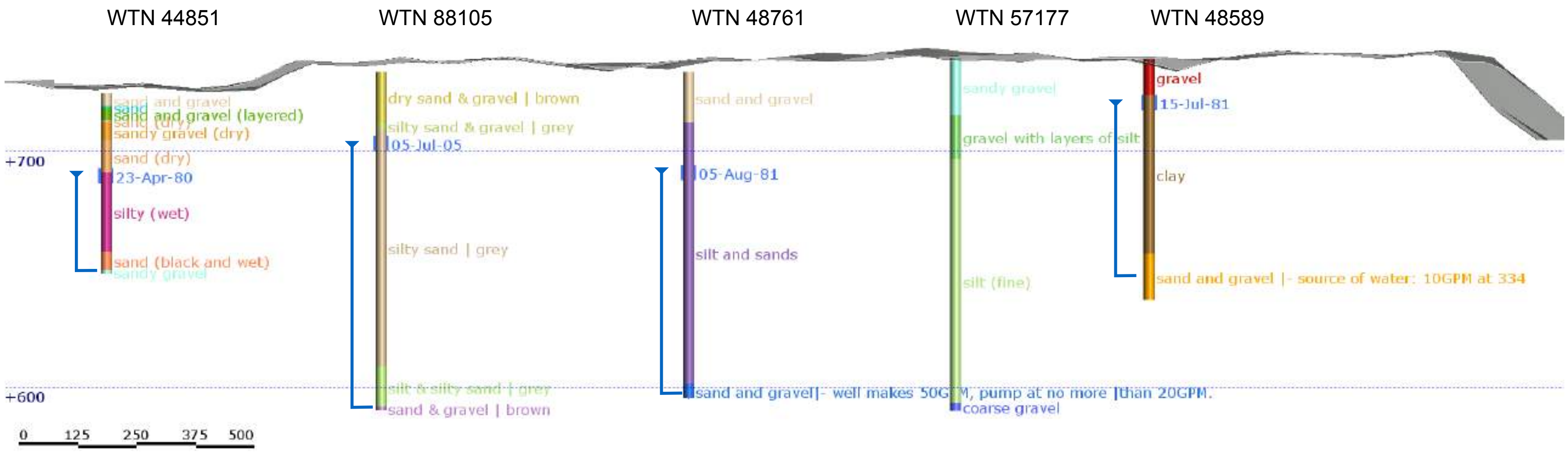


Figure 5. Representative cross-section ("model slice") from Jackfish Lake area showing original descriptions from the BC WELLS database. So many unique text descriptions exist in the driller's descriptions that it is difficult to see patterns in the data.

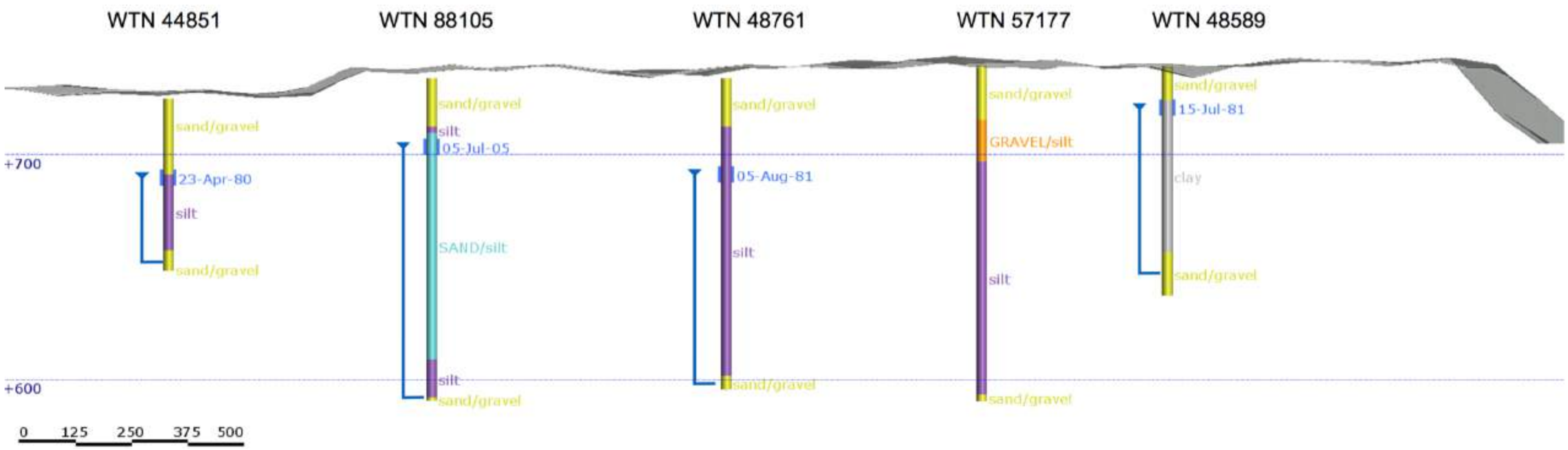


Figure 6. Standardized lithologies (i.e. Material Classes) alongside groundwater levels (blue dots) with dates measured. Arrows indicate probable interval with which the water levels are associated.

All well lithologies from the BC WELLS Database within the study area have been standardized to 12 Material Classes. Where possible, errors in the source data, such as erroneous bedrock picks or overlapping intervals, have also been corrected. Geological patterns begin to emerge from the standardized Material Classes, and we can begin to correlate permeable layers and possible hydrogeological units (Figure 6).

The next step is to classify standardized lithologies in terms of permeability: 1) permeable; 2) low-permeability; and 3) ambiguous (Figure 7). The ambiguous units are lithologies that may be subsequently re-interpreted as either having an affinity with aquifer or aquitard units, based on their relation to other information, such as details in the driller's notes (e.g. "water bearing"), depth of the screened interval, or the depth of groundwater.

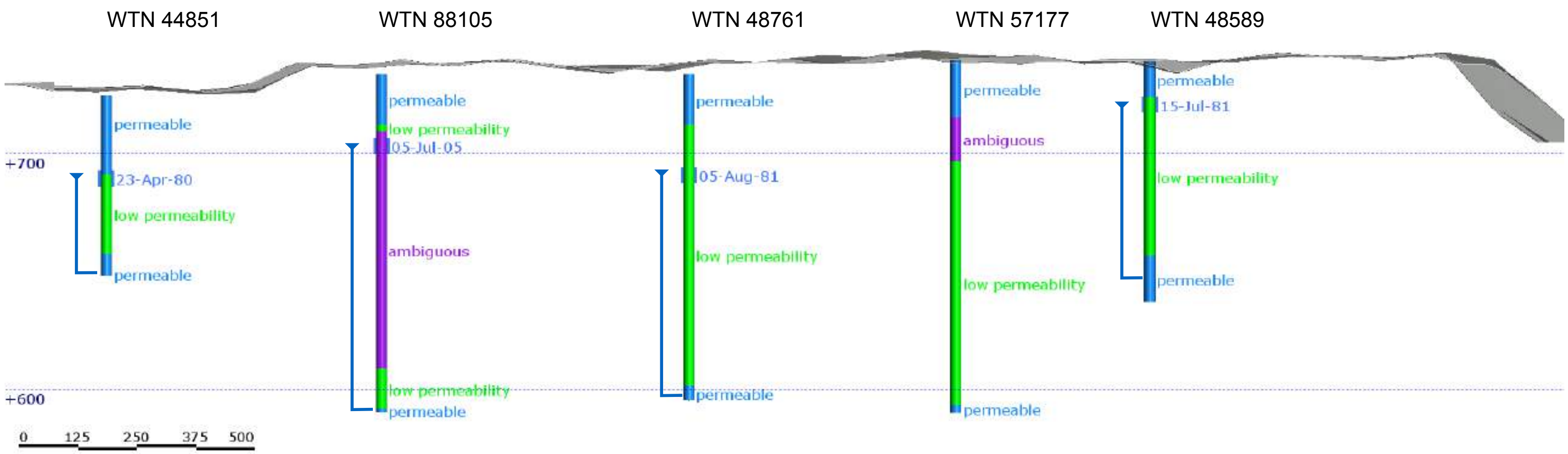


Figure 7. Permeable, Low-permeability, and Ambiguous lithologies assigned to boreholes. Water levels (blue dots with dates measured) in some wells rise to over 100 above the deep permeable aquifer layer. This means the water in the deep, permeable layers are pressurized and comprise a confined aquifer.

Next we interpret permeable/low-permeability units alongside available well completion data, groundwater elevations, surficial geology and topography. This step involves working with the 3D boreholes while juxtaposing various datasets in an iterative process that groups permeable and low permeability units according to hydrogeological characteristics (i.e. aquifers or aquitards). The grouping of hydrogeological units in borehole data partly results from our interpretation of the surficial geology of the area (e.g. glacial fluvial sand and gravels - typically aquifers, or glacial tills and lacustrine silts and clays - typically aquitards), since mapped surface units are frequently also encountered in the subsurface. Permeable units (blue) overlain by low permeability layers (green) are interpreted as confined aquifers. Water levels that rise above the deeper permeable layers reinforce this interpretation (blue dots with dates, Figure 7). By defining hydrogeological units directly in boreholes (Figure 8), we have moved from driller’s descriptions to hydrostratigraphic contacts, which can then be modelled as 3D geological volumes or “geovolumes” (Figure 9).

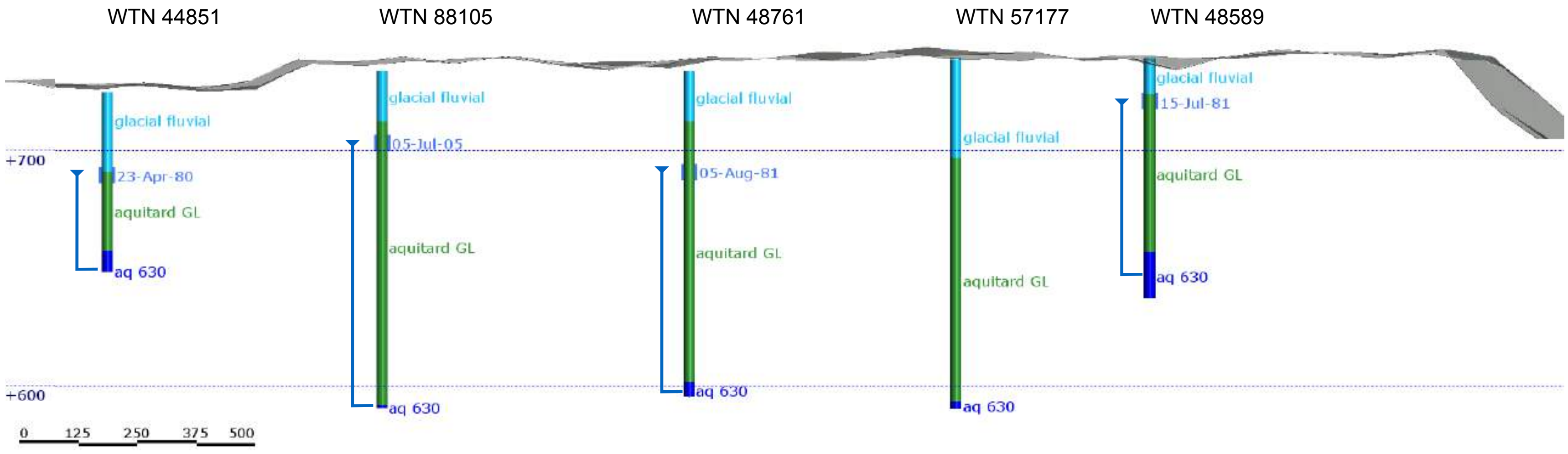


Figure 8. Aquifers and aquitards defined in boreholes from Jackfish Lake.

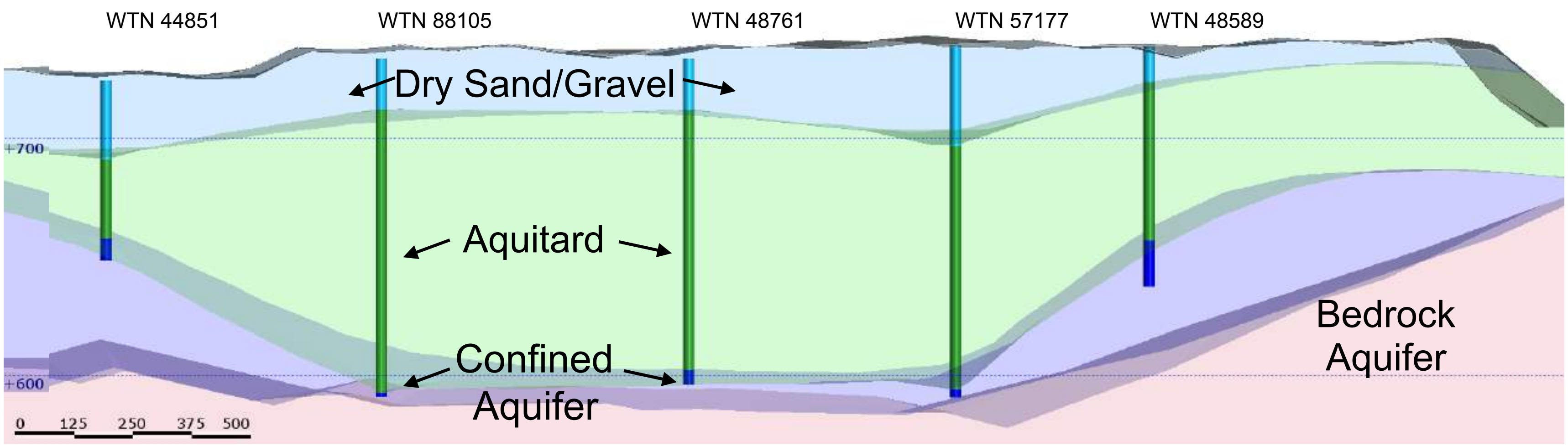


Figure 9. Modelled aquifers and aquitards as geological volumes (geovolumes) in cross section view. The hydrogeological units are from top to bottom: 1) dry, glacial fluvial sands and gravels (light blue); 2) a thick glacial lacustrine aquitard (green); and 3) confined fluvial sands and gravels (dark blue) corresponding to the BC MoE mapped aquifer #630.

1.3.1 Regional Integration

GW Solutions has developed a framework for naming and grouping hydrogeological units across the PRRD. By standardising terminology, the framework ensures that consistent information is available to support decision-making around groundwater resources. The framework aggregates borehole information into regionally consistent hydrogeological units and has three tiers:

1. Material Class (MC) - the smallest units.
2. Hydrogeological units (HGU); and
3. Hydrogeological group (HGG) - the most aggregated unit.

The borehole Material Classes are the smallest geological units that can be extracted from driller's descriptions, that are regionally consistent. Material Classes use standard geologic terms that relate to hydrogeological behaviour such as permeability and aquifer type (fractured bedrock or porous media).

Hydrogeological units (HGU) represent one or more Material Classes that have similar hydrogeological characteristics and behaviors. These units are created by aggregating materials based on our understanding of hydrogeology and by assigning named aquifers directly to the borehole intervals. By mapping HGU's, it is possible to query the database for summary statistics on aquifers (e.g. How many wells are completed in a given aquifer? What range of depths is typically drilled to reach a given aquifer?). Fortunately, in BC the aquifer naming and mapping system can readily be adapted to suit our need to map HGU's (Figure 10).

The hydrogeological group (HGG) is the most aggregated unit in the framework and represents the major division between the two dominant groundwater flow regimes and aquifer types: 1) flow through porous media in surficial aquifers, and 2) flow through fractured media in bedrock aquifers. The BC aquifer mapping system also makes this primary distinction between aquifer types.

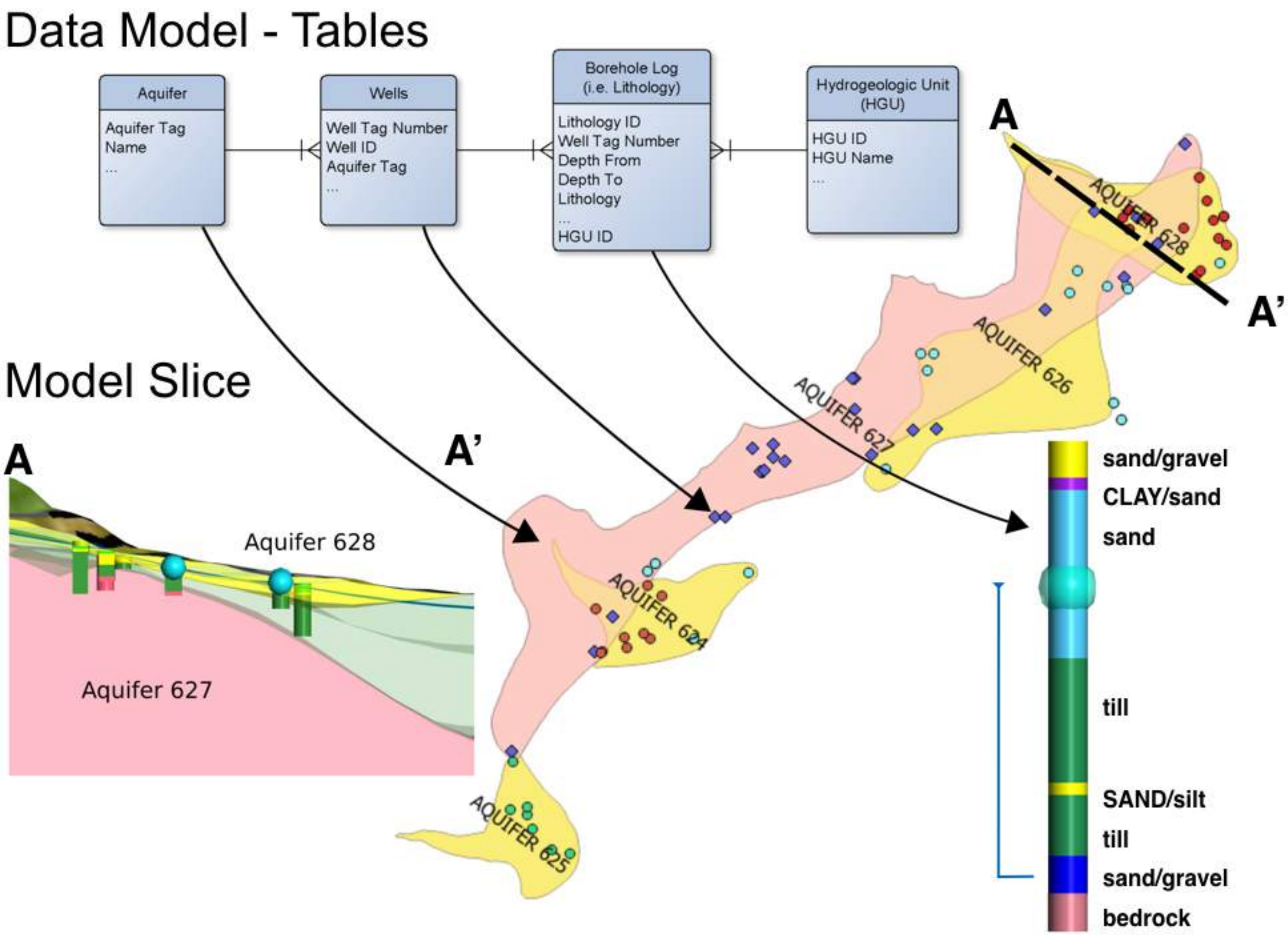


Figure 10. Everything in a groundwater database hinges on accuracy and completeness of the province's well records. Moving from well records, to aquifer and well maps in a GIS, to 3D models requires making the right link between the tables in the database. Maintaining unique "ID's" and a standardized schema is critical.

1.3.2 *Focus Areas*

The Peace River Regional District encompasses over 119,000 km^2, yet water wells are concentrated in areas of human habitation, agriculture and industry which represent a small portion of the regional footprint. GW Solutions selected key areas of focus, based on clustering of available data and perceived public interest, based on planning related activity within the PRRD (Figure 11). The PRRD focus areas include:

FOCUS AREA	
1	Fort St. John/Taylor/Charlie Lake
2	Rose Prairie
3	Cecil Lake/Goodlow
4	Prespatou/Altona
5	Moberly/Chetwynd/Jackfish Lake/East Pine
6	Hudson's Hope/Beryl Prairie
7	Wonowon
8	Groundbirch/Dawson Creek
9	Swan Lake
10	Tumbler Ridge
11	Sunset Prairie
11	Lower Kiskatinaw
12	Dawson Creek

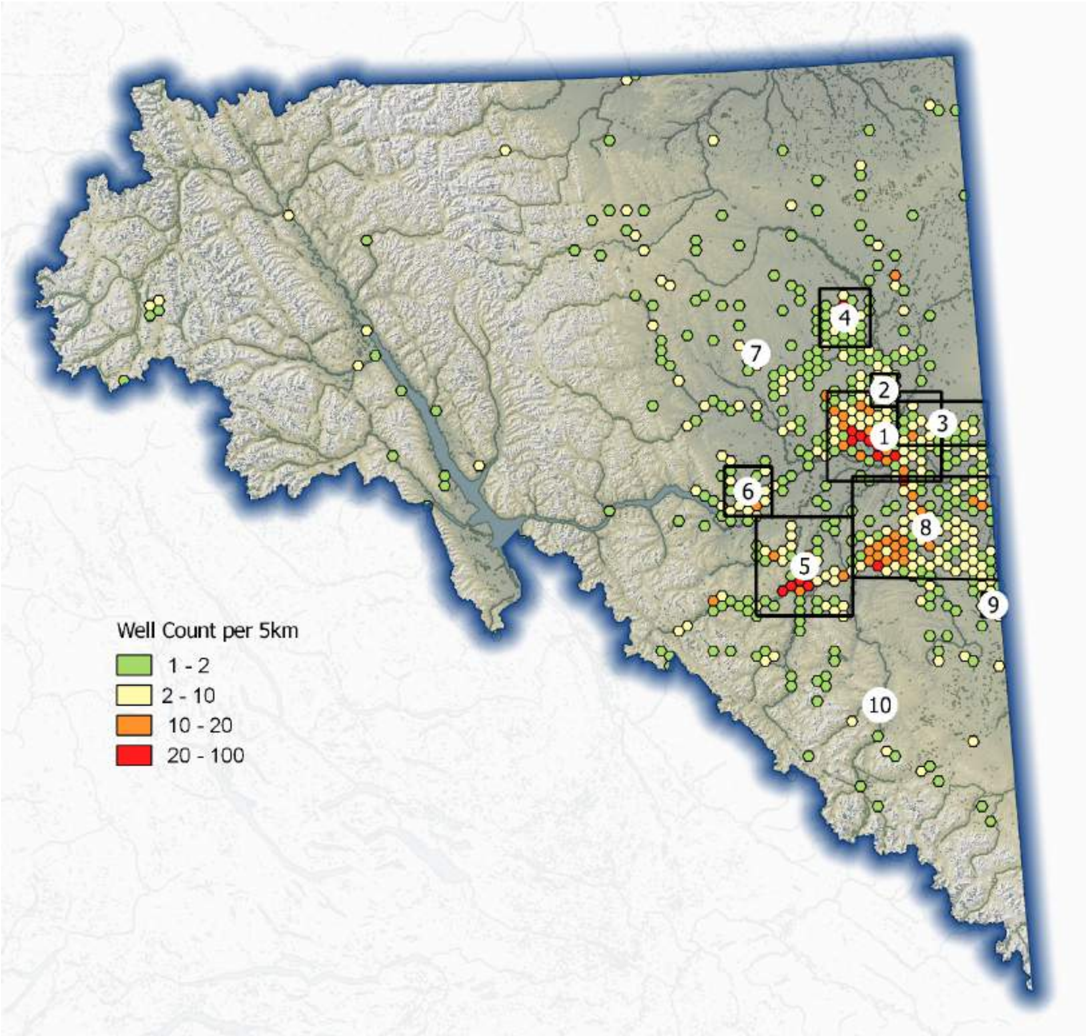


Figure 11. Focus Areas were selected to cover areas with sufficient data

1.3.3 Bedrock Topography and Overburden Thickness

The morphology of the buried bedrock surface exerts a powerful control on the movement of groundwater. Modern topography can mask the often highly variable and incised bedrock topography in the northeastern interior lowlands of BC (Hickin et al. 2008). Bedrock topography was modelled for each focus area within the PRRD in order to obtain bedrock structure and overburden thickness. The overburden thickness provides a proxy for the likelihood of occurrence of surficial aquifers, since the thicker (i.e. deeper) the overburden, the greater the likelihood of surficial aquifer occurrence.

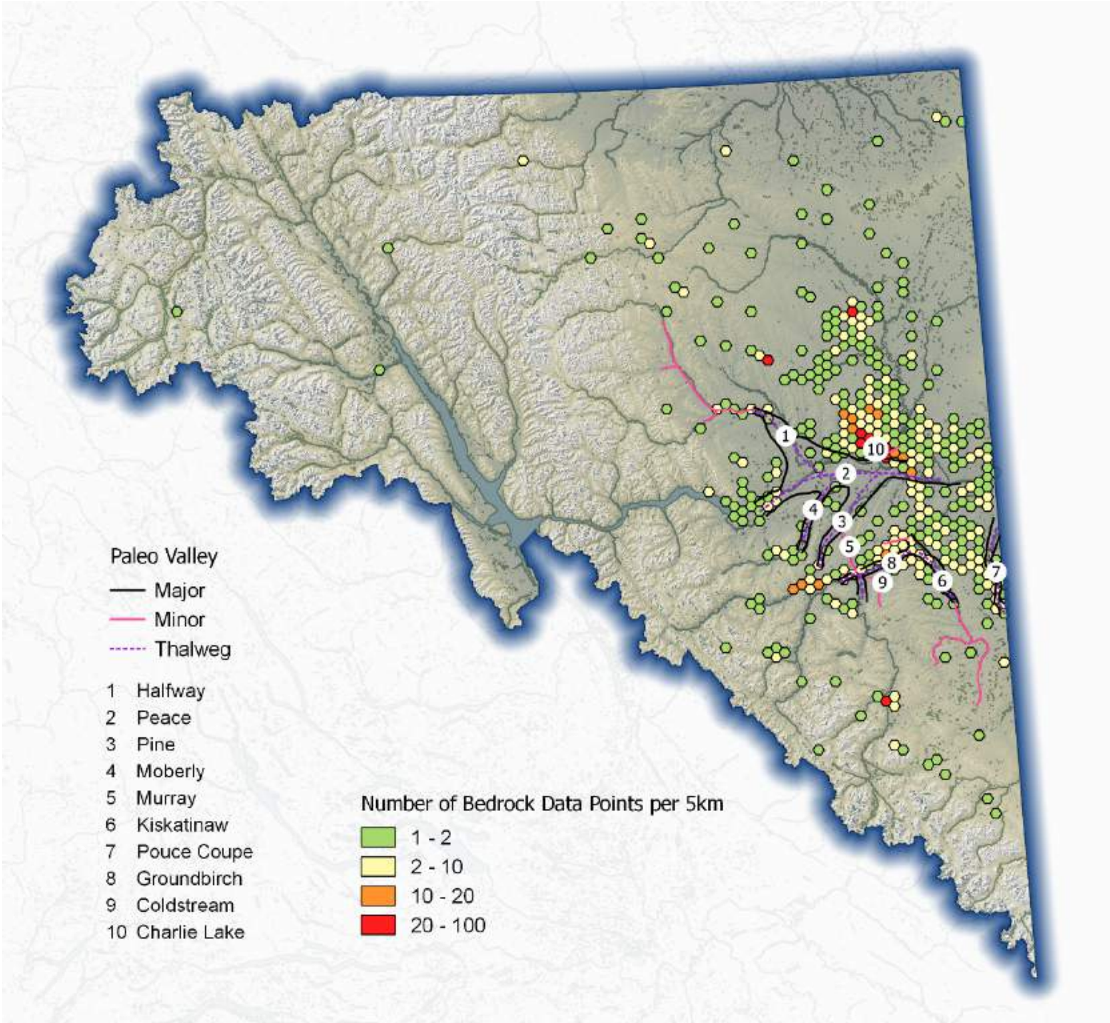


Figure 12. Information on bedrock topography.

3D models of the bedrock topography were interpolated in Leapfrog Hydro using available data and geological interpretation of bedrock occurrences at ground level and in the subsurface (Figure 12). Data on depth to bedrock were compiled from first occurrence of bedrock in the standardized Lithology records. Additional information was incorporated from bedrock topography mapping from the Geoscience BC Montney Water Project (Hickin 2011). In addition, the bedrock surface was manually corrected in areas where anomalous highs or lows were apparent. A minimum overburden depth of 2 m was applied to areas with sparse borehole data.

D. Physical Hydrogeological Framework

This report presents the physical hydrogeological framework of the Peace River Regional District using representative 3D slices and model images from five focus areas. Each focus area, in turn, comprises one or more conceptual models, each with multiple hydrogeological units (HGU's). The focus areas presented herein are:

1. Fort St. John, Charlie Lake, Taylor
2. Hudson's Hope, Beryl Prairie
3. Moberly Lake, Chetwynd, Jackfish Lake
4. Groundbirch, Dawson Creek
5. Tumbler Ridge

Within the focus areas, GW Solutions has highlighted the water-bearing HGU's, and we do not discuss the aquitards in great detail. Throughout the PRRD, GW Solutions has interpreted 36 sand and gravel, and 23 bedrock units and assigned these HGU's to borehole intervals in the BC WELLS database (Table 2). The numbering schema is based on the BC Aquifer classification scheme. Additional HGU's that are unclassified or that were not included in the BC aquifer mapping are also included (e.g. Charlie Lake Channel aquifer).

Table 2. Hydrogeological units in the Peace River Regional framework, identified at the borehole level.

Sand and Gravel Aquifer	
Hydrogeological Unit	Number of Occurrences
443	5
440	109
442	53
444	230
590	87
592	44
594	99
596	12
597	6
598	17
623	29

Bedrock Aquifer	
Hydrogeological Unit	Number of Occurrences
441	49
448	109
451	3740
589	10
591	303
593	284
595	35
621	18
622	128
627	88
631	22

Sand and Gravel Aquifer	
624	26
625	10
626	108
628	42
629	4
630	187
635	134
636	33
637	45
638	13
640	97
687	54
690	19
851	50
903	6
908	8
910	101
923	119
929	17
930	49
aquifer (alluvial)	47
aquifer (Charlie Lake Channel)	64
Unnamed aquifer (confined)	240
Unnamed aquifer (unclassified)	44
Unnamed aquifer (unconfined)	26
Total Number of Occurrences	**2234**

Bedrock Aquifer	
634	151
639	515
688	132
689	35
765	92
917	88
928	27
931	87
932	215
933	197
934	73
bedrock aquifer (unclassified)	982
Total Number of Occurrences	**7380**

Aggregate data for the overburden and bedrock HGU's allows us to group aquifers based on metrics such as average aquifer depth and thickness, and average depth to water table. Three distinct surficial aquifer groups can be distinguished: A) Unconfined aquifers: alluvial fan/terrace, river valley deposits; B) Confined aquifers: glacial, pre-glacial deposits; and C) Buried channel aquifers (Figure 13). Bedrock aquifers can be separated into two distinct groups based on piezometric level: Group 1 has piezometric levels above the top of the bedrock; Group 2 has piezometric levels within the bedrock itself (Figure 14).

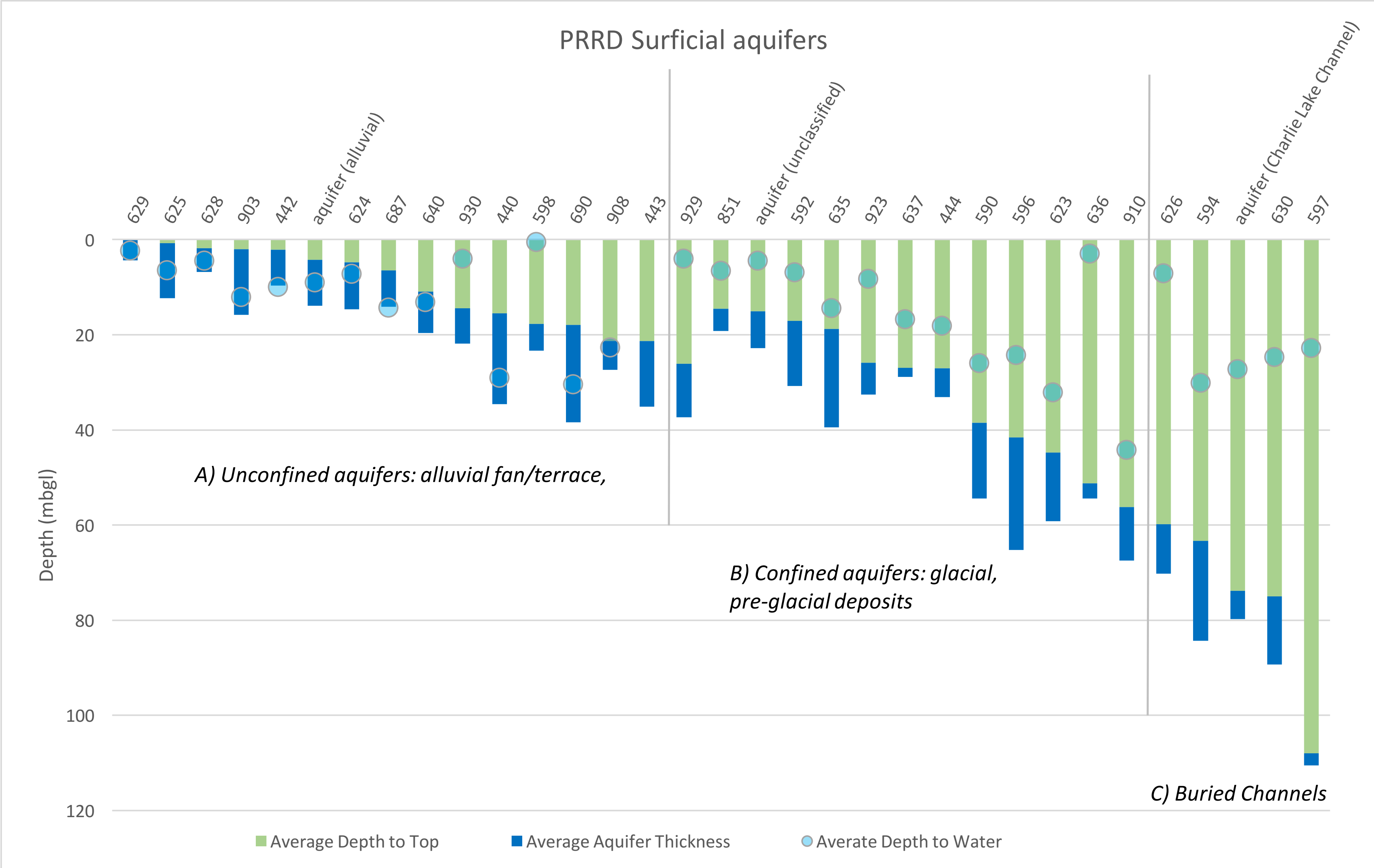


Figure 13. Summary statistics for surficial aquifers throughout the PRRD. Three distinct groups can be distinguished based on the aggregate data: A) Unconfined aquifers: alluvial fan/terrace, river valley deposits; B) Confined aquifers: glacial, pre-glacial deposits; and C) Buried Channels (note: in legend, “Average Depth to Top” refers to average depth to top of aquifer. This applies to similar figures in this document)

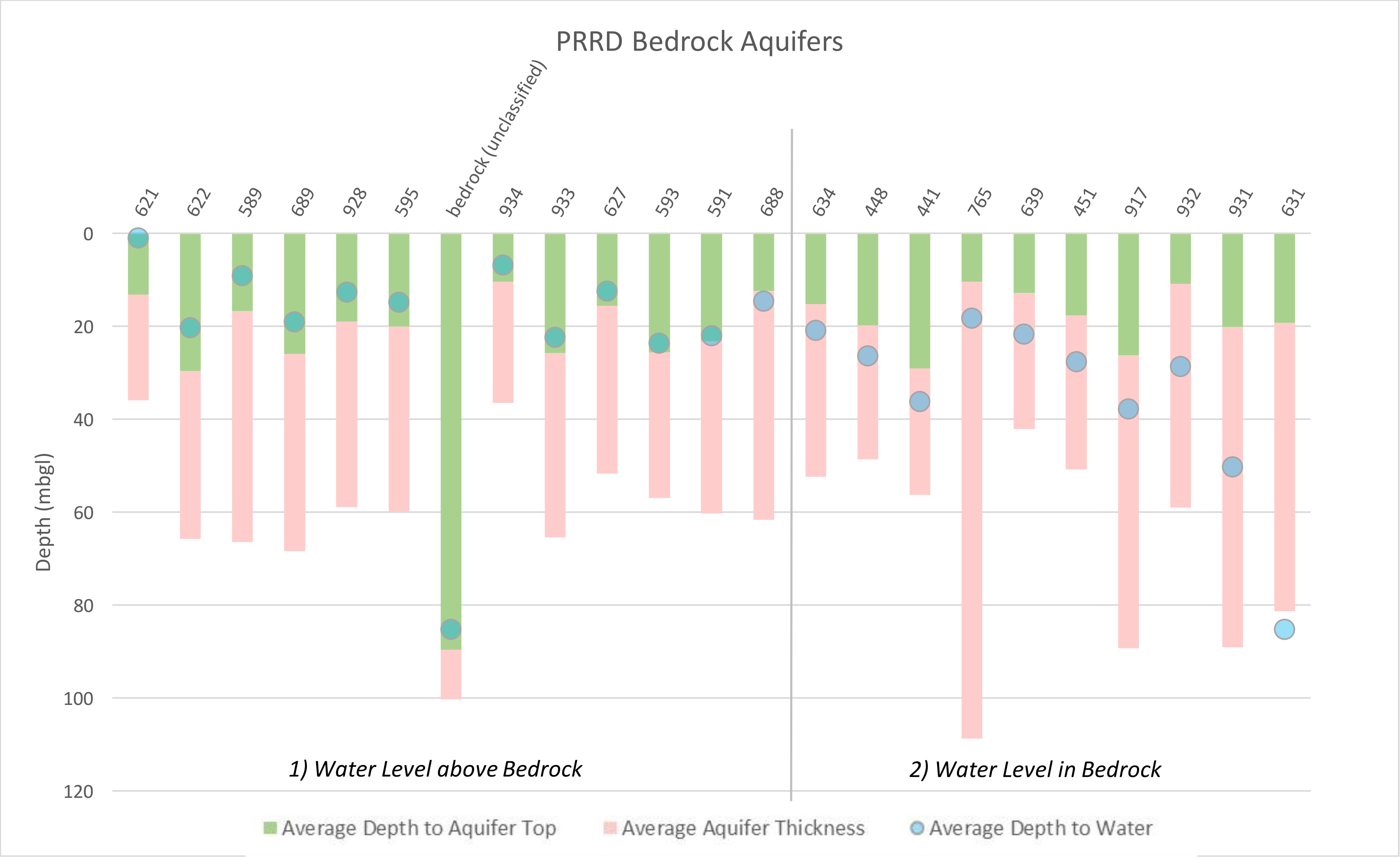


Figure 14. Summary statistics for bedrock aquifers throughout the PRRD. Bedrock aquifers throughout the PRRD can be separated into two distinct groups based on piezometric level: Group 1 shows piezometric levels within surficial materials above the bedrock; Group 2 has water levels within the bedrock itself.

1 Fort St. John Area

The Fort St John area supports one of the highest concentrations of groundwater users in the region, with the majority of that use originating from bedrock Aquifer 451, comprised of bedrock of the Dunvegan Formation (primarily sandstone) and Fort St. John Group (mudstone, siltstone, shale and fine clastic sedimentary rocks). Two other bedrock aquifers are mapped in the area, including HGU 931 between the Beatton and Doig Rivers and HGU 933 encountered east of the Beatton River. The deeply incised river valleys form the ostensible boundary between the mapped, "2-dimensional" aquifer polygons. In areas where rivers are deeply incised, it is reasonable to assume the bedrock aquifers are bounded by the river valleys. Only rarely are wells drilled to depths equivalent to the deep valley bottoms.

Five surficial and three bedrock aquifer types were assessed in the Fort St. John area, and these are summarized in Table 3.

Table 3. Summary of aquifer HGU's in the Fort St. John area.

Hydrogeological Unit (HGU)	Average Depth to Water (m)	Hydrogeological Group (HGG)	Description
442	0.9	Sand and Gravel	Peace River alluvial sand and gravel - 3.5 km West of Taylor
443	14	Sand and Gravel	Glacial fluvial terrace deposits - 2 km W. of Ft. St. John
444	19	Sand and Gravel	Fort St John upland
687	14	Sand and Gravel	Peace River valley south of Taylor
Charlie Lake Channel Aquifer	30	Sand and Gravel	Buried Channel aquifer east of Charlie Lake
451	28	Bedrock	
931	22	Bedrock	Dunvegan Formation (Sedimentary) - East of Blueberry River, North of Fort St John
933	16	Bedrock	Dunvegan Formation - Cecil Lake, North Peace River

1.1 Surficial Geology and Surficial aquifers

Surficial deposits in the Fort St. John area are dominated by a glacial till veneer over thick glacial lacustrine deposits. The latter were deposited in glacial Lake Mathews, a massive ice-dammed lake which blanketed the area following ice-damming of east-flowing rivers during the ultimate glacial (late Wisconsinan) phase. These two types of surficial deposits are typically aquitards; however, isolated pockets of permeable material (sand and gravel) do occur within these lower permeability strata.

Pre-glacial fluvial sand and gravel of the "Paleo-Peace" drainage system are mapped on the upper bench and lower, present-day Peace River Valley (Figure 15). We correlate these permeable units to the major sand and gravel aquifers of the area (Aquifers 444, 442 and 687).

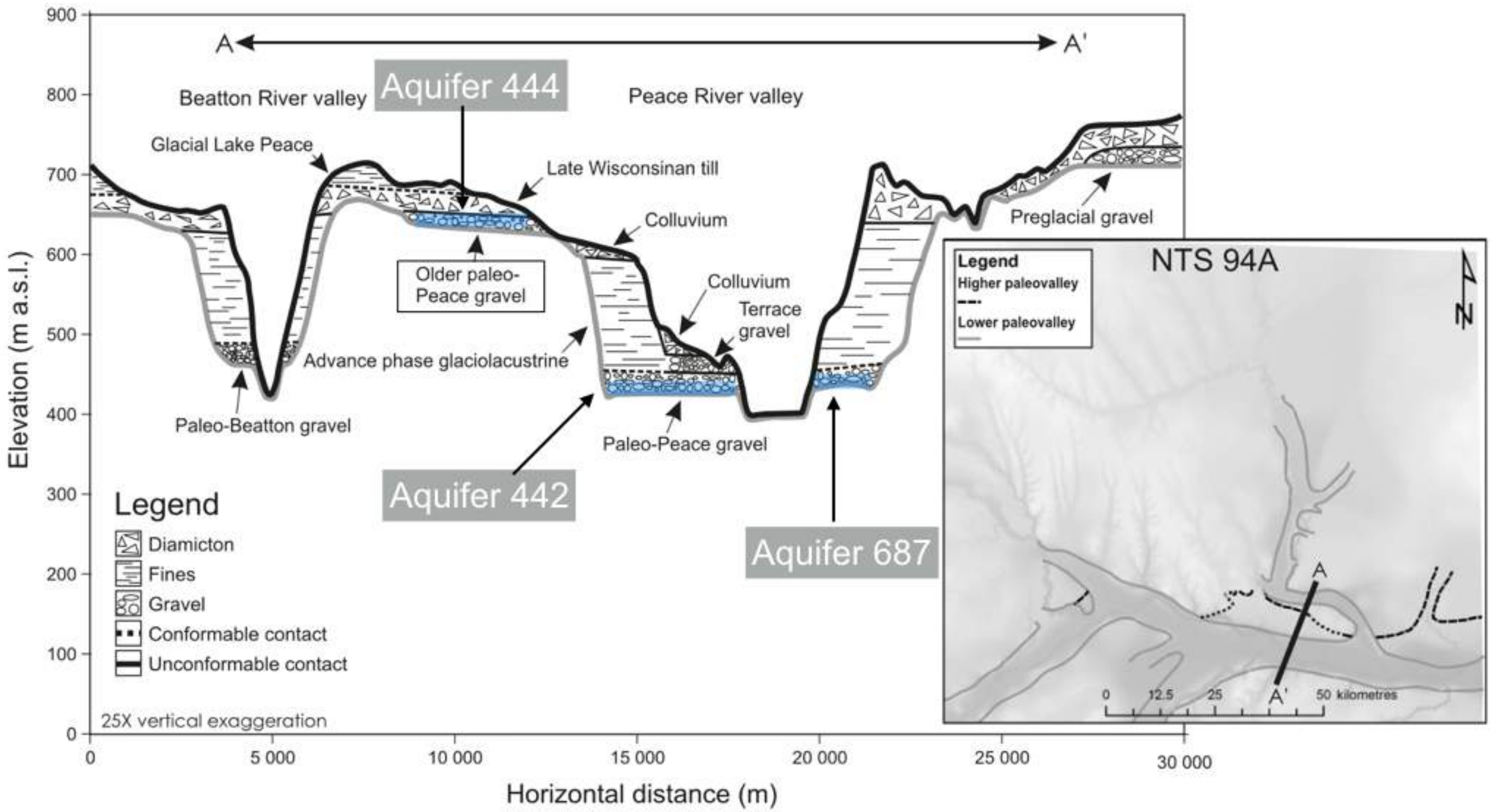


Figure 15. Conceptual geological cross section through the Beatton and Peace River Valley, and Fort St. John uplands showing the fluvial deposits of three relict drainage systems (Paleo-Peace and Paleo Beatton) which we correlate to the major sand and gravel aquifers of the area (Aquifers 444, 442 and 687). (Figure adapted from (Hartman & Clague 2008))

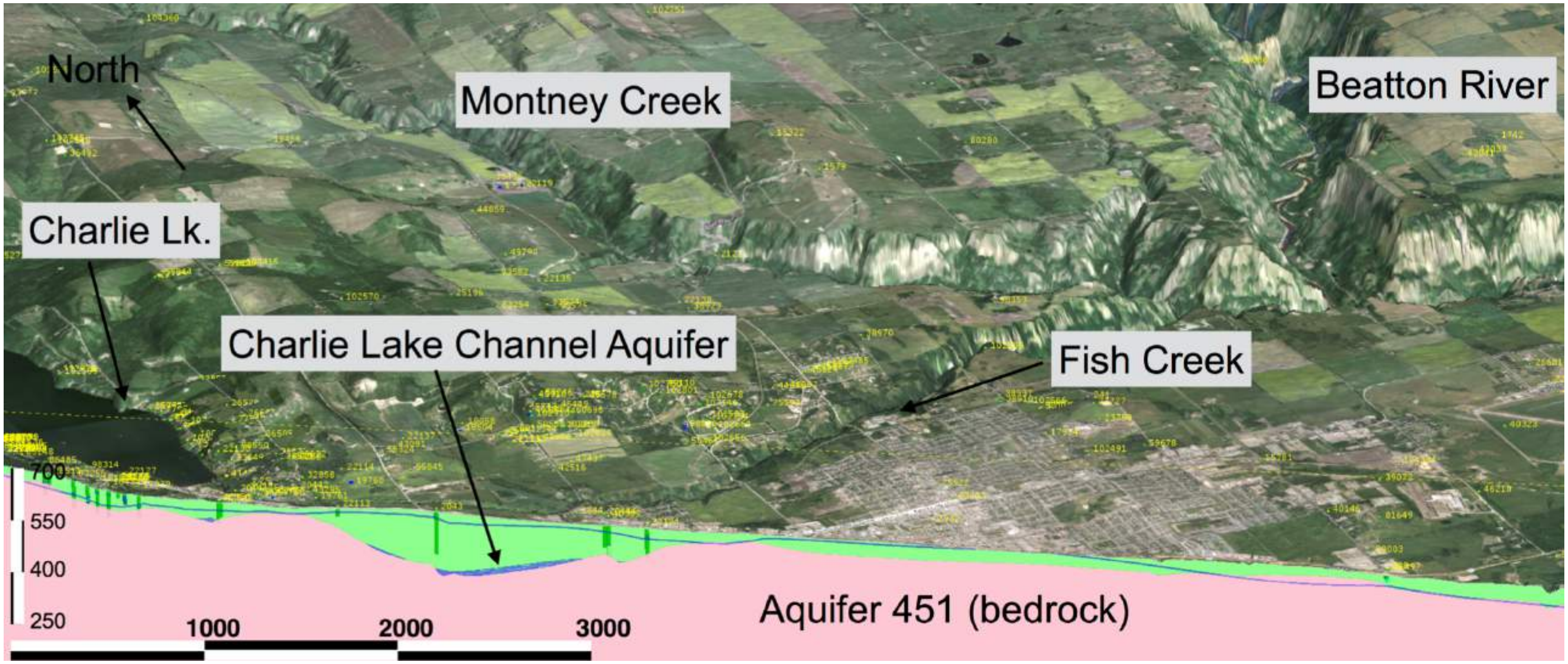


Figure 16. Fort St. John 3D model slice showing overburden (primarily green aquitard) and bedrock (pink). The deep bedrock depression west of Fort St. John is the Charlie Lake buried channel aquifer.

Aquifer 444 is a confined sand and gravel aquifer mapped in the area immediately surrounding the city of Fort St. John, extending west to Charlie Lake. The aquifer is not continuous across the whole area; rather it is interpreted as a series of discontinuous sand and gravel lenses with recorded aquifer top depths ranging from 8.5 m to 115 m below ground level and an average aquifer thickness of 6 m. Piezometric levels average approximately 20 m below ground level.

The most conspicuous feature in the overburden thickness/bedrock topography (Figures 16 and 17) is a linear channel approximately aligned with present-day Fish Creek, and runs from the southern part of Charlie Lake to the Beatton River. This is likely a buried valley scoured by Quaternary glacial or older erosional processes. Many such features have been mapped across western Canada, including the buried channels of the “Paleo-Peace” (Hickin 2011).

The fourth surficial aquifer mapped in the Fort St. John area is a deep, confined aquifer, present in the Charlie Lake buried valley (Figures 16, 17, 18). The aquifer top averages 74 m below ground level, and the average thickness of the water-bearing unit is 6 m. Piezometric levels for the Charlie Lake buried channel aquifer average 27 m below ground level, which is relatively high compared to the depth of the saturated unit, indicating the aquifer is under relatively high pressure compared to surrounding bedrock.

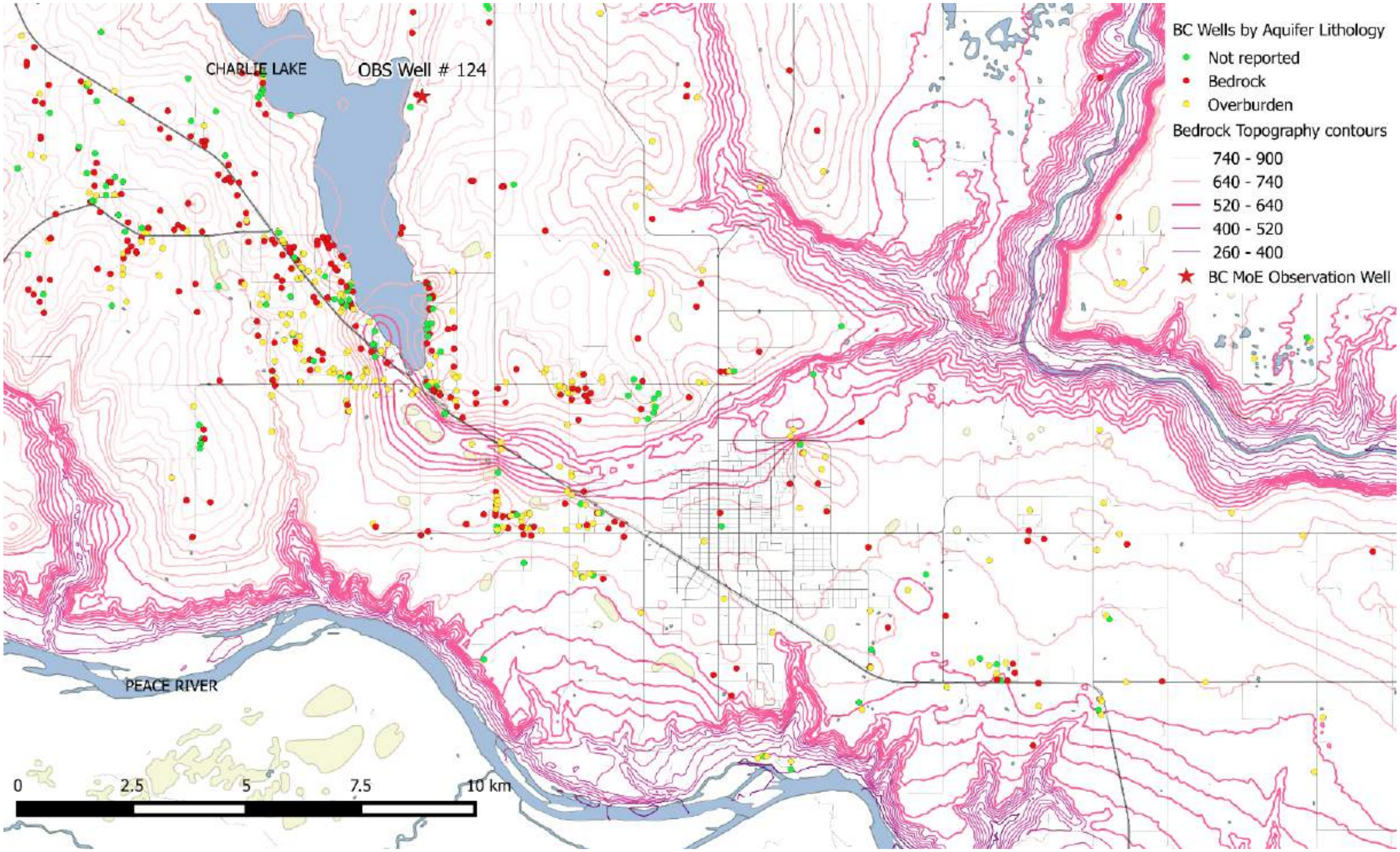


Figure 17. Bedrock topography contours indicating the structure of the bedrock surface beneath overburden material. The average depth drilled to the top of the bedrock aquifer is 18 m, and the average thickness drilled into bedrock is 33 m.

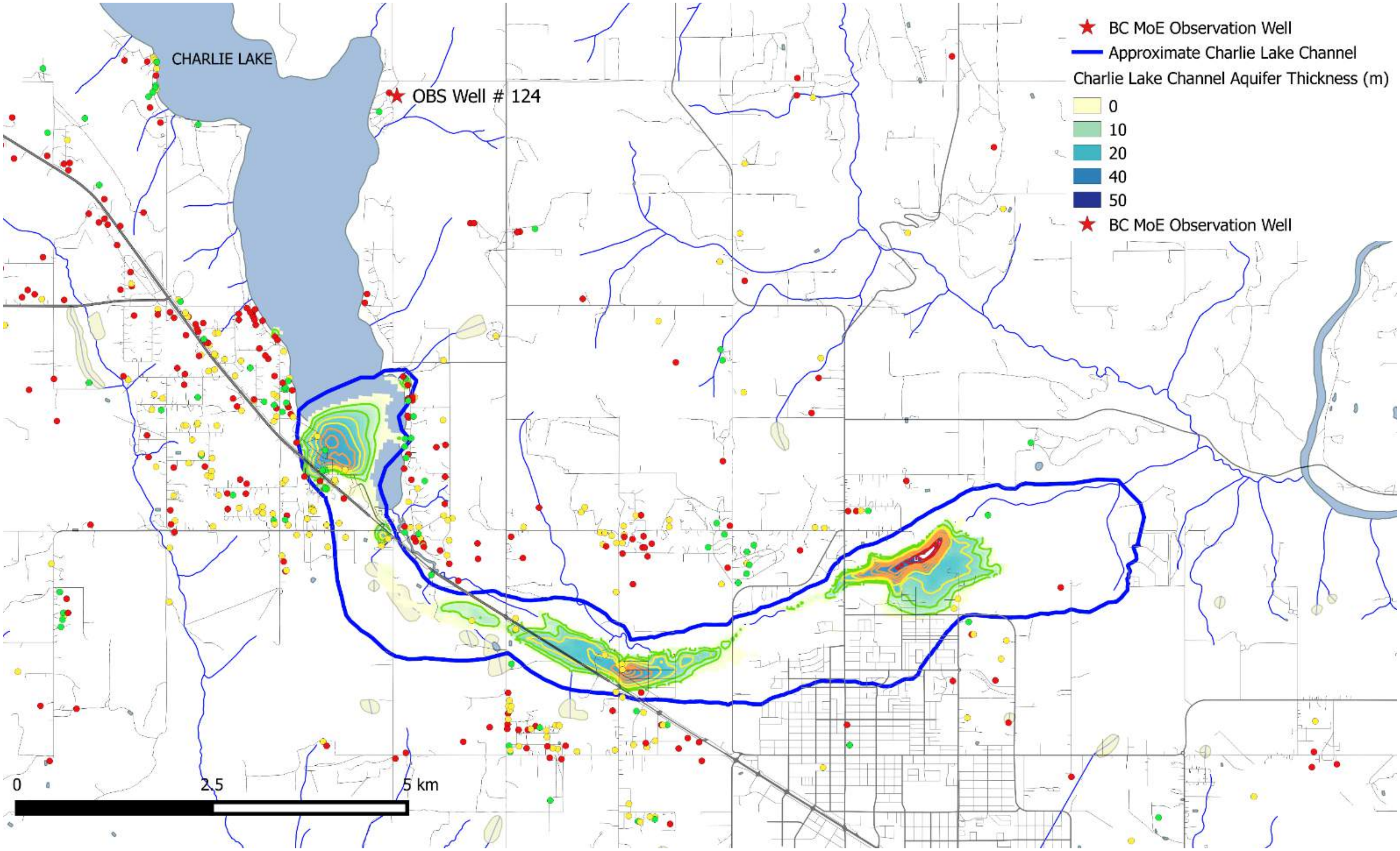


Figure 18. Charlie Lake channel aquifer thickness contours. Portions of the aquifer likely extend beneath Charlie Lake itself.

1.2 Hydrogeological Framework

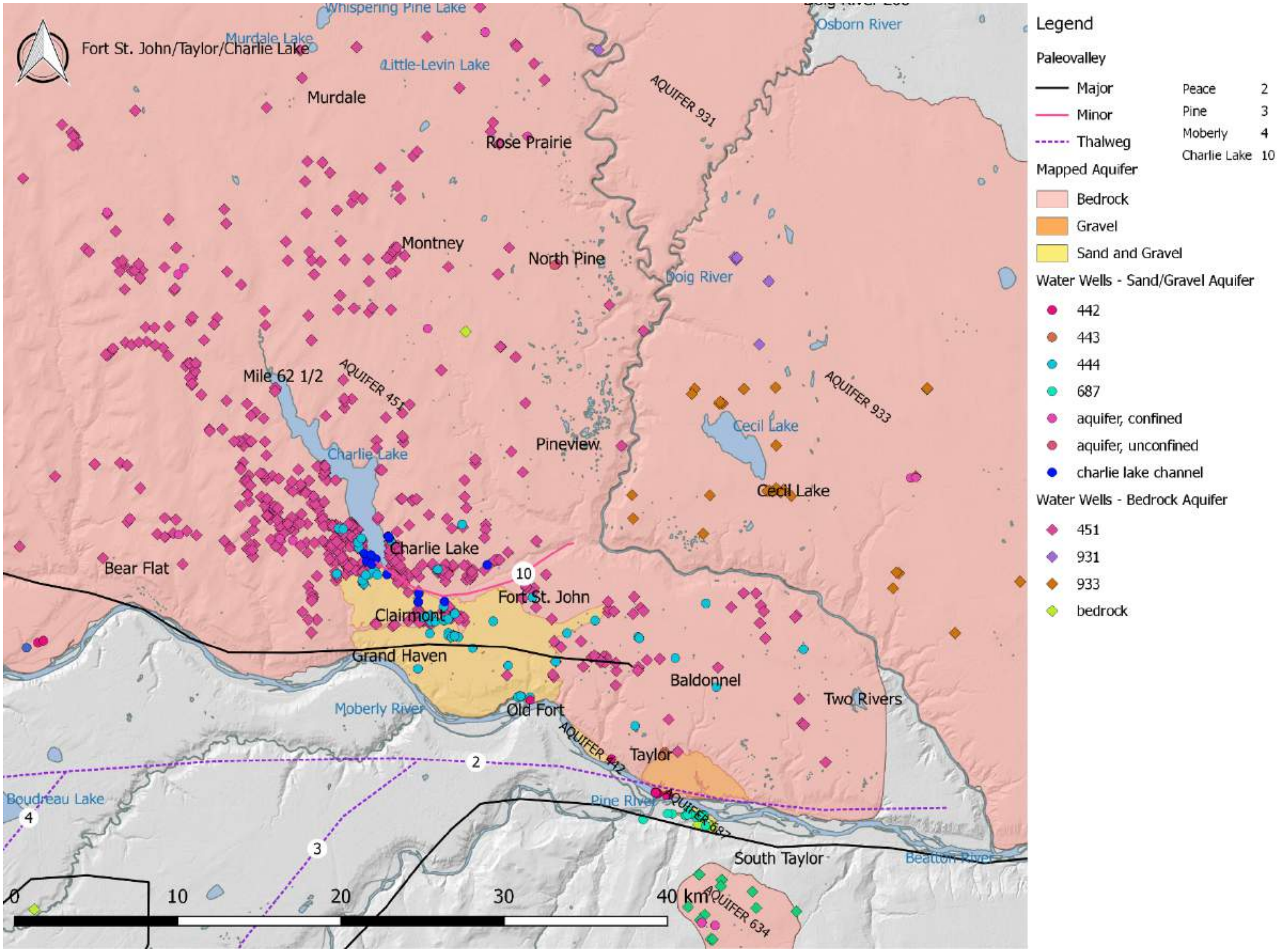


Figure 19. Wells linked to aquifers around Fort St. John.

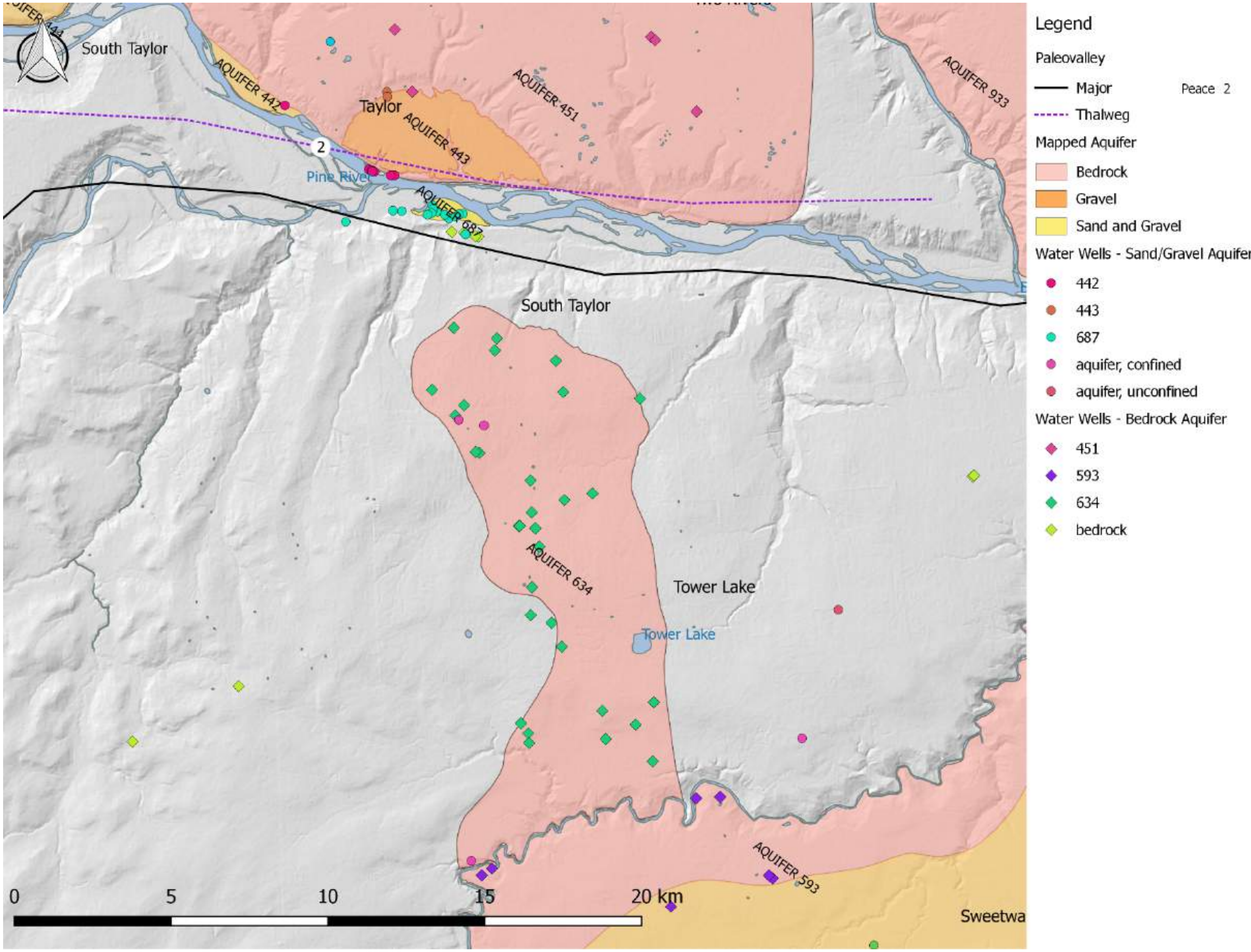


Figure 20. Taylor and areas south of the Peace River Valley

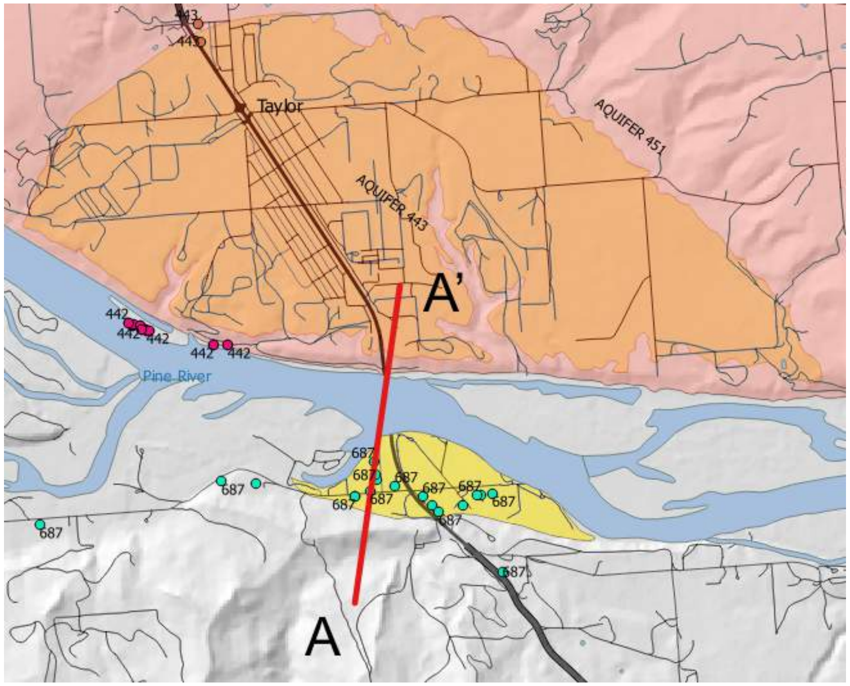
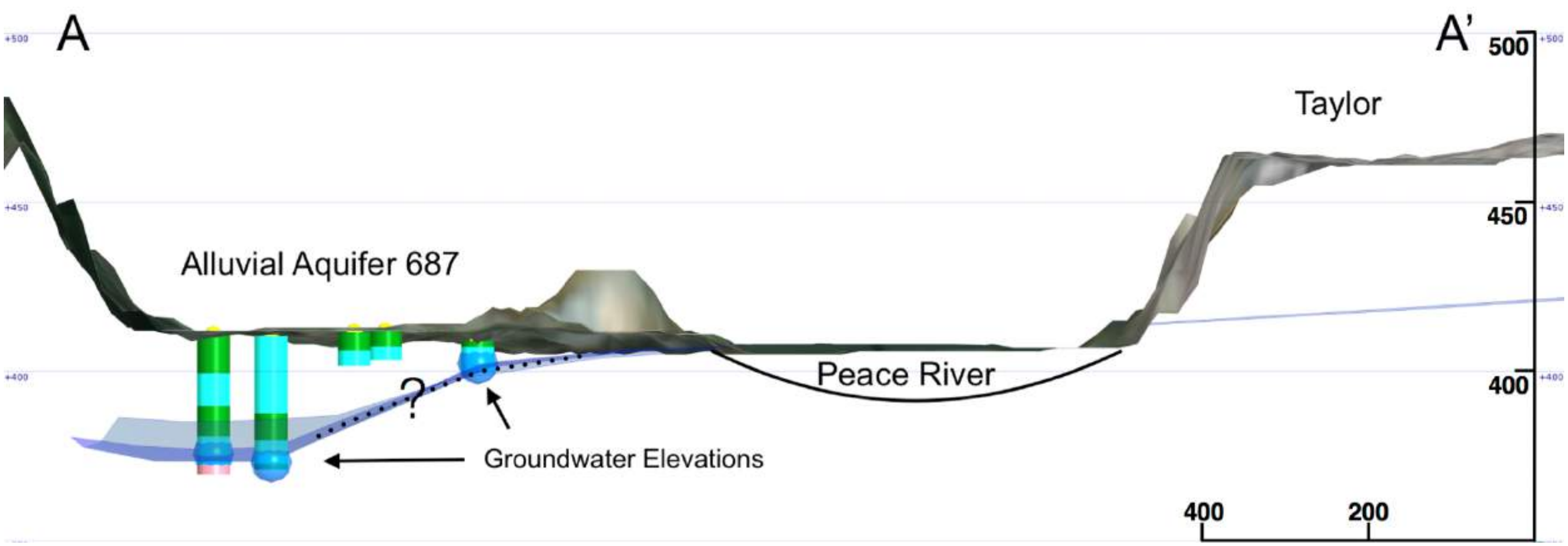


Figure 21. Model slice A-A' through Taylor to Peace River south, showing spatial relationship between the river and alluvial aquifer 687.



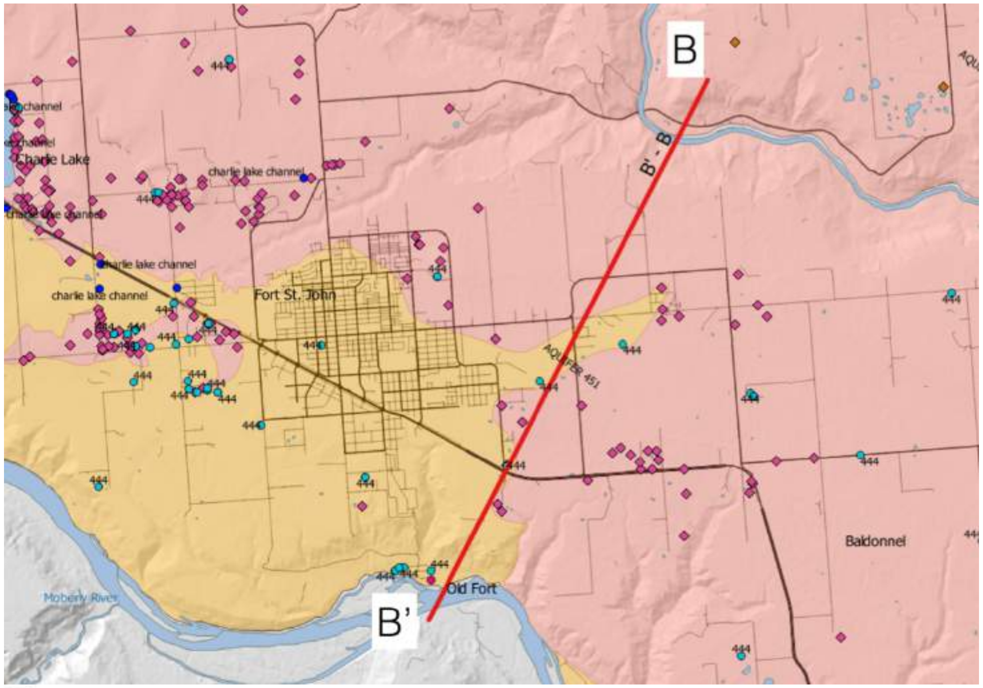
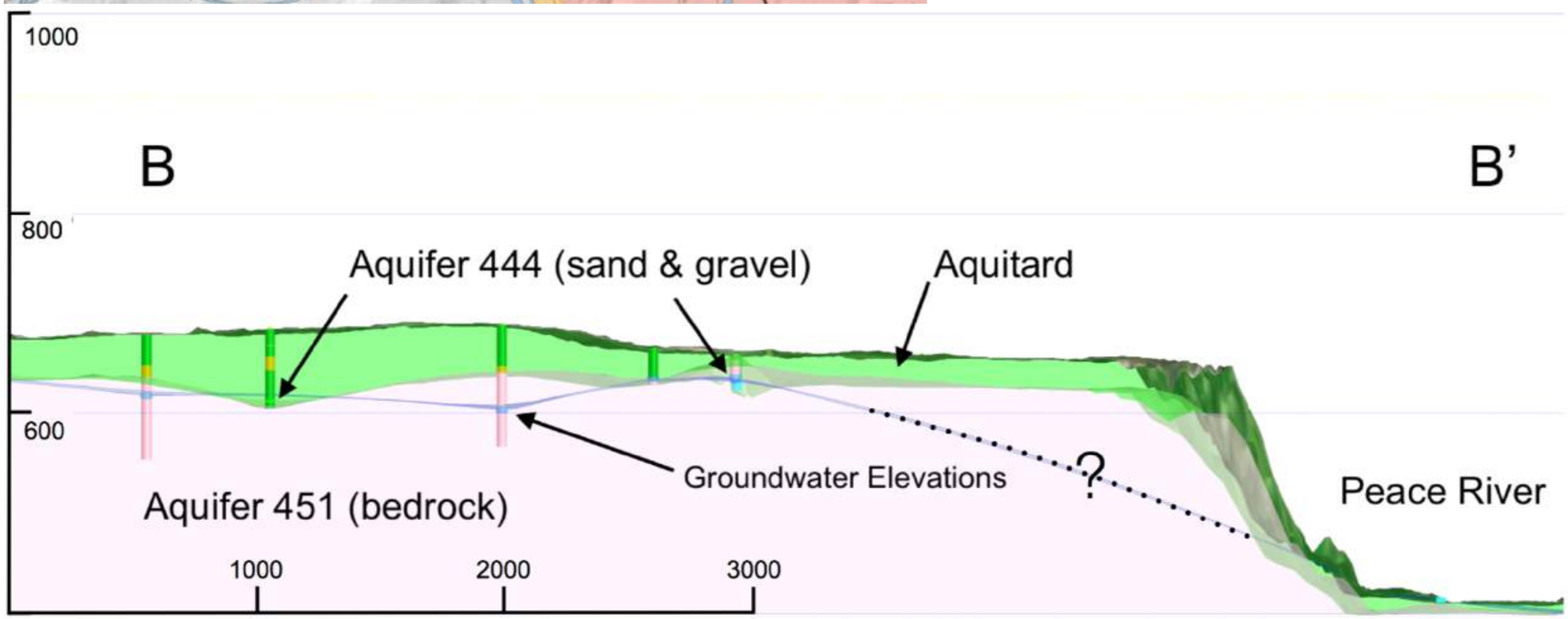
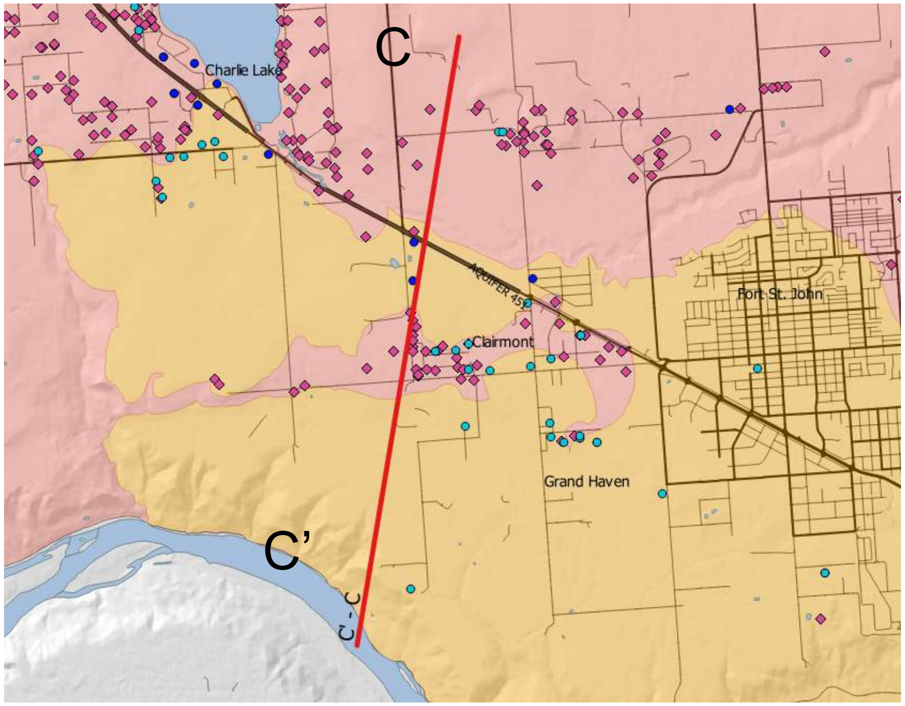


Figure 22. Model slice B-B' through east Fort St. John area shows relative position of aquifer 444 and bedrock aquifer 451, north of the Peace River. The groundwater elevation is over 200 m above the level of the river. Piezometric levels from bedrock wells are in many cases lower than those taken from overburden wells.





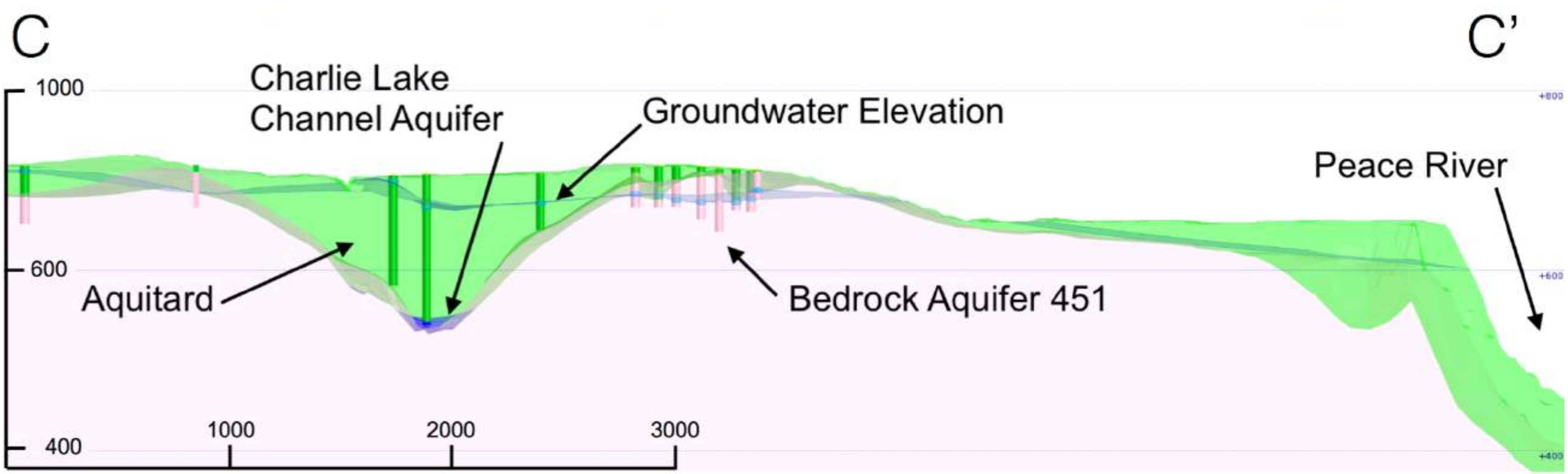


Figure 23. Model slice C-C' through west Fort St. John area from Charlie Lake buried channel aquifer through the bedrock aquifer 451 to the Peace River Valley.

1.3 Summary

Aggregate HGU physical data shown in Figures 24 and 25 illustrates the broad characteristics of each aquifer. Unconfined aquifers alluvial fan/terrace, river valley deposits tend to be shallow, moderately thick units with water table within the unit itself. Buried channel aquifers (Charlie Lake buried channel and possibly unit 630) tend to be deep, thin units with high pressure (i.e. piezometric levels). Note that only two wells were registered and interpreted to be completed within aquifer unit 443, and no water levels were recorded for this unit.

Bedrock aquifers have low piezometric levels, with water levels that are, on average, within the bedrock itself. Aquifer unit 933 is the one exception in the area, with piezometric levels just above the bedrock and within the overburden.

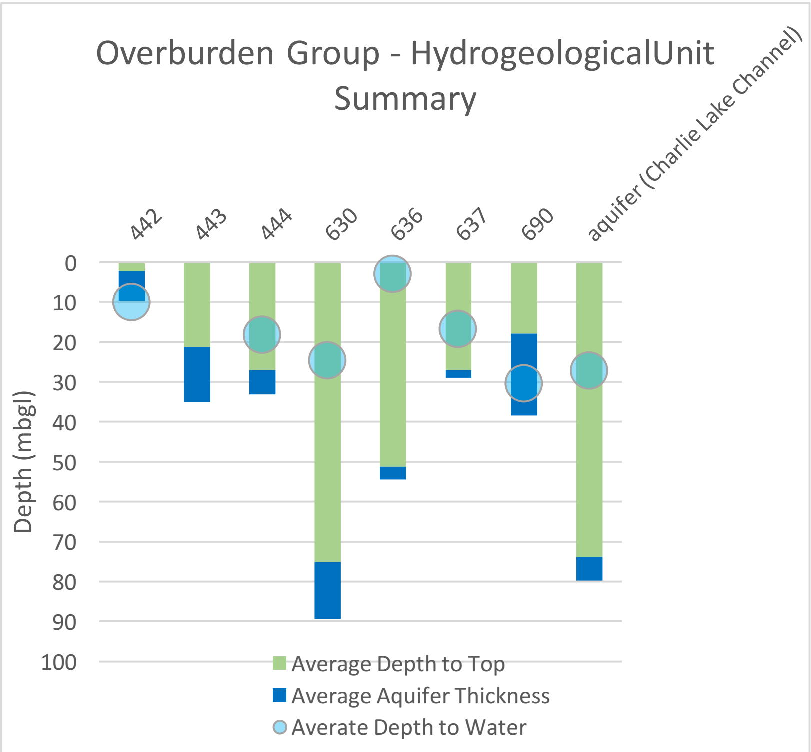


Figure 24. Aggregate HGU data for the surficial aquifer group – Fort St. John Area

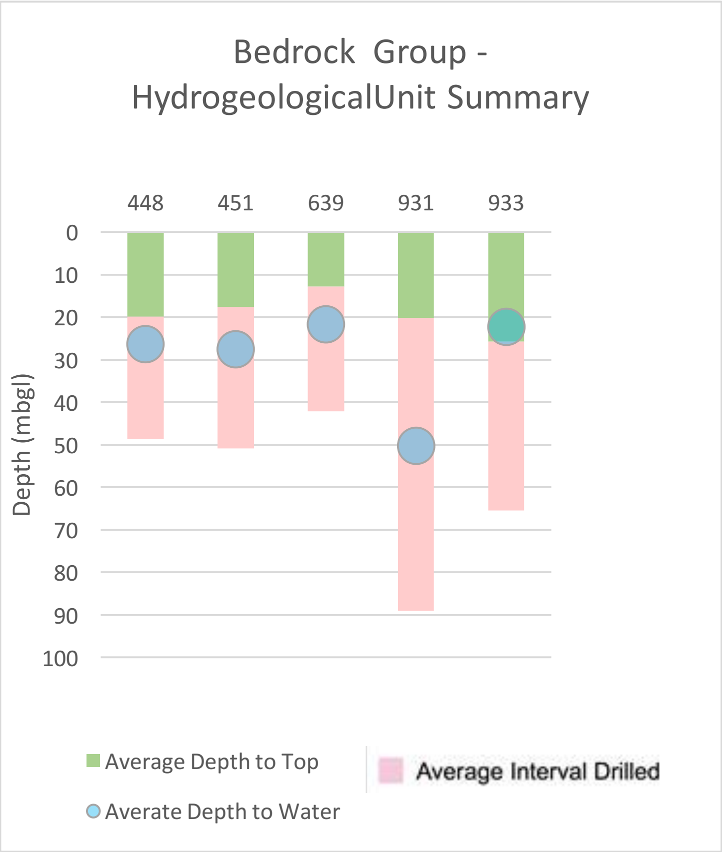


Figure 25. Aggregate HGU data for the bedrock aquifer group – Fort St. John Area

2 Hudson's Hope, Beryl Prairie

Two surficial aquifer units and two bedrock aquifer units are recognized in the Hudson's Hope and Beryl Prairie area and these are summarized in Table 4.

Table 4. Summary of aquifer HGU's in the Hudson's Hope, Beryl Prairie area.

Hydrogeological Unit	Average Depth to Water (m)	Hydrogeological Group	Description
440	28	Sand and Gravel	High energy glacio fluvial sand & gravel - Hudson Hope
910	48	Sand and Gravel	Fluvial deposits of sand & gravel - Beryl Prairie, East of Williston Lake
441	36	Bedrock	Fort St. John Group - Lynx Creek & Peace River
928	10	Bedrock	Fort St. John Group - Lynx Creek & Peace River

2.1 Surficial aquifers

The upper bench area of Beryl Prairie is mapped as glacial fluvial deposits and these host Aquifer 910. This is a confined sand and gravel aquifer capped by a thick silt and clay-rich layer. Groundwater depths in Aquifer 910 are relatively shallow, not much higher than the aquifer itself.

The Hudson's Hope area has surficial aquifer 440, situated in the alluvial terrace above the Peace River Valley. Aquifer 440 is unconfined.

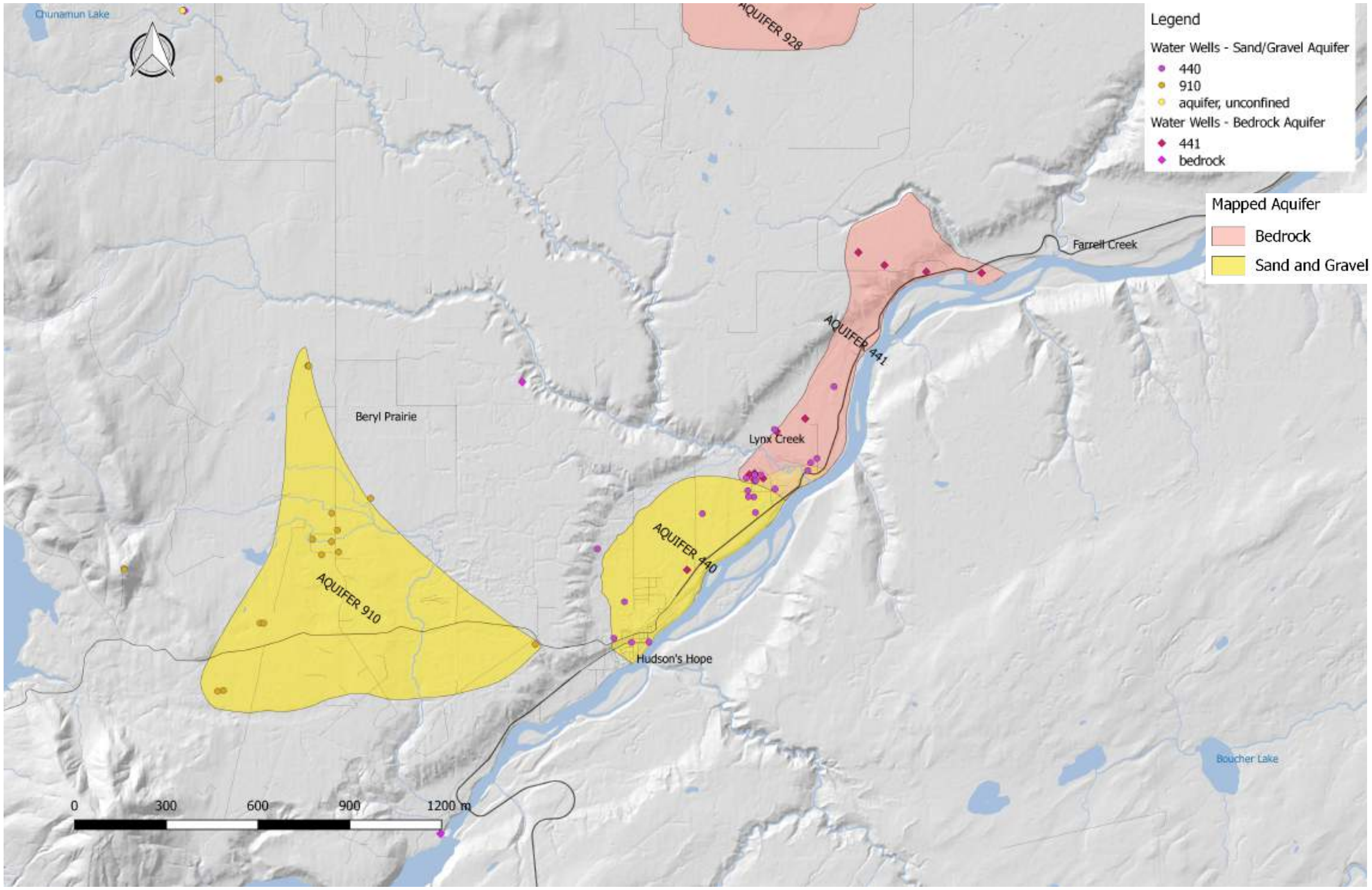


Figure 26. Aquifers and HGU's linked to individual wells it the Beryl Prairie and Hudson's Hope area.

Wells were linked to HGU's in the schema, based on the BC mapped aquifers in the Hudson's Hope area (Figure 26). Aquifer 910 throughout Beryl Prairie is a confined sand and gravel unit, with an overlying silt-rich confining unit. Groundwater levels in these wells were measured to be just above the upper level of the saturated sediment. Aquifer 440 is interpreted as several sand and gravel units in the alluvial terrace system. The alluvial sand and gravel is not everywhere saturated or groundwater-producing, as several wells indicating "dry conditions" were encountered and drilling proceeded into the underlying bedrock.

2.2 Hydrogeological Framework

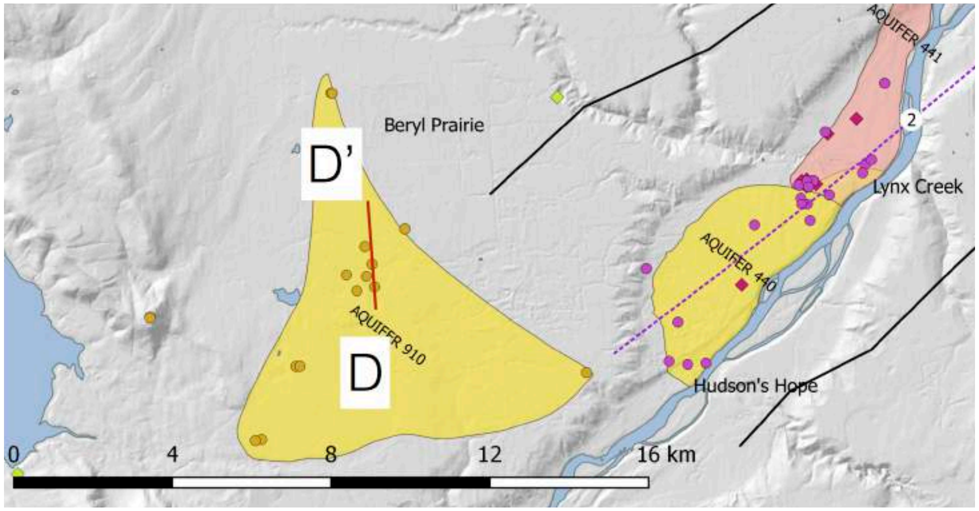
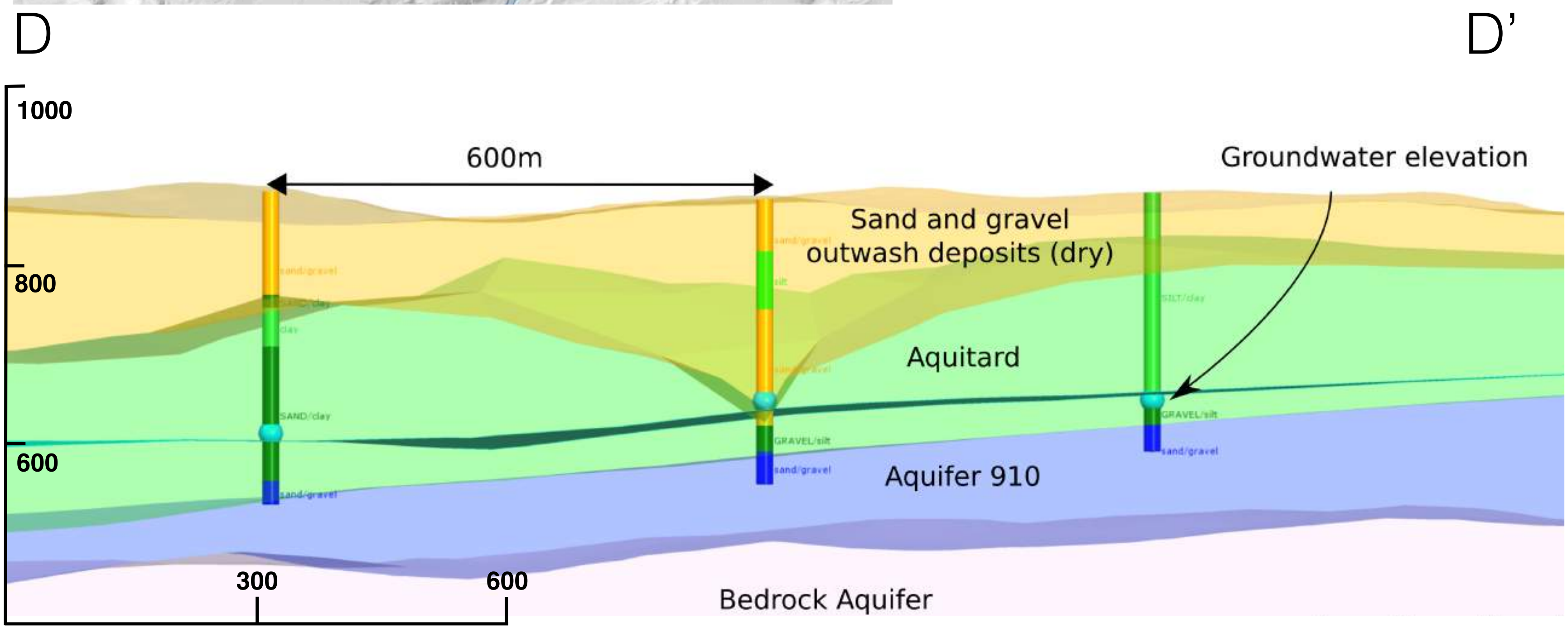


Figure 27. Model slice D-D' through aquifer 910 in the Beryl Prairie area. Aquifer 910 is a moderately deep sand and gravel unit (dark blue in the slice below), with an overlying silt-rich confining unit (green). Groundwater levels in these wells were measured to be just above the upper level of the saturated sediment. Aquifer 910 directly overlies bedrock.



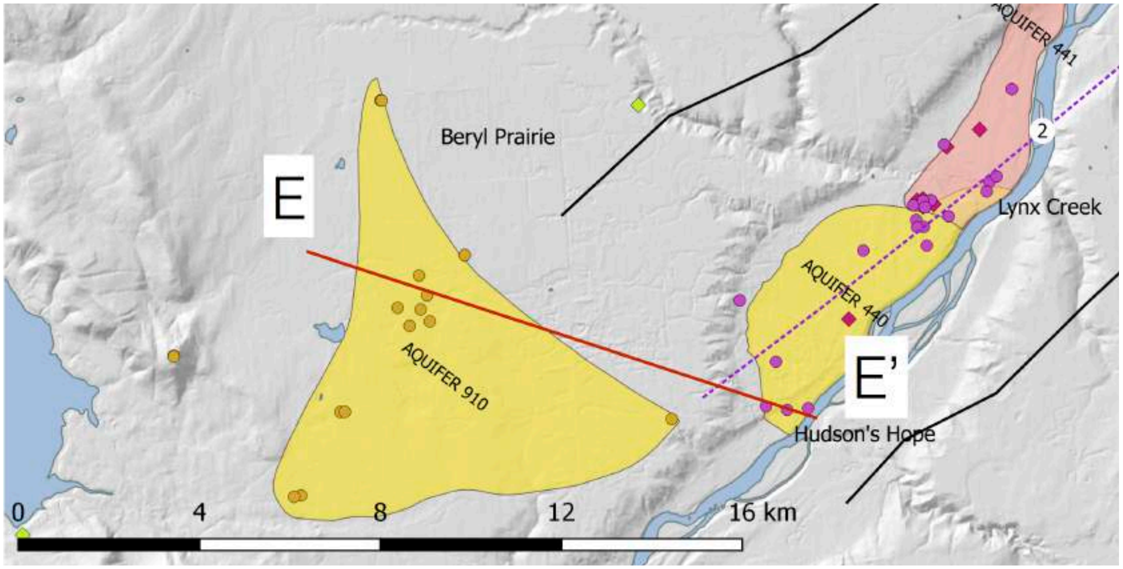
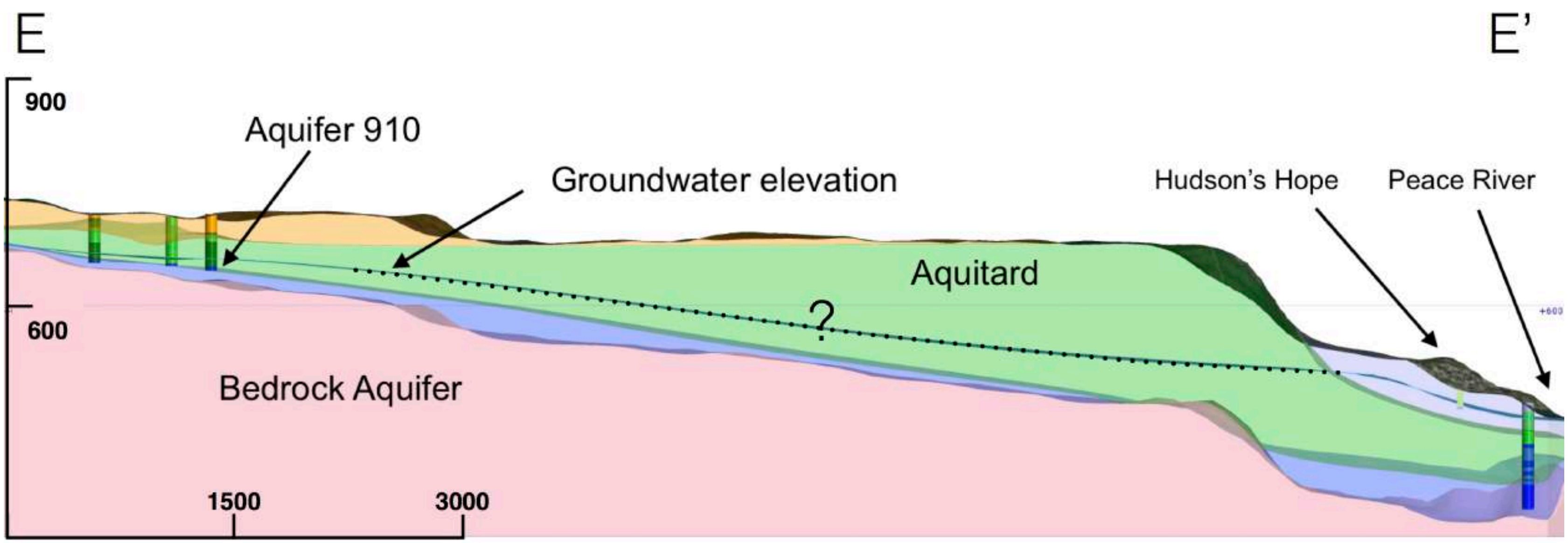


Figure 28. Model slice E-E' from Beryl Prairie to Hudson's Hope and Peace River. Aquifer 910 of Beryl Prairie and the deep aquifer supplying Hudson's Hope are likely pre-glacial fluvial deposits of the ancient Peace River drainage system.



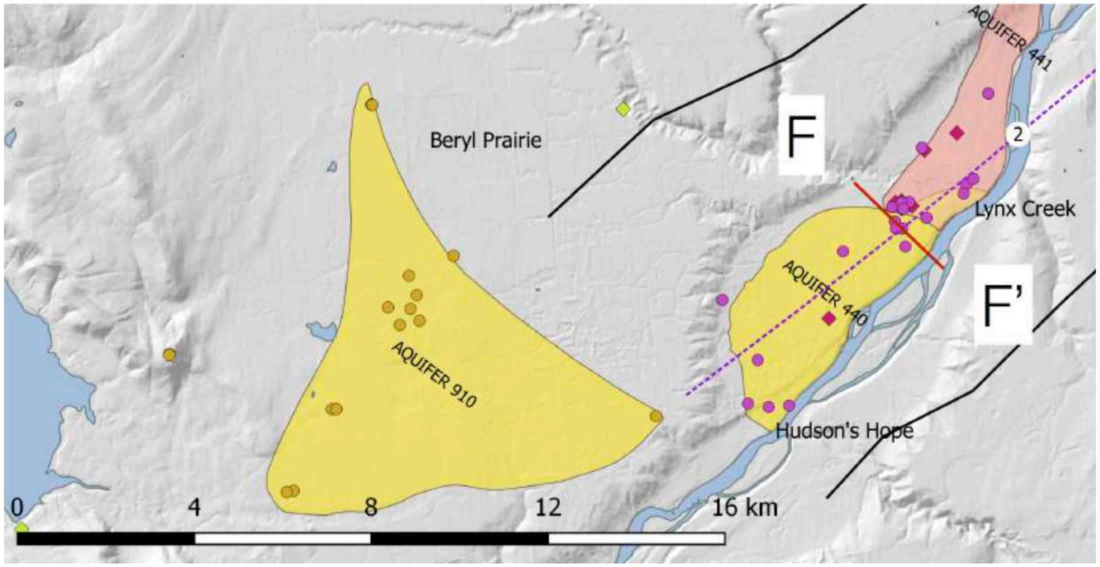
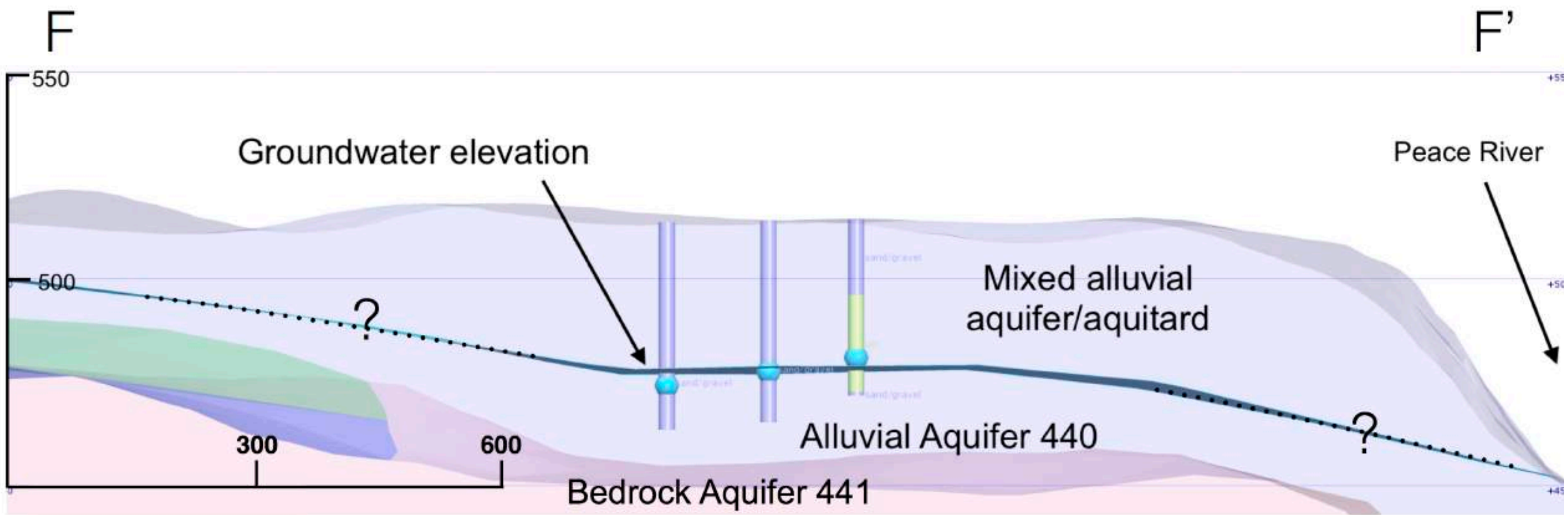


Figure 29. Model slice F-F' from Beryl Prairie to Hudson's Hope and Peace River. Aquifer 910 of Beryl Prairie and the deep aquifer supplying Hudson's Hope are likely pre-glacial fluvial deposits of the ancient Peace River drainage system.



2.3 Summary

Aggregate HGU physical data shown in Figure 30 illustrates the broad characteristics of each aquifer. Higher elevation aquifers display higher piezometric levels than do the lower elevation aquifers. Aquifer 440 is an unconfined aquifer, with the water table averaging 30 m below ground level, within the aquifer itself.

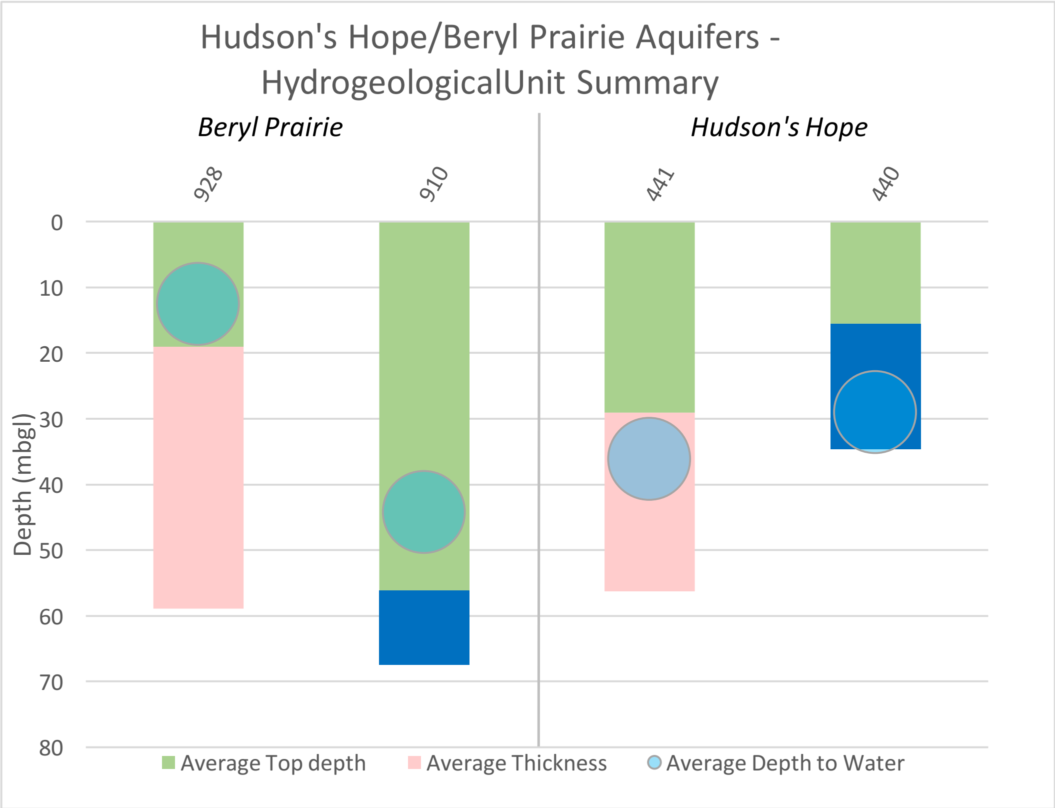


Figure 30. Aggregate HGU data for the overburden (blue) and bedrock (pink) aquifer groups.

3 Moberly Lake, Chetwynd, Jackfish Lake & Lone Prairie

We define a minimum of eight aquifer HGU's within the unconsolidated sediments of the Moberly, Chetwynd and Jackfish areas. Bedrock aquifers are treated as one unit in the models, although they are distinguished at the individual borehole level. Aquifers 626, 630, and alluvial fans aquifers are encountered in the Chetwynd to Jackfish Lake corridor; Aquifer 923 is found northeast of Moberly Lake.

Table 5. Summary of water-bearing Hydrogeological Units in the Moberly Lake/Chetwynd/Jackfish Lake area.

Hydrogeological Unit	Average Depth to Water (m)	Hydrogeological Group	Description	Geographic Area
623	22	Sand and Gravel	Sand & gravel of glacial or pre-glacial origin - Lone Prairie area	Chetwynd
624	10	Sand and Gravel	Alluvial fan and glaciofluvial deposits-intermixed - Wildmore Ck.; Chetwynd	Chetwynd
625	7	Sand and Gravel	Alluvial fan deposits - Dokie Siding	Chetwynd
626	10	Sand and Gravel	Buried channel aquifer – Chetwynd area	Chetwynd
628	4	Sand and Gravel	Alluvial fan deposits	Chetwynd
629	2	Sand and Gravel	Alluvial fan deposits	Chetwynd
630	28	Sand and Gravel	Buried channel aquifer – Jackfish Lake, northeast of Chetwynd	Jackfish Lake
923	9	Sand and Gravel	Glaciofluvial deposits of sand, gravel & silt - Moberly Lake	Moberly Lake
627	12	Bedrock	Cruiser Formation - Chetwynd area; West of Dokie Siding	Chetwynd
688	15	Bedrock	Dunvegan Formation - East of Chetwynd; North of Pine River	Chetwynd
689	19	Bedrock	Dunvegan Formation - Southeast of Chetwynd; South of Pine River	Lone Prairie
917	34	Bedrock	Dunvegan Formation - Near East Pine	East Pine

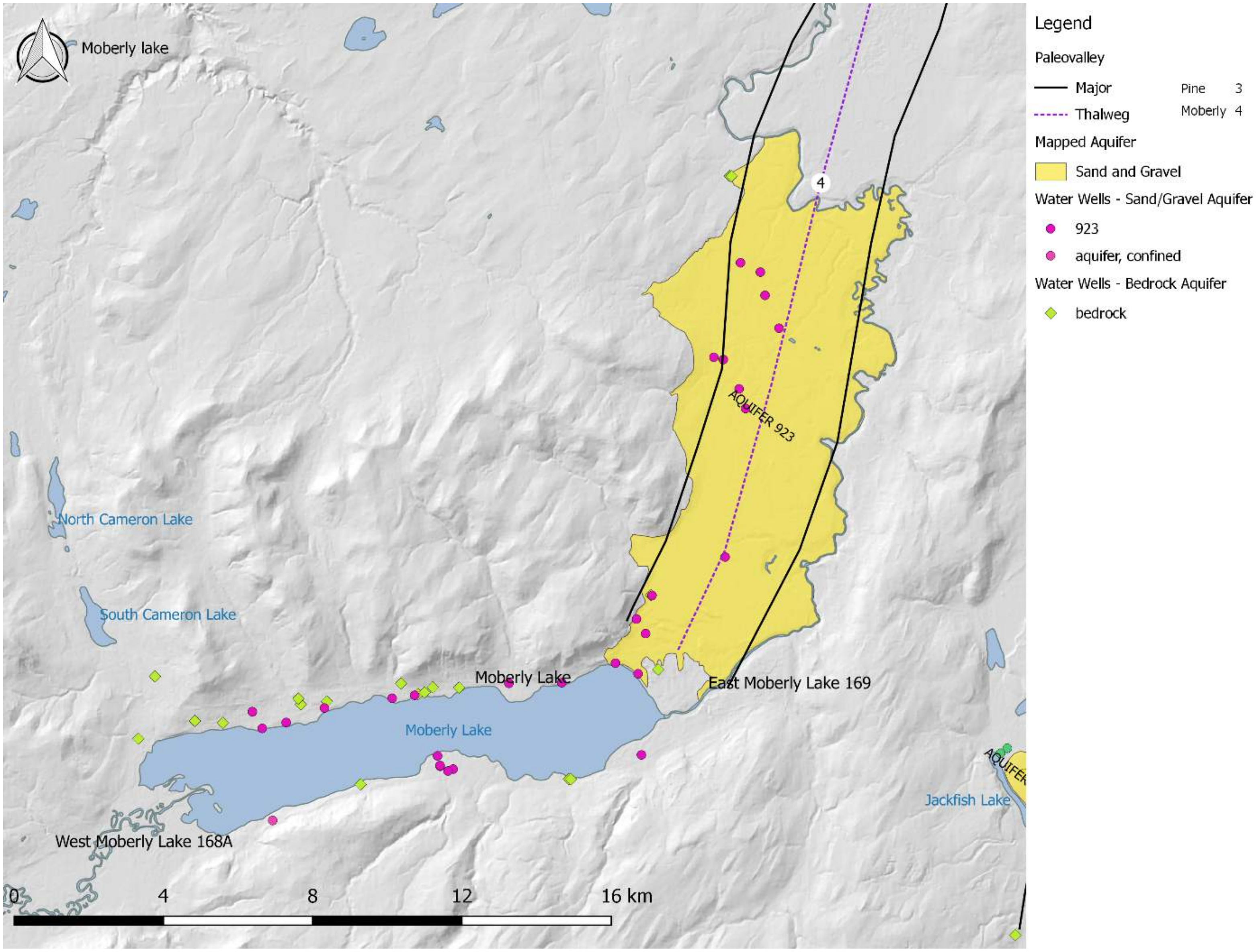


Figure 31. Moberly Lake wells draw from three aquifers: Aquifer 923 (the Moberly channel aquifer); a local unconfined sand and gravel aquifer (likely dug wells); and a bedrock aquifer in locations where the surficial aquifers are absent.

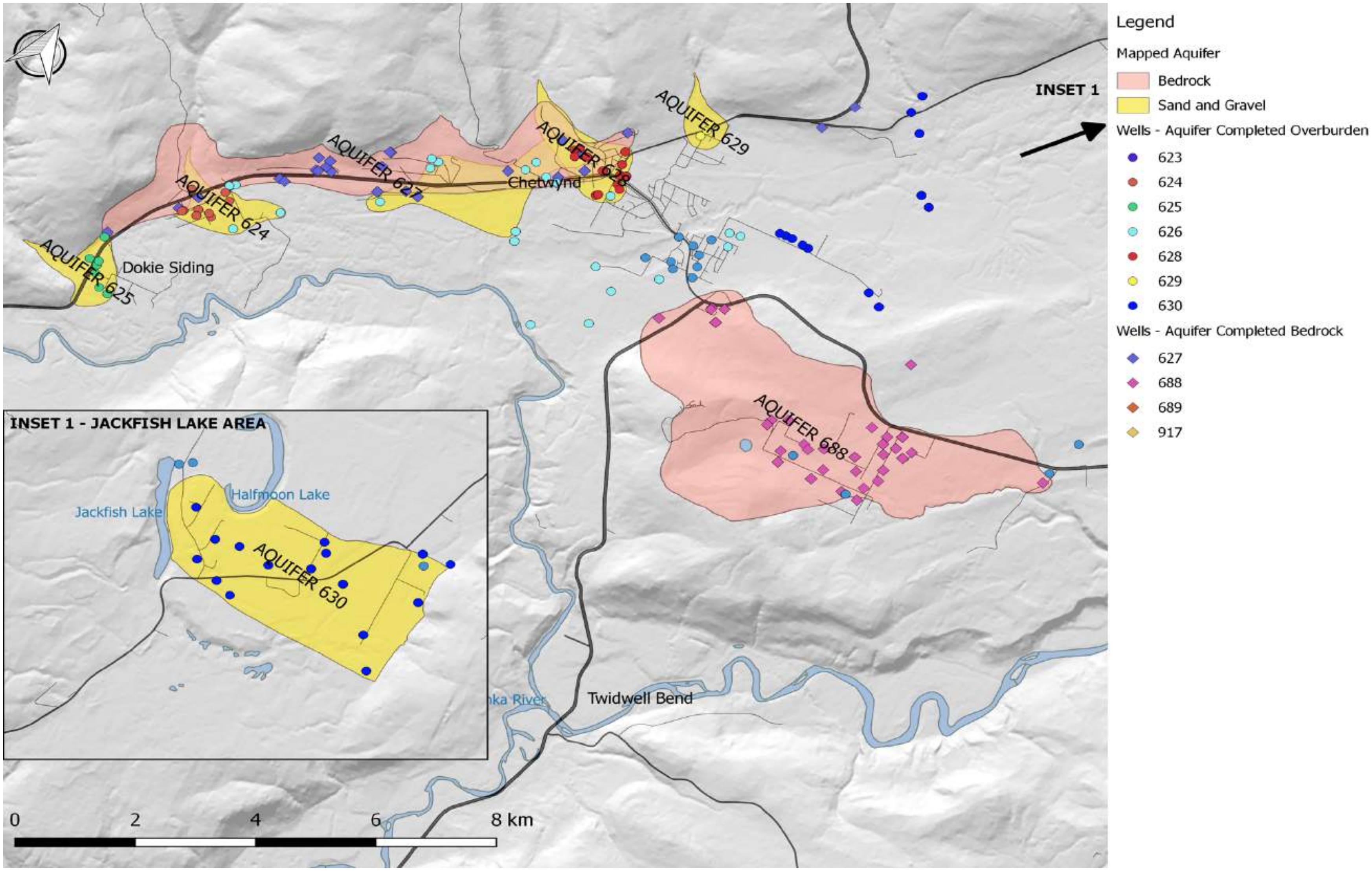


Figure 32. Chetwynd area wells draw from a host of surficial aquifers, ranging from shallow unconfined, alluvial deposits (624, 625, 628, 629) to deep, buried channels (626, 630). Bedrock aquifers (627, 688) are dominant in upland areas where surficial materials are thin.

The Lone Prairie area southeast of Chetwynd is between the Pine and Murray Rivers. This primarily agricultural area relies on one sand and gravel aquifer (623) and one bedrock aquifer (689) (Figure 33).

- Aquifer 623 is a sand and gravel aquifer encountered at depths in the order of 45 m below ground level.
- Aquifer 689 is comprised of bedrock of the Dunvegan Formation (primarily sandstone) and Kaskapau Formation (mudstone, siltstone, shale and fine clastic sedimentary rocks).

Surficial geology mapping indicates the Lone Prairie is blanketed by a mantle of fine-grained glacial lacustrine deposits throughout the central valley, and a till and colluvium-dominated upland portion. The relative thickness of surficial material versus bedrock encountered in boreholes from the Lone Prairie area indicates that the central valley contains the thickest cover of surficial material whereas, outlying, upland areas are bedrock-dominated.

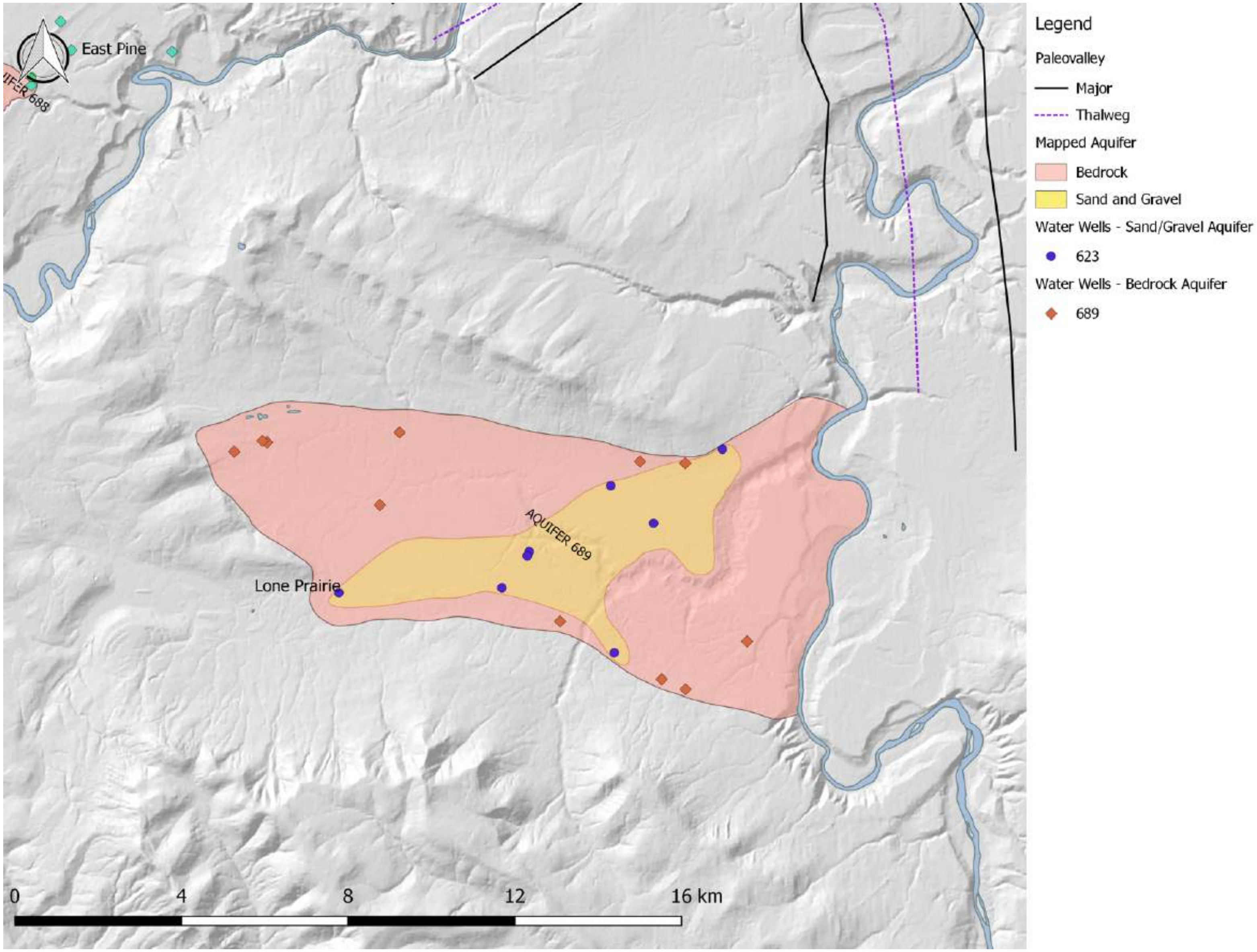


Figure 33. Wells linked the two aquifers mapped in the Lone Prairie area.

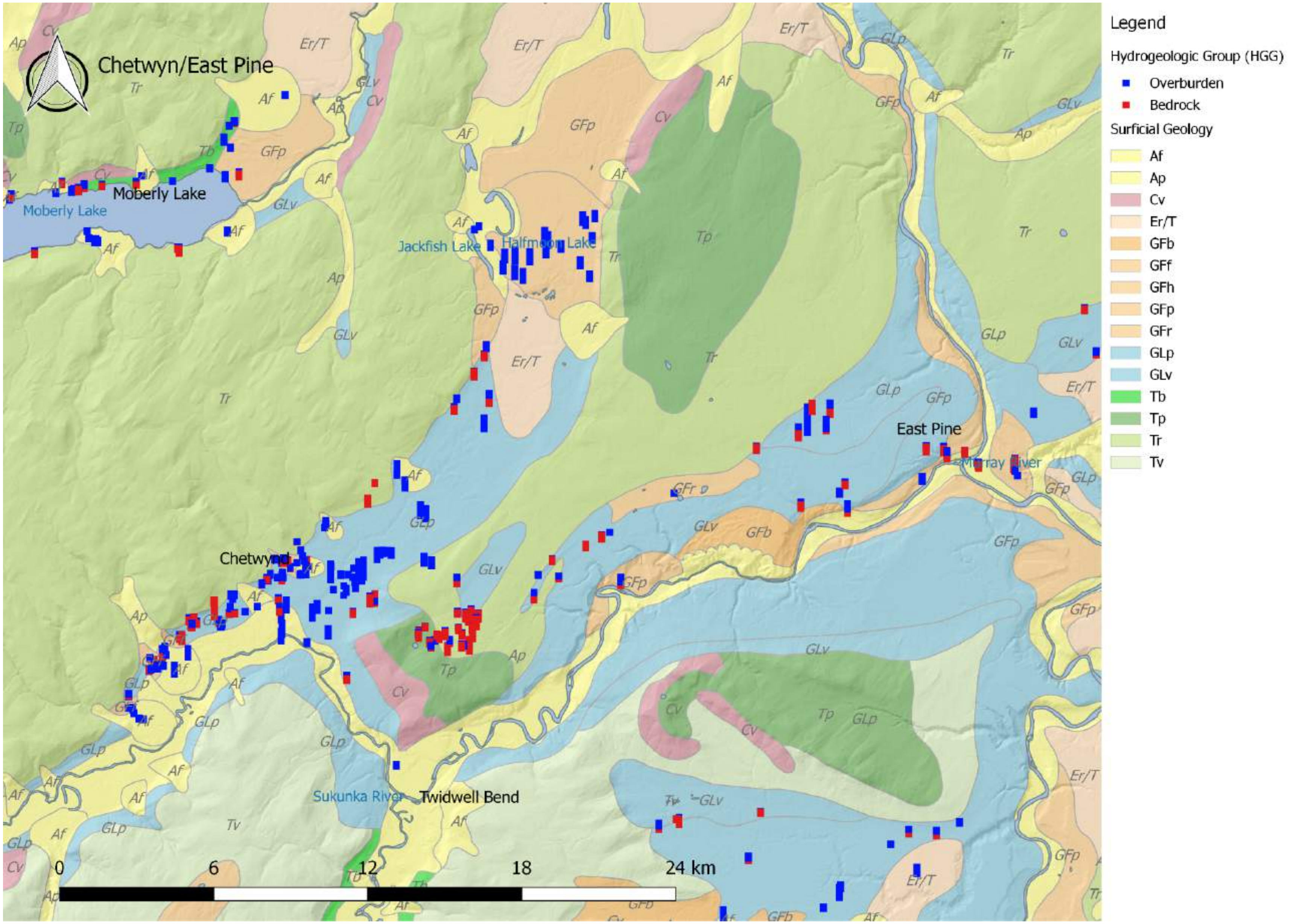


Figure 34. Borehole colours indicate the spatial clustering of bedrock wells (red) versus overburden wells (blue). Upland areas have thinner overburden and consequently have a groundwater regime in bedrock.

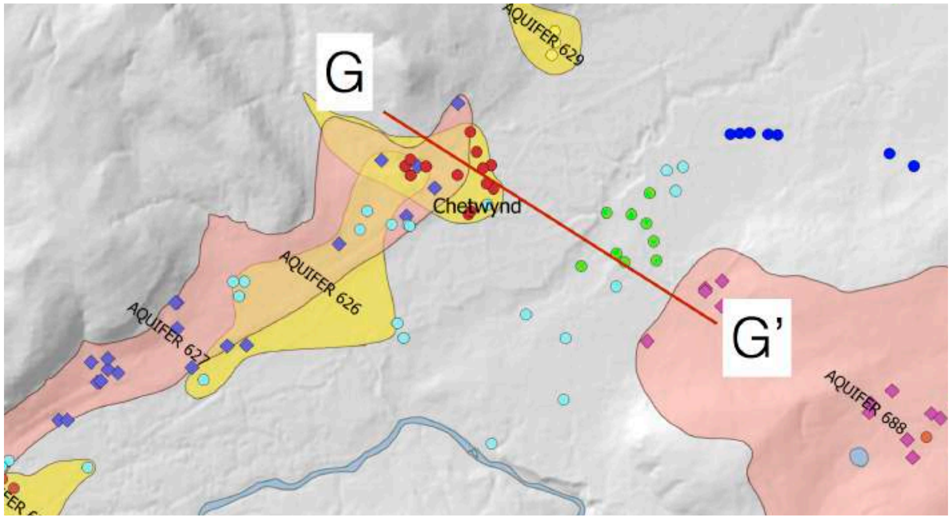
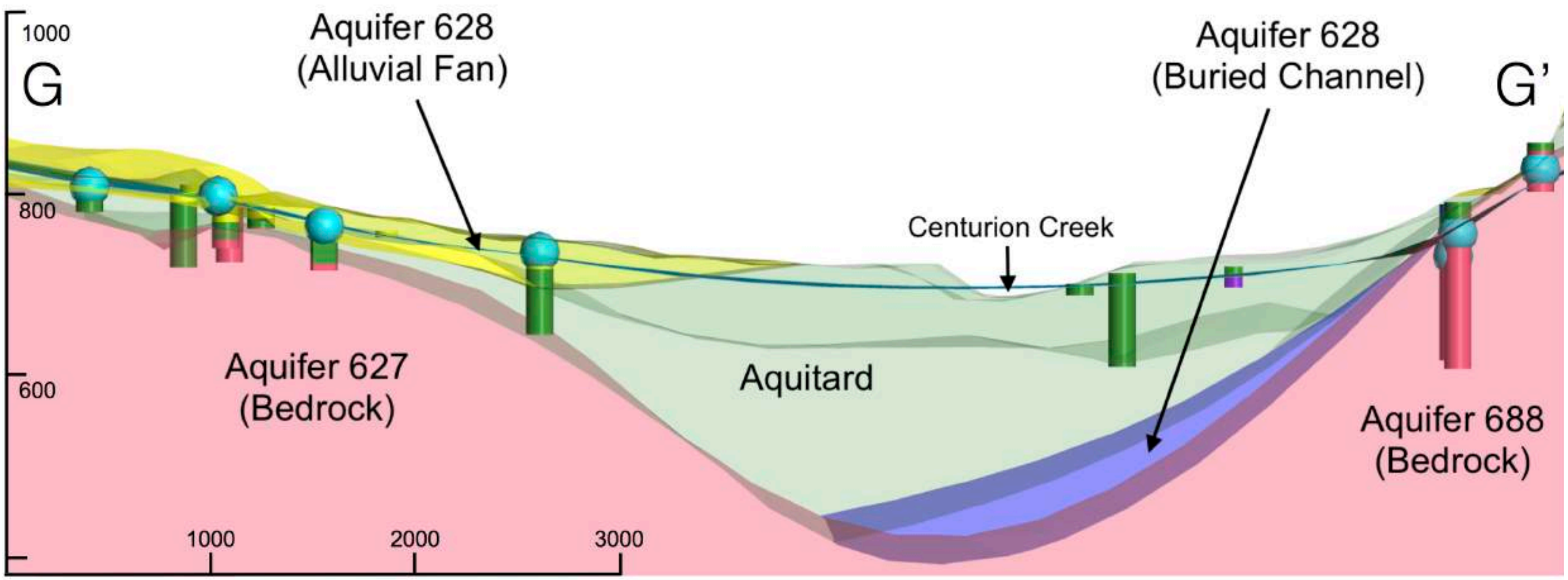


Figure 35. Model slice G-G' through Chetwynd showing alluvial fan aquifer 628 adjacent to bedrock-dominated uplands. A deep, buried channel along the Pine River Valley is filled with thick deposits of fine-grained material with aquitard characteristics.



3.1 Framework Summary

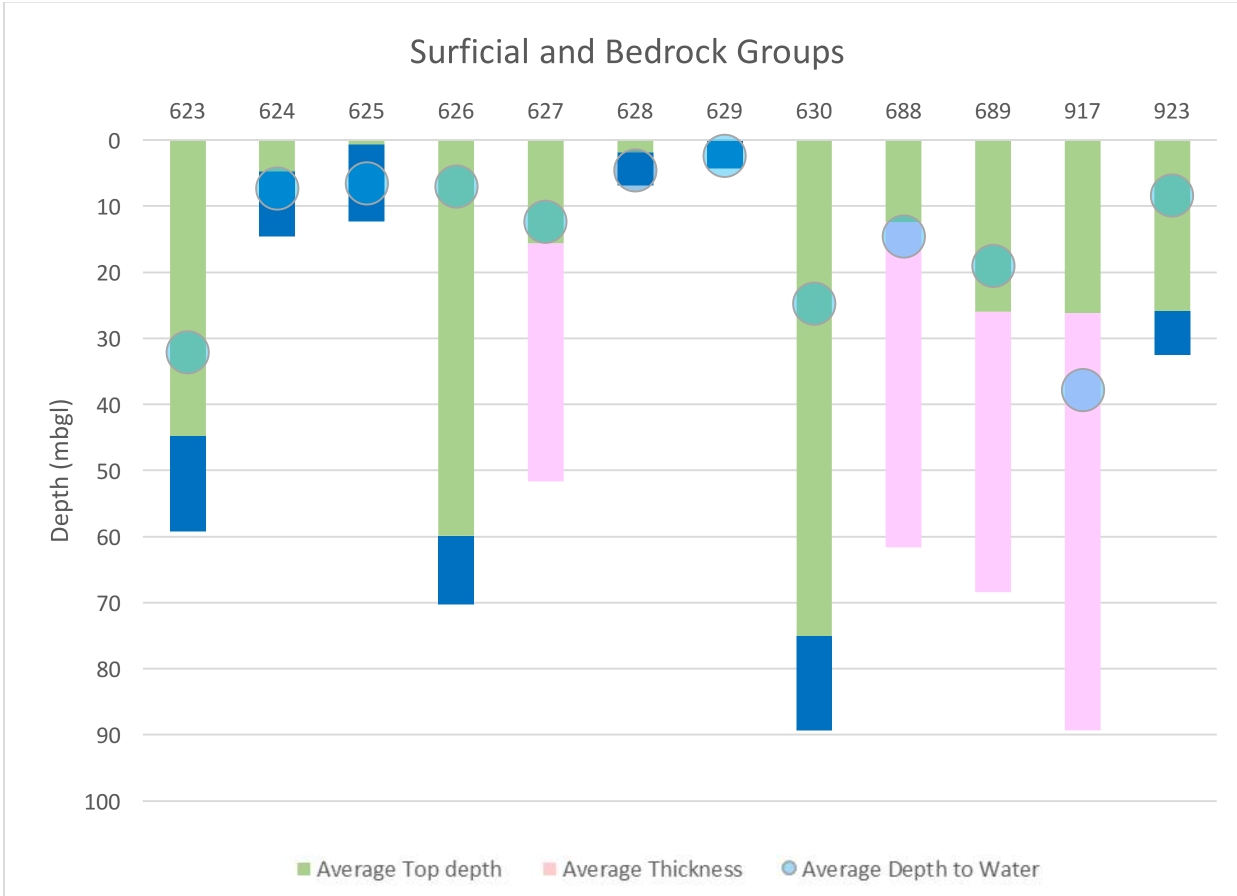


Figure 36. Summary statistics for hydrogeological aquifer units. All three surficial aquifer types are represented in the area, including: unconfined alluvial (624, 625, 628, 629); moderately deep, confined (923, 623) and buried channels (626, 630). With the exception of 917, bedrock aquifers in the Chetwynd area have piezometric levels within the overburden. Outlying areas such as Lone Prairie (688) and East Pine (917) have, on average, piezometric levels within the bedrock.

4 Groundbirch, Dawson Creek Area

The Groundbirch/Dawson Creek area has six surficial aquifers and five bedrock aquifers, according to BC aquifer mapping (Table 6). Thicker accumulations of surficial material are concentrated along the axes of paleo-drainage systems running through the Groundbirch area in a southwest-northeast direction. Upland areas have poor potential for surficial aquifers and the wells are in bedrock (Figure 37). Based on currently available data, there was deemed to be insufficient data to allow a 3D interpolation of surficial aquifers in the area. In addition, we understand that this area is the subject of a hydrogeological characterisation project by BC MoE and FLNRO, in collaboration with Simon Fraser University; therefore, GW Solutions did not want to duplicate efforts.

Nevertheless, GW Solutions has correlated borehole data to mapped aquifers in the area (Figure 38). Bedrock wells could be correlated to the established aquifer classification scheme. An attempt was made to correlate overburden units; however, more borehole data is needed in order to reduce the uncertainty of these correlations.

Table 6. Summary of water-bearing Hydrogeological Units in the Groundbirch/Dawson Creek area.

Hydrogeological Unit	Average Depth to Water (m)	Hydrogeological Group	Description
590	25	Sand and Gravel	West Groundbirch area
592	7	Sand and Gravel	Willow Valley area
594	27	Sand and Gravel	Wisconsinan sediments - Groundbirch Buried Channel
596	24	Sand and Gravel	Laurentide Glacial lake - Progress
597	23	Sand and Gravel	Wisconsinan sediments - Arras Buried Channels
598	2	Sand and Gravel	Recent fluvial deposits - Pouce Coupe
589	9	Bedrock	Dunvegan Formation - East of Pine and Murray River confluence
591	21	Bedrock	Smoky Group, Kaskapau Formation - Groundbirch, Willow Valley, Sunset Prairie
593	23	Bedrock	Kaskapau Formation, Smoky Group - Bear Mountain, Dawson Creek area
595	19	Bedrock	Dunvegan Formation - North of Sunset Creek, Sunset Prairie
622	38	Bedrock	Dowling, Thistle, Hanson and Muskiki Members - South of Pouce Coupe

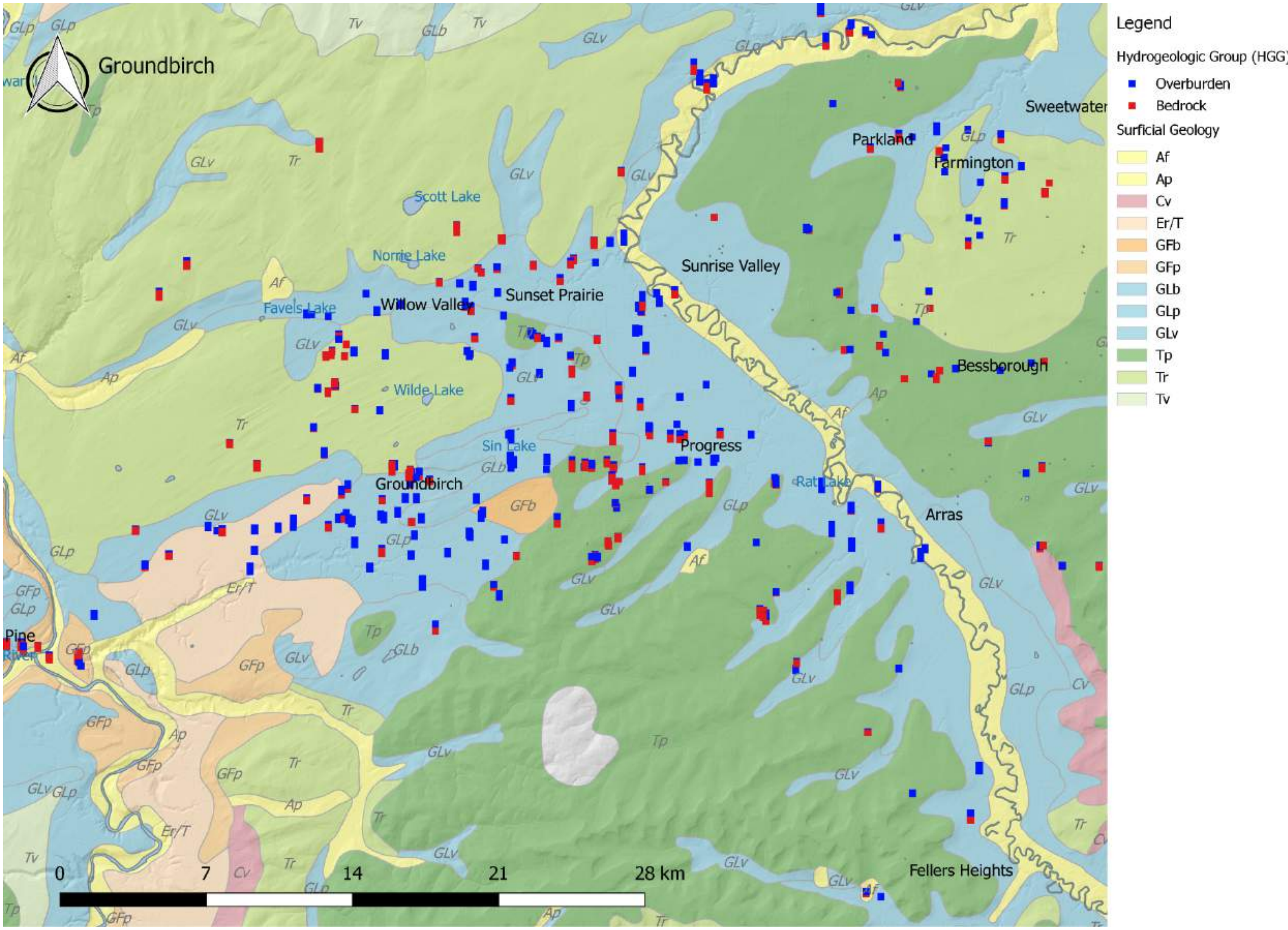


Figure 37. Borehole colours indicate the spatial clustering of bedrock wells (red) versus overburden wells (blue).

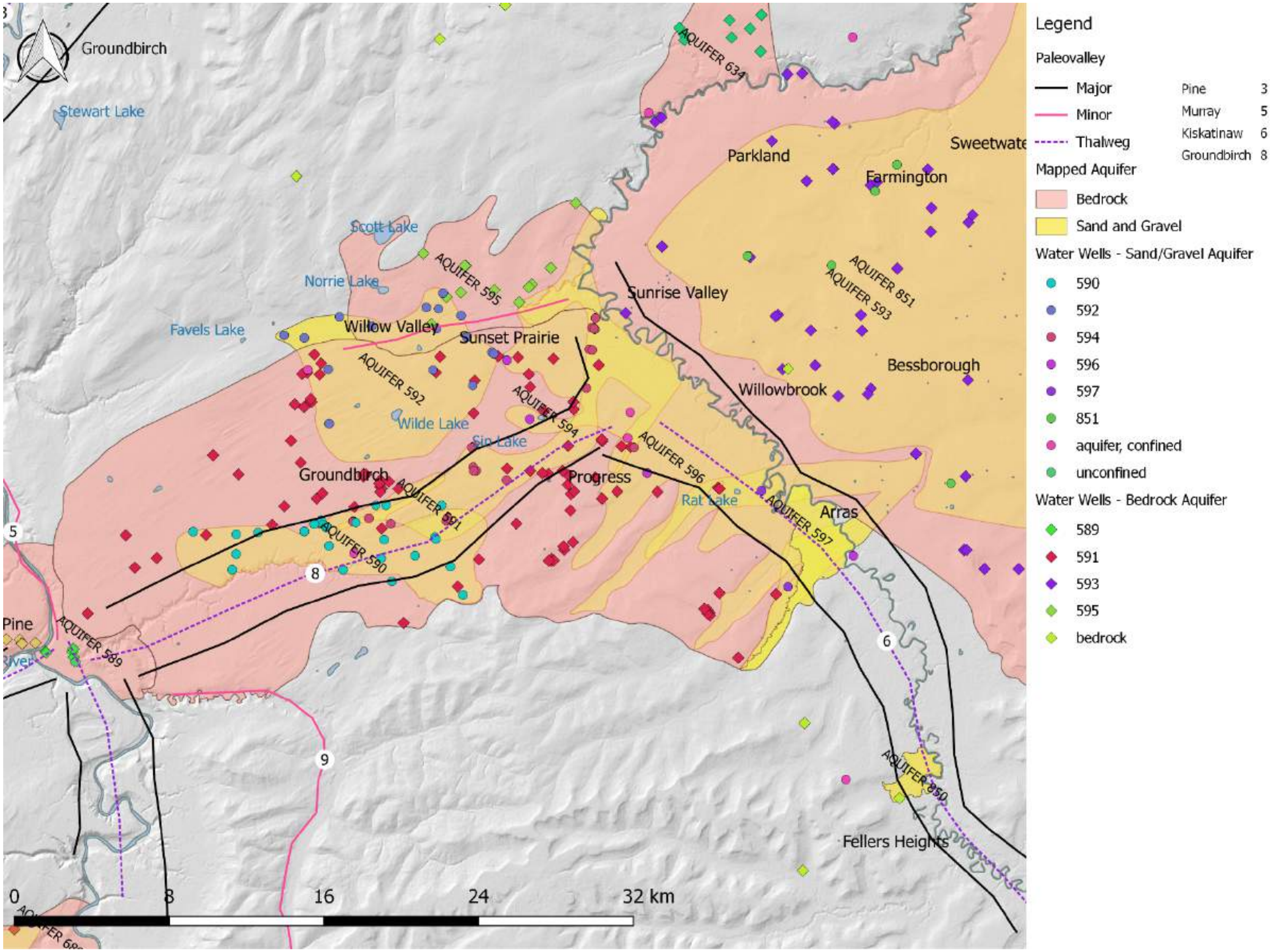


Figure 38. Individual wells linked to the hydrogeological unit and mapped aquifers.

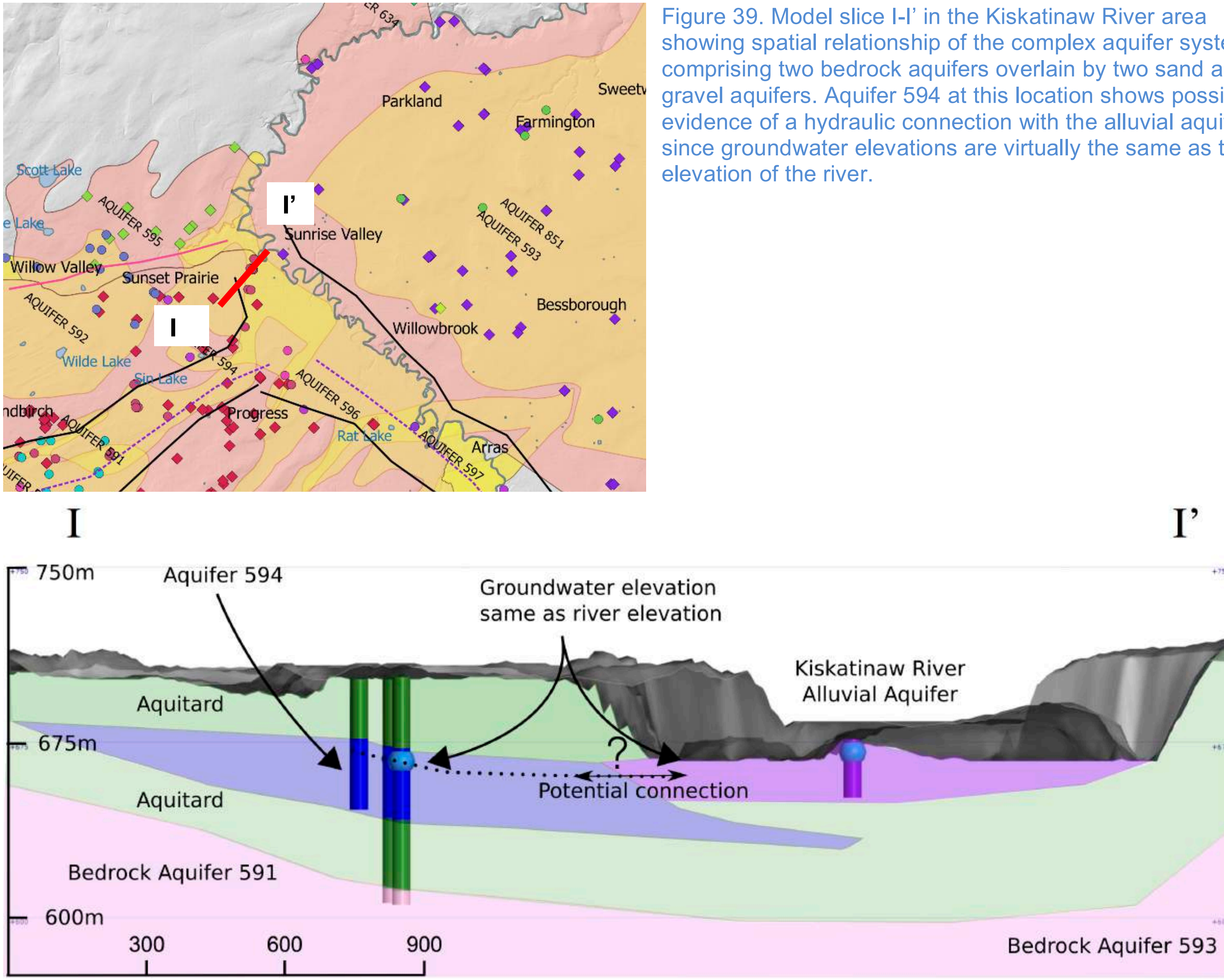


Figure 39. Model slice I-I' in the Kiskatinaw River area showing spatial relationship of the complex aquifer system comprising two bedrock aquifers overlain by two sand and gravel aquifers. Aquifer 594 at this location shows possible evidence of a hydraulic connection with the alluvial aquifer since groundwater elevations are virtually the same as the elevation of the river.

4.1 Framework Summary

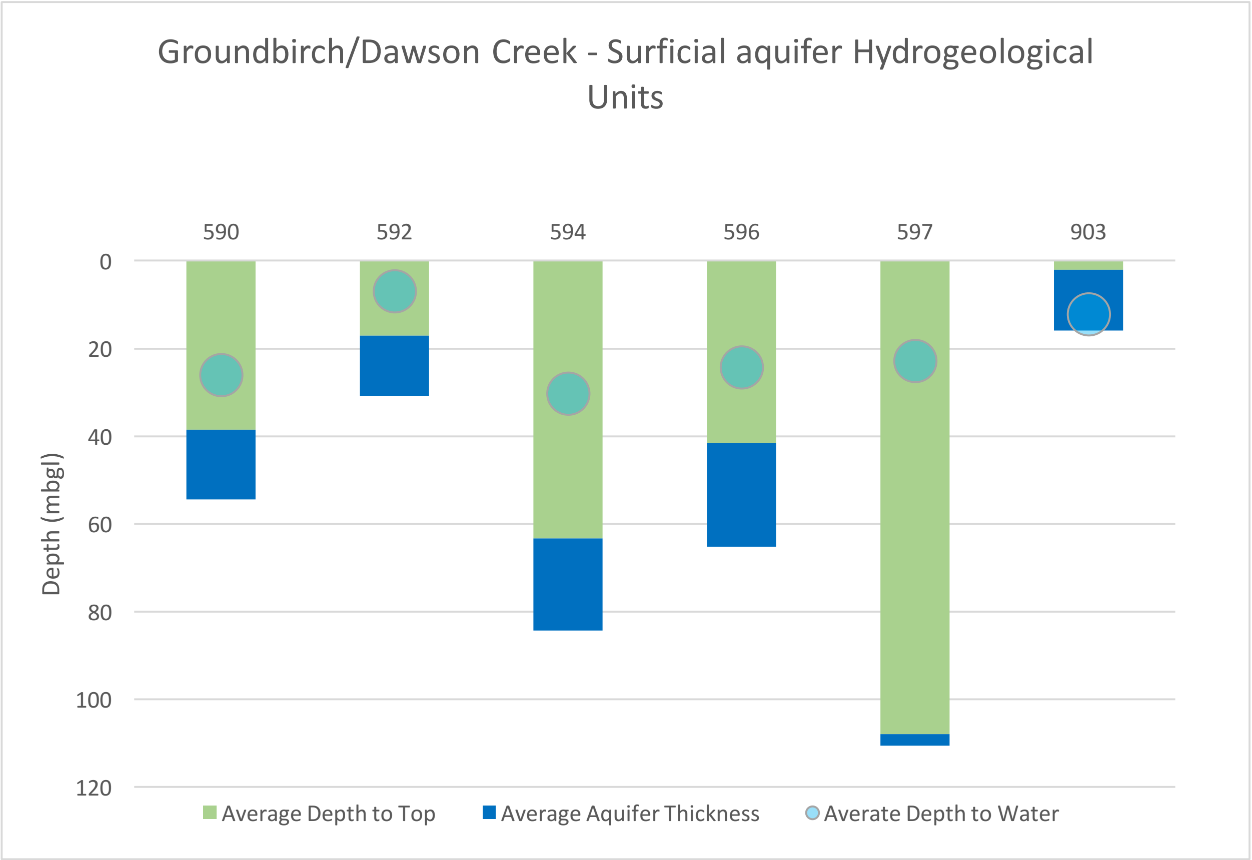


Figure 40. All three surficial aquifer types are represented in the Groundbirch/Dawson Creek area, including: unconfined alluvial (903); moderately deep, confined (590, 592, 598, 596) and buried channels (594, 597). Several HGU's were classified according to type, but could not be given a number from the BC mapping schema due to lack of data.

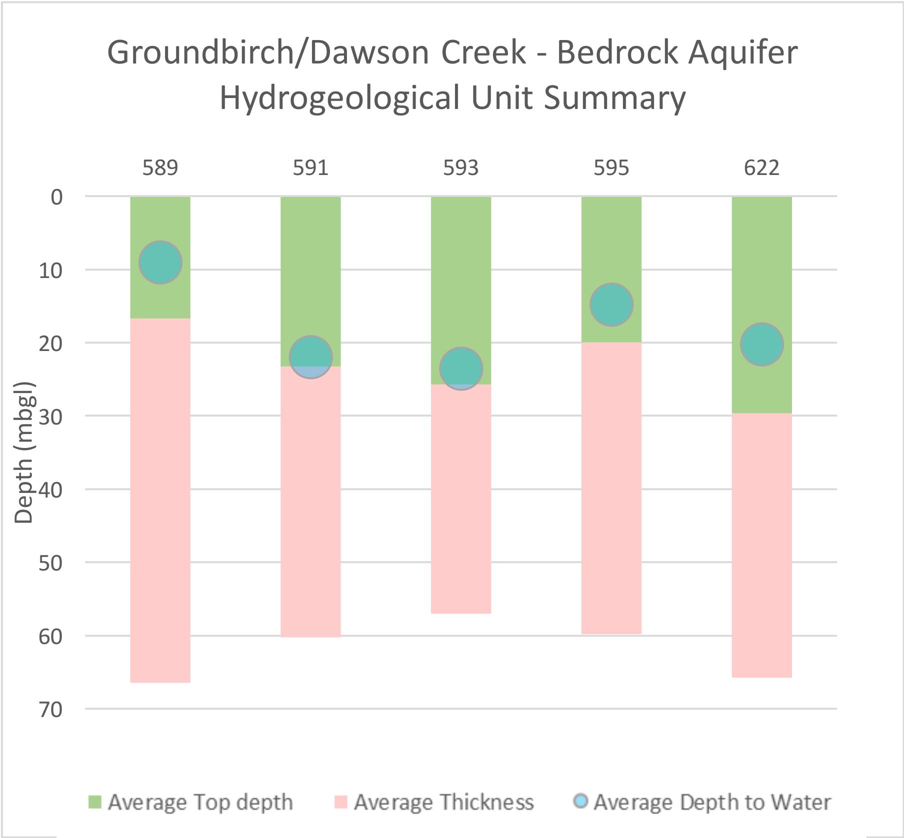


Figure 41. Bedrock aquifers in the Groundbirch/Dawson Creek area have, on average, piezometric levels above the top of bedrock.

5 Tumbler Ridge

The Tumbler Ridge area has two mapped surficial aquifers (Figure 42):

- Aquifer 635, located in the Flatbed Creek valley is unconfined or possibly "semi-confined", and comprised of thick, valley-fill and alluvial deposits.
- Aquifer 640, located on the upper bench of Tumbler Ridge itself, above the valley, is unconfined and comprised of alluvial terrace deposits.

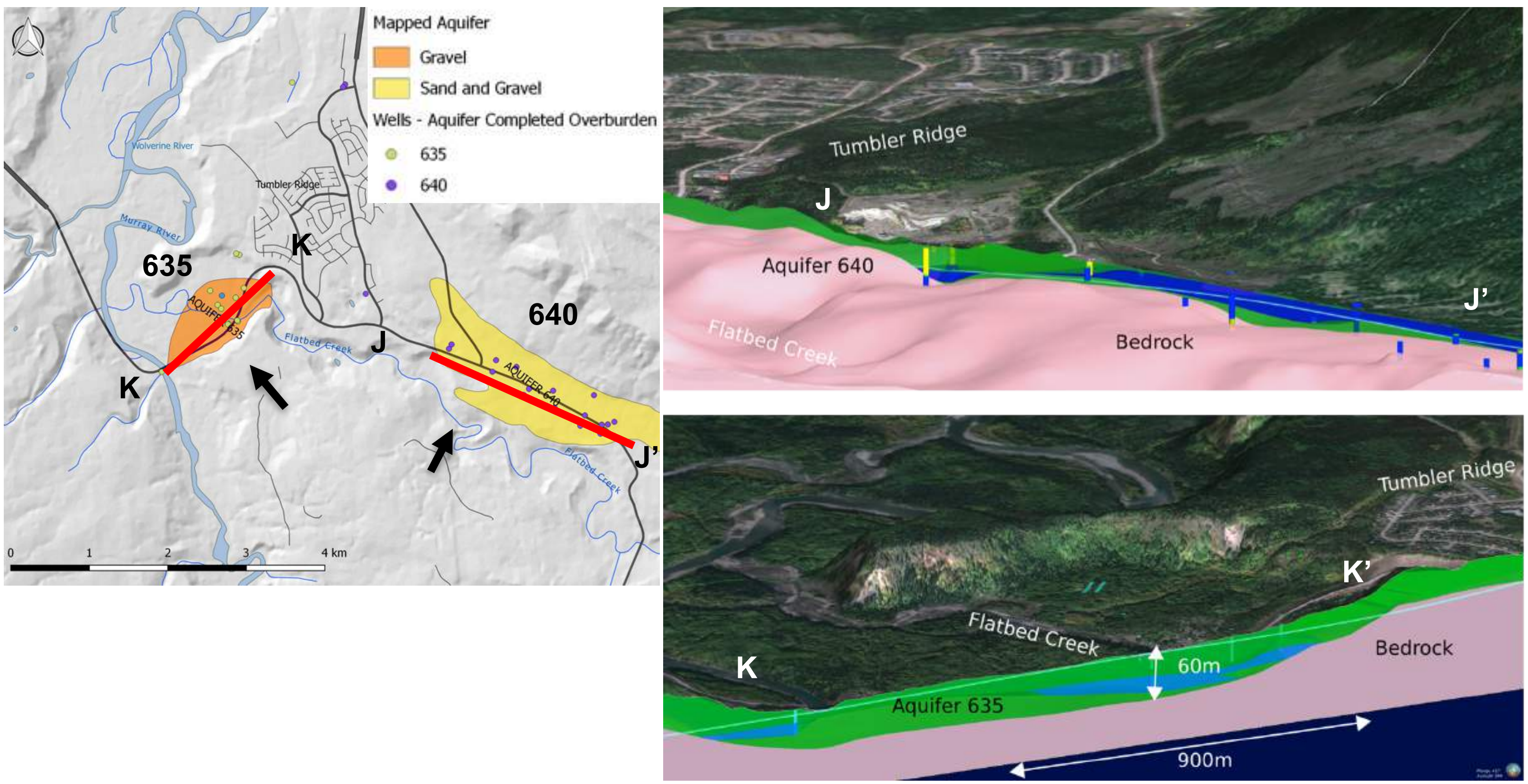


Figure 42. Tumbler Ridge aquifers 635 and 640 are two unconfined or "semi-confined" alluvial aquifers.

E. Groundwater Flow

Maps of piezometric levels are derived from water levels in wells. The shape of the piezometric contours across an aquifer may offer insight into the direction of groundwater movement. The water table in unconfined aquifers generally conforms to topography, and dips towards lower elevations (i.e., river valleys and lakes). Water levels measured in wells completed in deeper aquifers (i.e. confined or bedrock aquifers) produce contours that do not necessarily coincide with local topography. In addition, it is very complex to define piezometric contours over the whole region since water level data is spatially (sparse and patchy) and temporally (different timeframe) complex. Interpolating water table or piezometric surfaces and contours will be influenced by the density of data and the degree of clustering, as well as the season or year a measurement was taken. A lot of manual interpretation is necessary to clip out areas with insufficient data density, or manually edit areas with highly clustered data, that may not produce reliable contour lines.

In the draft report, we have produced general maps to illustrate groundwater flow directions. The peer reviewers indicated that each aquifer would have its own hydraulic gradient and flow direction. We agree with this and have reprocessed the water level data to address this concern. However, for the reasons outlined above, this interpretation is complex and exacerbated by the lack of information across large areas of the region. Instead, we have opted to present information on water levels and piezometric contours clipped to specific areas where there is a minimum data density of three wells per square kilometer.

All water level data (WELLS Database and FLNRO) were compiled into a master table and the elevation of groundwater at each location was calculated from the 1:50k dem. Piezometric elevation surfaces were interpolated using Radial Basis interpolation between points, which attempts to find a best fit surface between points and does not necessarily pass through the points themselves. This is appropriate since we are using water level data that is not contemporaneous. Hydraulic gradients can be inferred from the resulting contours. Since bedrock underlies the whole study area, piezometric levels from bedrock wells were interpolated for the region, irrespective of mapped aquifer boundaries. Surficial sand and gravel aquifers, however, have limited spatial extent. To address this fact, the interpolated piezometric contours from confined sand and gravel aquifers were clipped to their mapped aquifer boundaries.

The produced maps provide an approximate and preliminary definition of the piezometric levels (Figures 43, 44, and 45). More detailed studies with appropriate sets of data will be required to generate a more accurate mapping of the piezometric levels.

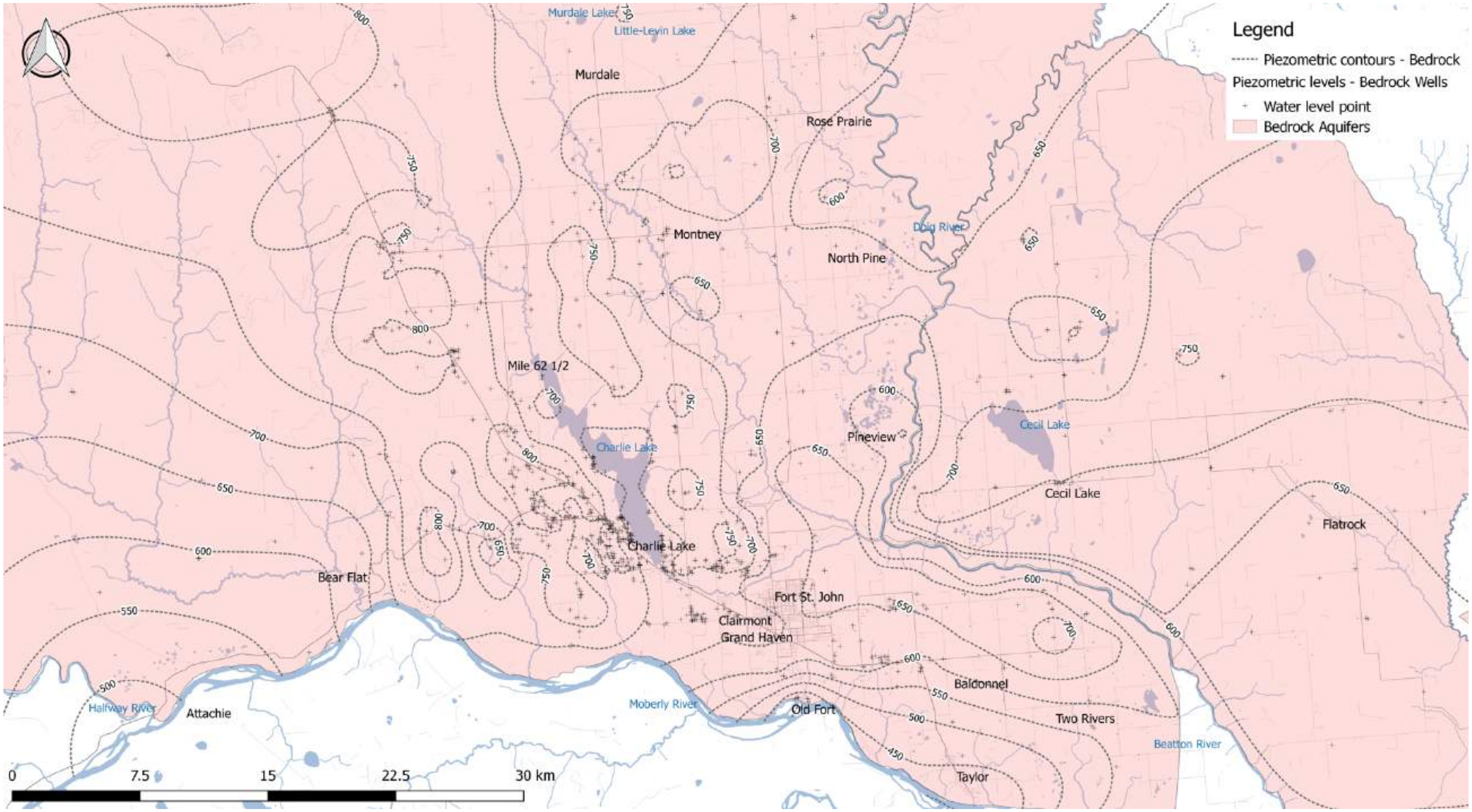


Figure 43. Piezometric contours from bedrock aquifers north of the Peace River. Hydraulic gradients indicate that groundwater flow is directed towards the incised river valleys, notably the Halfway, Beatton and Peace rivers. Piezometric contours bend around these surface features, indicating that groundwater flows through these bedrock aquifers and contributes to the creeks and rivers.

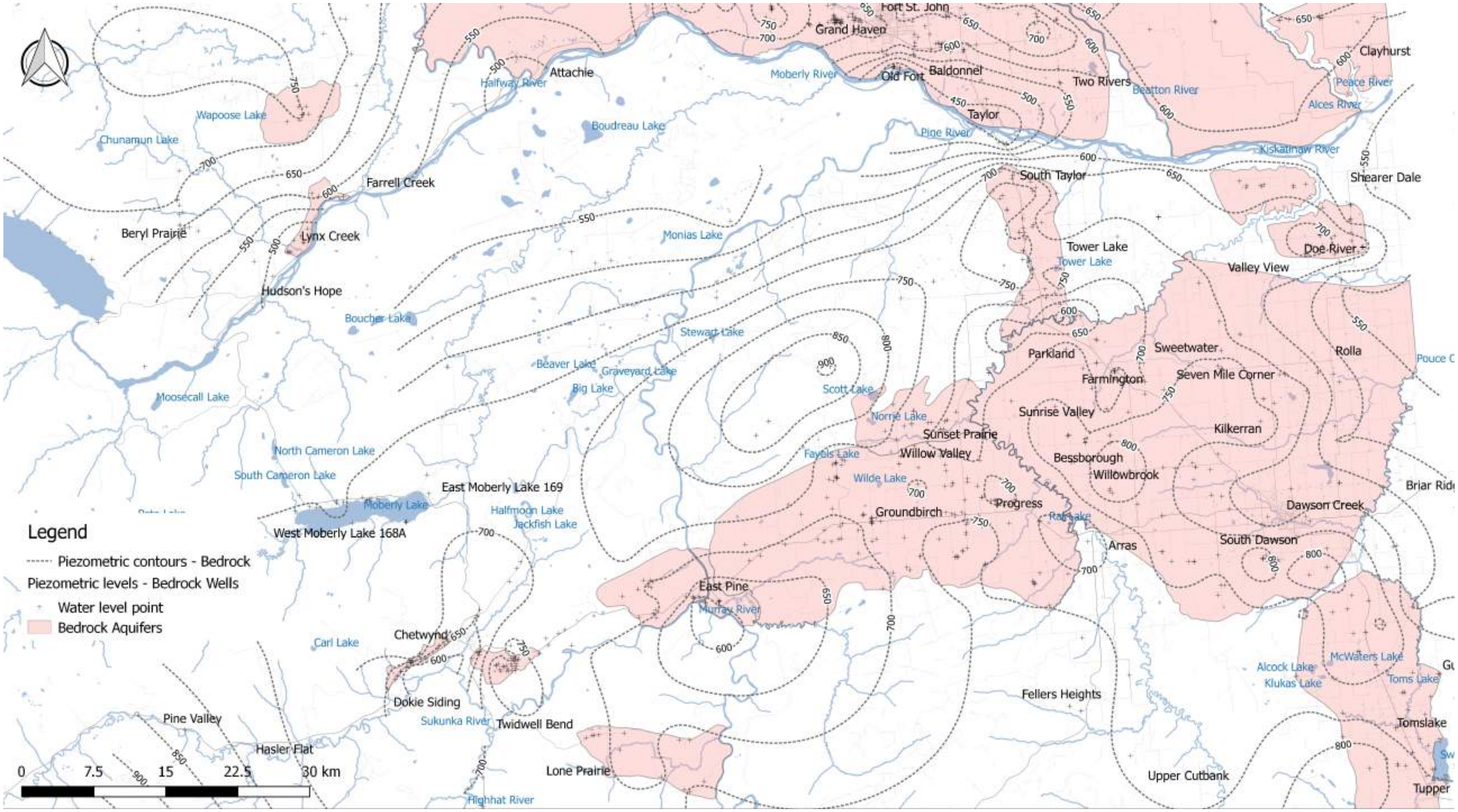


Figure 44. Piezometric contours from bedrock aquifers south of the Peace River.

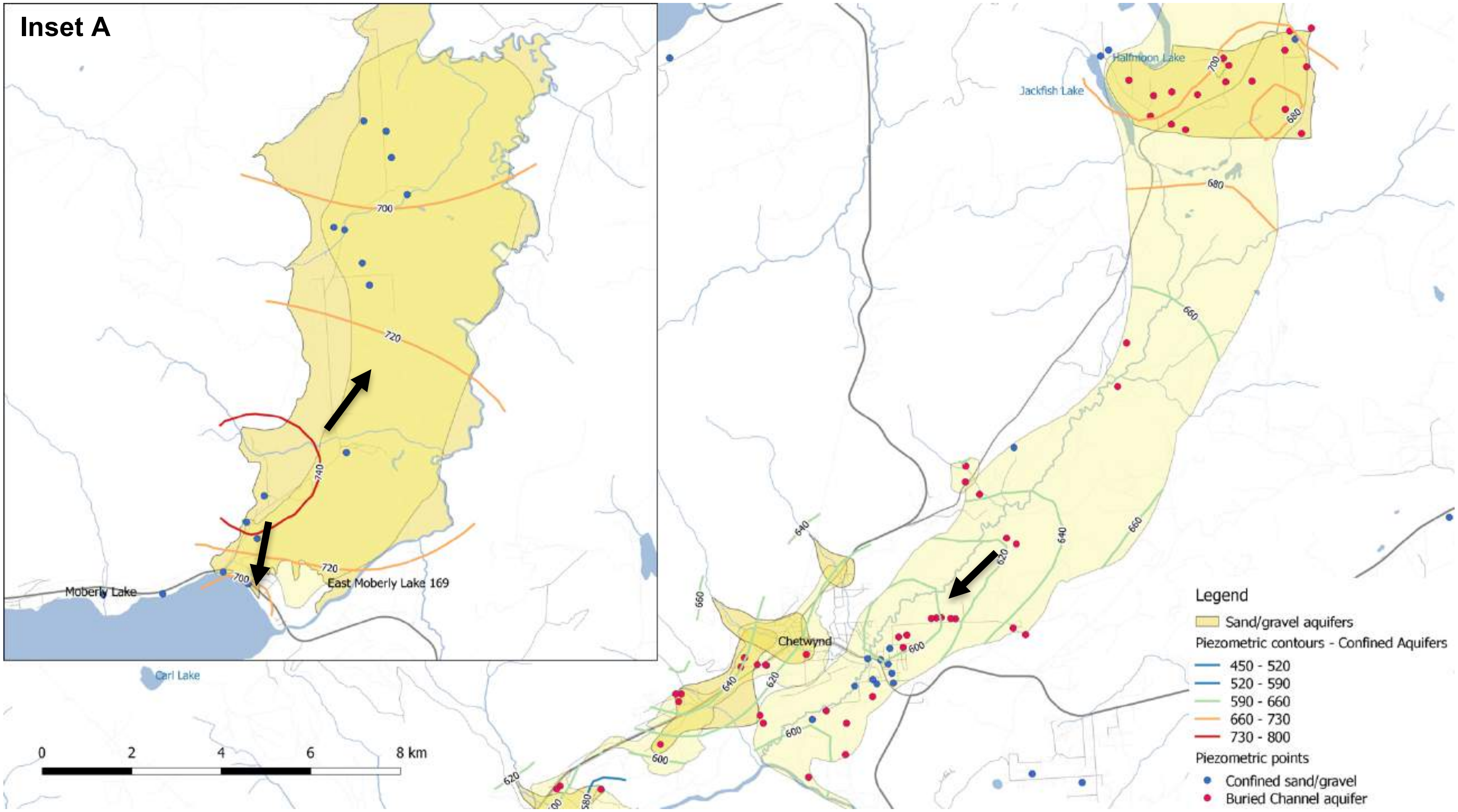


Figure 45. Example of piezometric contours from confined aquifers of the Moderly Lake (Inset A) and Chetwynd/Jackfish Lake areas. Arrows indicate probable groundwater flow directions.

F. Limitations

This report was prepared for the PRRD and T8TA. In evaluating the available information, GW Solutions has relied in good faith on information provided by others.

The produced graphs, images, maps, have been generated to visualize results and assist in presenting information in a spatial and temporal context. The conclusions and recommendations presented in this report are based on the review of information available at the time the work was completed, and within the time and budget limitations of the scope of work.

The findings and conclusions documented in this report have been prepared for the specific scope of work of this project, and have been developed in a manner consistent with that level of care normally exercised by hydrogeologists currently practicing under similar conditions in BC.

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If new information is discovered during future work, including sampling, predictive geochemistry or other investigations, GW Solutions should be requested to re-evaluate the conclusions of this report and to provide amendments, as required, prior to any reliance upon the information presented herein.

G. Acknowledgement

This project could not have started and got completed without the support of many people. GW Solutions expresses its gratitude to:

- Staff and directors of the PRRD;
- The BC Real Estate Foundation;
- Treaty 8 Tribal Association;
- The reviewers from BC Ministry of Forest, Lands, Natural Resources and Operation, Simon Fraser University, and the Oil and Gas Commission.

This project was completed with support and expertise provided by Interraplan and Hoggan and Associates. Thank you Nancy McHarg and Reg Whiten.

H. Closure

This report was prepared by personnel with professional experience in the fields covered. Reference should be made to the General Conditions and Limitations attached in Appendix 1.

Yours truly,
GW Solutions Inc.

Gilles Wendling, Ph.D., P.Eng.
President

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APPENDIX 1

GW SOLUTIONS INC. GENERAL CONDITIONS AND LIMITATIONS

This report incorporates and is subject to these "General Conditions and Limitations".

1.0 USE OF REPORT

This report pertains to a specific area, a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment. This report and the assessments and recommendations contained in it are intended for the sole use of GW SOLUTIONS's client. GW SOLUTIONS does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than GW SOLUTIONS's client unless otherwise authorized in writing by GW SOLUTIONS. Any unauthorized use of the report is at the sole risk of the user. This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of GW SOLUTIONS. Additional copies of the report, if required, may be obtained upon request.

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This report is based solely on the conditions which existed within the study area or on site at the time of GW SOLUTIONS's investigation. The client, and any other parties using this report with the express written consent of the client and GW SOLUTIONS, acknowledge that conditions affecting the environmental assessment of the site can vary with time and that the conclusions and recommendations set out in this report are time sensitive. The client, and any other party using this report with the express written consent of the client and GW SOLUTIONS, also acknowledge that the conclusions and recommendations set out in this report are based on limited observations and testing on the area or subject site and that conditions may vary across the site which, in turn, could affect the conclusions and recommendations made. The client acknowledges that GW SOLUTIONS is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the client.

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

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The client recognizes that property containing contaminants and hazardous wastes creates a high risk of claims brought by third parties arising out of the presence of those materials. In consideration of these risks, and in consideration of GW SOLUTIONS providing the services requested, the client agrees that GW SOLUTIONS's liability to the client, with respect to any issues relating to contaminants or other hazardous wastes located on the subject site shall be limited as follows:

(1) With respect to any claims brought against GW SOLUTIONS by the client arising out of the provision or failure to provide services hereunder shall be limited to a maximum of $20,000, whether the action is based on breach of contract or tort;

(2) With respect to claims brought by third parties arising out of the presence of contaminants or hazardous wastes on the subject site, the client agrees to indemnify, defend and hold harmless GW SOLUTIONS from and against any and all claim or claims, action or actions, demands, damages, penalties, fines, losses, costs and expenses of every nature and kind whatsoever, including solicitor-client costs, arising or alleged to arise either in whole or part out of services provided by GW SOLUTIONS, whether the claim be brought against GW SOLUTIONS for breach of contract or tort.

4.0 JOB SITE SAFETY
GW SOLUTIONS is only responsible for the activities of its employees on the job site and is not responsible for the supervision of any other persons whatsoever. The presence of GW SOLUTIONS personnel on site shall not be construed in any way to relieve the client or any other persons on site from their responsibility for job site safety.

5.0 DISCLOSURE OF INFORMATION BY CLIENT
The client agrees to fully cooperate with GW SOLUTIONS with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The client acknowledges that in order for GW SOLUTIONS to properly provide the service, GW SOLUTIONS is relying upon the full disclosure and accuracy of any such information.

6.0 STANDARD OF CARE
Services performed by GW SOLUTIONS for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Engineering judgement has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of this report.

7.0 EMERGENCY PROCEDURES
The client undertakes to inform GW SOLUTIONS of all hazardous conditions, or possible hazardous conditions which are known to it. The client recognizes that the activities of GW SOLUTIONS may uncover previously unknown hazardous materials or conditions and that such discovery may result in the necessity to undertake emergency procedures to protect GW SOLUTIONS employees, other persons and the environment. These procedures may involve additional costs outside of any budgets previously agreed upon. The client agrees to pay GW SOLUTIONS for any expenses incurred as a result of such discoveries and to compensate GW SOLUTIONS through payment of additional fees and expenses for time spent by GW SOLUTIONS to deal with the consequences of such discoveries.

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The client acknowledges that in certain instances the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by GW SOLUTIONS in its reasonably exercised discretion.

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The client acknowledges that all reports, plans, and data generated by GW SOLUTIONS during the performance of the work and other documents prepared by GW SOLUTIONS are considered its professional work product and shall remain the copyright property of GW SOLUTIONS.

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