WATER SCIENCE SERIES

Hydrostratigraphic, Hydraulic and Hydrogeochemical Descriptions of Dawson Creek-Groundbirch Areas, Northeast BC

Andarge Baye, P. Geo., Klaus Rathfelder, Mike Wei, P. Eng., Jun Yin, P. Geo.

No. 2016-04

The **Water Science Series** is a water-focused technical publication for the Natural Resources Sector. The Water Science Series focuses on publishing scientific technical reports relating to the understanding and management of B.C.'s water resources. The series communicates scientific knowledge gained through water science programs across B.C. government, as well as scientific partners working in collaboration with provincial staff. For additional information visit: http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-science-series.

ISBN: 978-0-7726-6984-1

Citation:
Baye, A., Rathfelder, K., Wei, M., and Yin, J (2016). *Hydrostratigraphic, hydraulic and hydrogeochemical descriptions of Dawson Creek-Groundbirch areas, Northeast BC*. Victoria, Prov of B.C. Water Science Series 2016-04.

Author's Affiliation:
Jun Yin, P. Geo
Province of British Columbia, Ministry of Forests, Lands and Natural Resource Operations
5th Floor - 499 George Street
Prince George, BC V2L 1R5

Mike Wei, P. Eng
Province of British Columbia, Ministry of Environment
395 Waterfront Crescent, 4th Floor
Victoria, BC V8T 5K7

Klaus Rathfelder
Province of British Columbia, Ministry of Environment
395 Waterfront Crescent, 4th Floor
Victoria, BC V8T 5K7

Andarge Baye, P. Geo
Province of British Columbia, Ministry of Environment
395 Waterfront Crescent, 4th Floor
Victoria, BC V8T 5K7

Cover Photograph: Landscape of northeast B.C., photo by Baye, A.

Acknowledgements

The authors are grateful to all the collaborators of the Montney Aquifer Characterization Project. The authors sincerely thank the contributors (Cn) and peer reviewers (Pr) of this report: Allan Chapman, P. Geo. (Cn), Carlos Salas, P.Geo. (Pr), Chelton van Geloven, R.P.F. (Cn & Pr), Dave Wilford, P. Geo. (Cn & Pr), Diana Allen, P. Geo. (Cn & Pr), Dirk Kirste (Cn & Pr), Elizabeth Johnson, P.geo (Pr) and Laurie Welch, P.geo (Pr). Many thanks to Chelton van Geloven and Catherine Henry for managing the field work operation of the private well survey program. A special thanks to Dr. Dave Wilford for coordinating and leading the project. Funding for this project was provided by the FLNRO Water Intended Outcome Research Program and from the ENV Environmental Monitoring, Reporting and Economics (EMRE) Branch.

EXECUTIVE SUMMARY

Limited information about aquifers, reliance on groundwater for use, and active oil and gas development with heavy use of water were drivers to improve understanding of aquifer characteristics in northeast British Columbia. A collaborative project was initiated in 2011 with the objective of collecting and synthesizing data to better understand the groundwater resource in the Dawson Creek-Groundbirch area.

An integrated approach was used to characterize aquifers in the Dawson Creek-Groundbirch area. Available water well information, private well survey data, core drilling data, water chemistry, drilling, pumping test analysis and monitoring data of observation wells have been used to improve understanding of groundwater resources in the study area.

A data set of well records was compiled from different sources, and the drillers' description of lithology was standardized to characterize the subsurface hydro-stratigraphy. Well logs were interpreted using standardized lithology to identify the major hydrostratigraphic units in the study area. The local litho-hydrostratigraphic relationships were interpolated using 2D cross sections. In addition to this, the geophysical data and analysis was also used to support the hydrostratigraphic interpretation. Unconsolidated sand and gravel aquifers are identified in three settings: 1) fluvial/alluvial sediments found in major river valleys and low lying areas, 2) minor, localized units confined underneath till/clay/silts, and 3) in a buried, confined paleovalley in the Groundbirch area. Weathered and fractured sedimentary and sandstone aquifers underlie unconsolidated sediments throughout much of the study area. In parts of the study area aquifers were mapped as moderately or lightly developed bedrock or unconsolidated aquifers as per the provincial aquifer classification scheme.

Measured groundwater level elevations generally mimic topography. Upland areas appear to be local recharge areas and low lying areas and river valleys appear to be local discharge areas. Recharge modelling of the study area using the Hydrologic Evaluation of Landfill Performance (HELP) software program indicates vadose zone materials comprised of low-conductivity tills and glaciolacustrine sediments are found throughout a vast majority of the study area and have a dominant influence on the groundwater recharge rate. In comparison, the more conductive surficial soil type has a limited influence on groundwater recharge due to lesser thickness.

Seven provincial groundwater observation wells were drilled to monitor the groundwater level fluctuation over time and to characterize aquifer hydraulic properties and baseline groundwater quality. Five of the observation wells were drilled into bedrock aquifers 591 and 593 around the City of Dawson Creek. Two observation wells were drilled into unconsolidated sand and gravel aquifers 590 and 592 in the Groundbirch paleovalley valley. Short-term groundwater level monitoring data exhibit limited change in groundwater elevations. Water levels in deeper bedrock wells are generally stable throughout the year, while shallower bedrock wells exhibit small increases in groundwater levels following freshet. These observations are consistent with low aquifer conductivity values measured in pumping tests, and low recharge estimates controlled by the presence of overburden deposits of till and glaciolacustrine sediments. Long term groundwater level trends will be established over time with ongoing monitoring in the provincial observation wells.

Groundwater quality information has been compiled from two sources: 1) historical groundwater quality data available in the Ministry of Environment, Environmental Monitoring System (EMS) database, and 2) groundwater samples collected in a voluntary private wells survey program. The groundwater chemical composition showed considerable variability ranging from Ca-Mg-HCO3 to Na-HCO3 and Na-SO4-HCO3 type. The Ca-Mg-HCO3 types are predominately in the Quaternary sediment sand/gravel

aquifers, while Na-rich groundwaters are predominantly sourced from wells that are completed in the bedrock aquifers. Groundwater quality in the study area is characterized through comparison to the Canadian drinking water guidelines, and through development of groundwater quality maps. The available groundwater quality data were grouped by aquifer hydrostratigraphy (unconsolidated or bedrock) based on lithology information in the well log. Arsenic is the main health based constituent of concern, with about 30 percent of samples exceeding the maximum allowable concentration (MAC) guideline. Several constituents have significant exceedances of aesthetic objectives (AO) guidelines, including iron, manganese, sodium, sulfate, total dissolved solids, and hardness. The majority of the groundwater samples identified as originating from the unconsolidated aquifers have stable isotopic composition with a similar range to that of the spring and fall precipitation. The bedrock sourced groundwater has two different stable isotopic compositions; one similar to and the other with a more depleted isotopic composition compared to the unconsolidated aquifers.

Based on converging lines of evidence from observation well drilling and testing, core drilling, litho-hydrostratigraphic relationships and hydrogeochemistry, a conceptual model was developed depicting the groundwater occurrence and flow in the study area. The paleovalley area in the west central part of the study area around Groundbirch is characterized by intercalations of less permeable silty clay/till and more permeable sand/gravel deposits. The major river valleys are dominated by unconfined fluvial sand and/or gravel aquifers. The eastern part of the study area is dominated by thick deposits of till/silty clay with thin lenses of sand which can sustain private wells. The major portion of the study area is underlain by bedrock aquifers, covered by clay/till deposits of variable thickness.

The following are recommendations as a result of the study:

- Well owners diverting groundwater for domestic and waterworks purposes should routinely test for arsenic, given the prevalence of this chemical in groundwater in the study area and the potential health effects associated with arsenic.
- As the province authorizes the use of groundwater under the Water Sustainability Act, new information on transmissivity of aquifers will be submitted by applicants for authorizations. This new data should be entered into the ENV WELLS database to build a dataset of aquifer transmissivity over time.
- Longer term 72-hour pumping test is recommended to assess the aquifer’s long term response and implication to water supply for wells drilled into bedrock aquifers.
- The delineation and description for aquifer 851 should be reviewed.
- Observation well monitoring should be expanded to other parts of the region and include unconsolidated aquifers so as to understand the groundwater occurrence and flow in these potential aquifers.
- The current observation wells should be reviewed in 1-3 years’ time to assess whether all of them are needed.
- A plan should be developed for flowing observation well 419 to either equip the well for monitoring or to decommission the well.
- A study along a more regional Rocky Mountain-foothill-plateau transects could help in understanding the regional groundwater occurrence and flow and ultimate recharge areas for groundwater in the bedrock aquifers.
- Future aquifer characterization initiatives should consider generating new properly described borehole lithological data by drilling exploratory wells to ground truth existing driller’s descriptions.

Contents

LIST OF ACRONYMS

AMS	Accelerator Mass Spectrometry
AO	Aesthetic Objectives
BC	British Columbia
DO	Dissolved Oxygen
EC	Electrical Conductivity
EM	Electromagnetic
ENV	Ministry of Environment
FLNR	Ministry of Forests, Lands and Natural Resource Operations
GSC	Geological Survey of Canada
HELP	Hydrologic Evaluation of Landfill Performance (U.S. EPA)
IC	Ion Chromatography
ICP-AE	Inductively Coupled Plasma Atomic Emission Spectrometer
IRMS	Isotope Ratio Mass Spectrometry
MAC	Maximum Allowable Concentration
MEM	Ministry of Energy and Mines
NEWT	North East Water Tool
Obs. Wells	Provincial Observation Wells
OGC	B.C. Oil and Gas Commission
SFU	Simon Fraser University
SWL	Static water level
TDS	Total Dissolved Solids
TOC	Top of Casing
TU	Tritium Units
USgpm	US Gallons per Minute
V-SMOW	Vienna Standard Mean Ocean Water
WELLS	The ministry of Environment WELLS Database
WTN	Well Tag Number

1. INTRODUCTION

1.1 Study Purpose and Scope

In northeast British Columbia, groundwater is a primary water supply source for domestic, industrial and agricultural uses, and contributes significantly to the maintenance of healthy ecosystems. The Montney Aquifer Characterization Project was initiated in 2011 with the objective of collecting and synthesizing data to better understand the groundwater resource for domestic, industrial, agricultural and environmental use in the Dawson Creek-Groundbirch area. The project focused on using conventional hydrogeological investigation approaches - available water well information, conducting an extensive field well survey to collect information on groundwater levels and water chemistry, as well as drilling, carrying out pumping tests and monitoring observation wells to determine the hydrostratigraphy, water table elevations and fluctuations over time, groundwater chemistry, and the hydraulic properties of aquifers in the study area. The project was carried out in partnership with the Ministry of Forests, Lands and Natural Resource Operations (FLNRO), Ministry of Environment (ENV), Simon Fraser University (SFU), Ministry of Energy and Mines (MEM), Geological Survey of Canada (GSC), the B. C. Oil and Gas Commission (OGC), and Geoscience BC. In addition to this project, another project was carried out at the same time, led by the Ministry of Energy and Mines, using ground-based geophysics to identify paleovalley-valley aquifers in the Groundbirch area (Hickin and Best, 2016). This report synthesizes the results of the project work in the study area and incorporates a summary of the work of Hickin and Best (2016) on the paleovalley-valley aquifers to present the state of knowledge of the hydrogeology of the Dawson Creek-Groundbirch area.

1.2 Previous Studies

There has been very few regional hydrogeological studies done in the area. The most notable include studies by Mathews (1955), Holland (1964), Callan (1970), McMechan (1994), Cowen (1998), Catto (1999), and Lowen Hydrogeology Consulting Ltd (2011). Recent studies have focused on , identifying and characterizing buried paleovalleys where coarser grained sediments deposited in old river valleys may represent potential aquifers (Cowen, 1998; Catto, 1999; Hicken and Best, 2013). In 2015, a large-scale airborne electromagnetic survey was launched by Geoscience BC to further identify the paleovalleys in addition to the small scale survey conducted previously at Groundbirch area (Hickin and Best, 2013). Though techniques such as electromagnetic surveying (Hickin and Best, 2013) and gamma ray logging (Levson, 2014) are able to infer the water bearing units from other low permeable units (clay, bedrock, etc.), however, characterization of the complex geology and hydrogeology of the area remains incomplete. Additional work is needed to confirm the presence of the water bearing units, and to better characterize the three dimensional geological and hydrogeological framework, the lateral and vertical extent of aquifers, the hydraulic connections between aquifers, and the hydrochemistry, spatial variations and surface water/ groundwater interaction of the aquifers. A better understanding of the complex hydrogeological framework, groundwater dynamics and geochemistry will further support future groundwater resource development and management in the area.

1.3 Approach and Methodology

A converging lines of evidence approach was followed using integrated hydrogeological investigation techniques; including litho-hydrostratigraphic relationships, private well field surveys, observation well drilling, pumping tests and monitoring, hydrochemistry and geophysics.

1.3.1 Well Lithology Data

A data set of well records was compiled from different sources and the drillers' description of lithology was standardized based on the method developed by SFU (Toews, 2007 unpublished report). Four hundred and sixteen (416) well records were selected from the provincial WELLS database and compared with the SFU standardized well lithology. Forty (40) additional well records were also included in the data set from the Geoscience BC database. This well dataset was interpreted to identify the main hydrostratigraphic units and to construct cross sections to illustrate their spatial relationships.

1.3.2 Private Well Survey Program (by: Chelton Van Geloven)

The Ministry of Forest, Lands and Natural Resource Operations (FLNR) initiated a private well survey program in October 2011 as a field component of the Montney aquifer study. The private well survey supports the objective of this project by accurately locating wells, measuring depth to groundwater level and well surface elevation, and collecting groundwater samples to characterize groundwater flow and chemistry.

The well survey program was conducted in three phases as shown in Table 1. Depending on the status of the well, data collection activities varied from simply locating an abandoned well to multiple visits over the duration of the study to measure the depth to water level and to collect samples to observe seasonal variations. The “Location” and “Activities” columns in Table 1 describe the area of focus and program objective at each phase and the “Outcome” column shows the number of new stations sampled.

Generally, for each water well, the GPS location of the wellhead was measured using a Magellan® Professional (2011 – September 2014); or Leica CS10 (September 2014 – February 2015). Prior to sample collection, a YSI hand held multi-parameter meter was used to record the water chemistry parameters in the field: temperature, pH, specific conductance (SC), and dissolved oxygen (DO). A sonic water level meter (Ravensgate Co. Sonic Water Level Meter, Model 200) was used to measure the depth to groundwater level at the same time as the water sample was collected.

Table 1 Summary of fieldwork from October 2011 to March 2014.

Program Phase	Locations	Activities	Outcome
October 2011 – March 2012	Rural Dawson Creek	• Static water level[1] and well sampling	• 41 stations
June 2012 – March 2013	Rural Dawson Creek, South Taylor Springs	• Static water level and well sampling • Static water level only • Precipitation (rain and snow) sample collection	• 65 stations • 76 wells • Various locations
October 2013 – March 2014	Rural Dawson Creek Beryl Prairie	• Static water level and well sampling (C_{14}, tritium, methane gas) • Precipitation (rain and snow) sample collection	• 20 stations • Various locations

[1] The groundwater level elevation in the wells (above mean sea level – amsl) was computed based on the well head elevation and the depth to water level (Appendix A).

1.3.3 Collection and Analysis of Groundwater and Precipitation

As part of the private well survey program, groundwater samples were collected from wells with installed pumps. Water was run through the flow cell of the multi-parameter YSI Professional Plus Meter for a maximum of 30 minutes. The flow cell was fed with Tygon tubing attached to a barbed garden hose tap and discharged through a second Tygon tubing line. The groundwater sample collection points were located upstream of any water treatment and, where possible, upstream of the pressure tank. In most instances, a connection before the pressure tank was unavailable; therefore, a

30 minute flush-out and field parameter monitoring period was performed to ensure collection of representative groundwater samples.

The YSI Professional Plus Meter is equipped to measure temperature, dissolved oxygen (DO), pH, redox and specific conductance (SC). These parameters were recorded at 2-3 minute intervals until readings were stable. A stable reading indicated the water source was likely representative of groundwater in the aquifer. An in-line high capacity 0.45 microns filter was attached to the tubing and water was run into a 1 L high density polyethylene (HDPE) beaker. One 125 mL HDPE bottle and one 250 mL HDPE bottle were filled after a triple rinse for general parameters analysis. The 125 mL bottle was preserved with 1 mL of nitric acid (HNO3).

The samples for tritium analysis were collected as 1 L of filtered water. The samples for Carbon 14 (C14) were collected in 500 ml bottles filtered and preserved with 2 ml of sodium hydroxide. Dissolved gases were collected in 250 ml evacuated glass bottles containing a biocide capped with silicone septa (Table 2). Atmospheric monitoring stations were installed in June 2012 and rain and snow samples were collected and analyzed for chemical and isotopic composition.

Table 2 Summary of field procedures for sample collection, techniques and preservations.

Parameter	Bottles	Filter	Technique	Preservative	Storage and handling
Major cation/anion	1 x 125mL 1 x 250 mL	Yes	Flow cell, stabilization	125 ml = 1mL HNO3	Refrigerate, quick turn around for alkalinity and ammonia measurements
Tritium	1 L	No	Flow cell, stabilization	No	Refrigerate
C14	500 mL	Yes	Brimmed, flow cell, stabilization	2 mL NaOH	Refrigerate, tape shut, quick turn around
Methane	Glass, evacuated, silicone stopper	No	5 gal bucket continuous overflow, needle prick, flow cell, stabilization	No	Record if water is degassing, bubble wrap, refrigerate

Water samples were analyzed for in-situ physical parameters such as temperature, pH, specific conductance, oxidation-reduction potential, dissolved oxygen and chemical composition including alkalinity, ammonia (NH4+), element concentrations (Al, As, B, Ba, Ca, Fe, K, Li, Mg, Mn, Mo, Na, Si, Sr, Zn by ICP-AES Jobin-Yvon Horiba Ultima II), common anions (F-, Cl-, Br-, NO3-, PO4-3 and SO4-2 by ion chromatography IC Dionex (ICS 3000 with AS22 column) and stable isotope content (δ18O and δ2H by laser isotope analyzer LGR DT-100). Groundwater samples were analyzed for tritium content by enrichment and low level proportional counting at the University of Miami Tritium Laboratory. Tritium in the rain and snow samples was analyzed at the University of Waterloo Environmental Isotopes Laboratory using enrichment and liquid scintillation counting. Initial samples for carbon-14 were determined by accelerator mass spectrometry (AMS) and δ^{13}C by isotope ratio mass spectrometry (IRMS) at the University of Georgia. The current set of samples is analyzed for carbon-14 by AMS and δ^{13}C by IRMS at the University of Ottawa.

1.3.4 *Observation Well Drilling, Test Pumping and Monitoring*

As part of the project, ENV, FLNR and MEM worked collaboratively to drill seven new groundwater observation wells in the study area to the north and west of Dawson Creek (Jillian Kelly and Ed Janicki, 2011). Five of the wells were completed in bedrock aquifers 591 and 593, while two wells were completed in unconsolidated sand and gravel aquifers 590 and 592. Pumping tests were performed on four of the observation wells (416, 417, 418 and 420) which intersected bedrock formations (Baye, 2013). Borehole geophysical logging was also carried out in observation well 421 to aid in the interpretation of the paleovalley.

Observation Wells 416, 417, 418, 420, and 445 are now instrumented with data collection equipment to log the groundwater levels, and satellite telemetry is transmitting, non-validated, near real time data. Information on the groundwater level from the observation wells is publically available on the Observation Well Network Interactive Map (http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html).

Observation well 419 exhibited artesian conditions during drilling. The artesian condition was controlled by installing a packer. Due to the flowing artesian condition, the well was not equipped with water level monitoring equipment.

2. STUDY AREA DESCRIPTION

2.1 Location of Study Area

The study area is located in northeast B.C. around the City of Dawson Creek-Groundbirch area. It is bounded by Peace River in the north, upper Murray River in the west, middle and lower Kiskatinaw River in the south central and British Columbia-Alberta boundary in the east. The area is delineated based on sub watershed boundaries with a total surface area of approximately 3760 square kilometers (Figure 1).

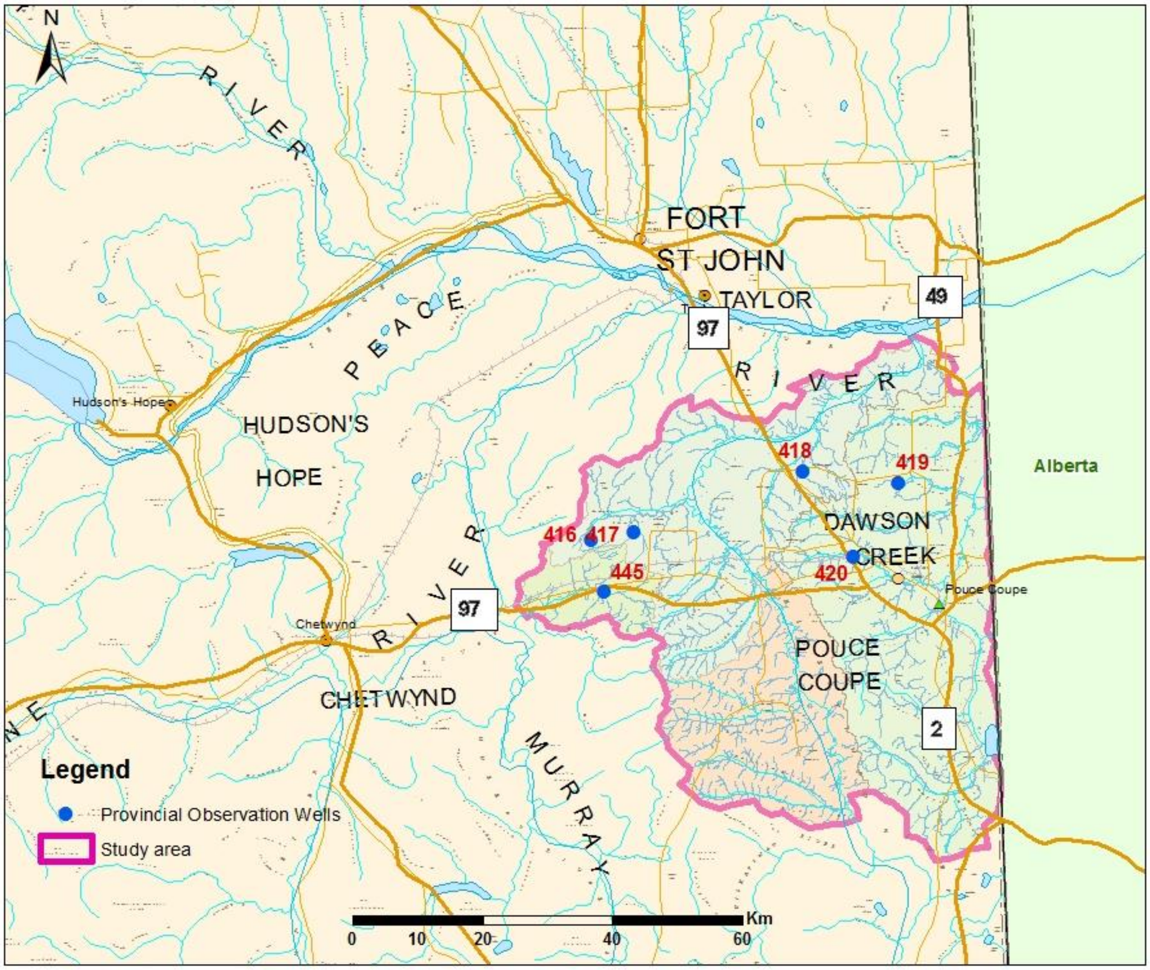


Figure 1 Location and drainage map of the study area (pink outline) and provincial observation wells (blue dots).

2.2 Climate and Hydrology (by: Allan Chapman and Dave Wilford)

2.2.1 Climate

The study area is located in the Peace River Basin Ecoregion and the Boreal Plains Ecoprovince of British Columbia.

The climate is cold, continental, characterized by an extended period of below freezing temperatures (typically November to March) followed by warm summers. There are two long-term climate stations in and around the study area; Dawson Creek Airport (ID 1182285) and Fort St John Airport (ID 1183000). They have similar climatological records (Figure 2, Table 3).

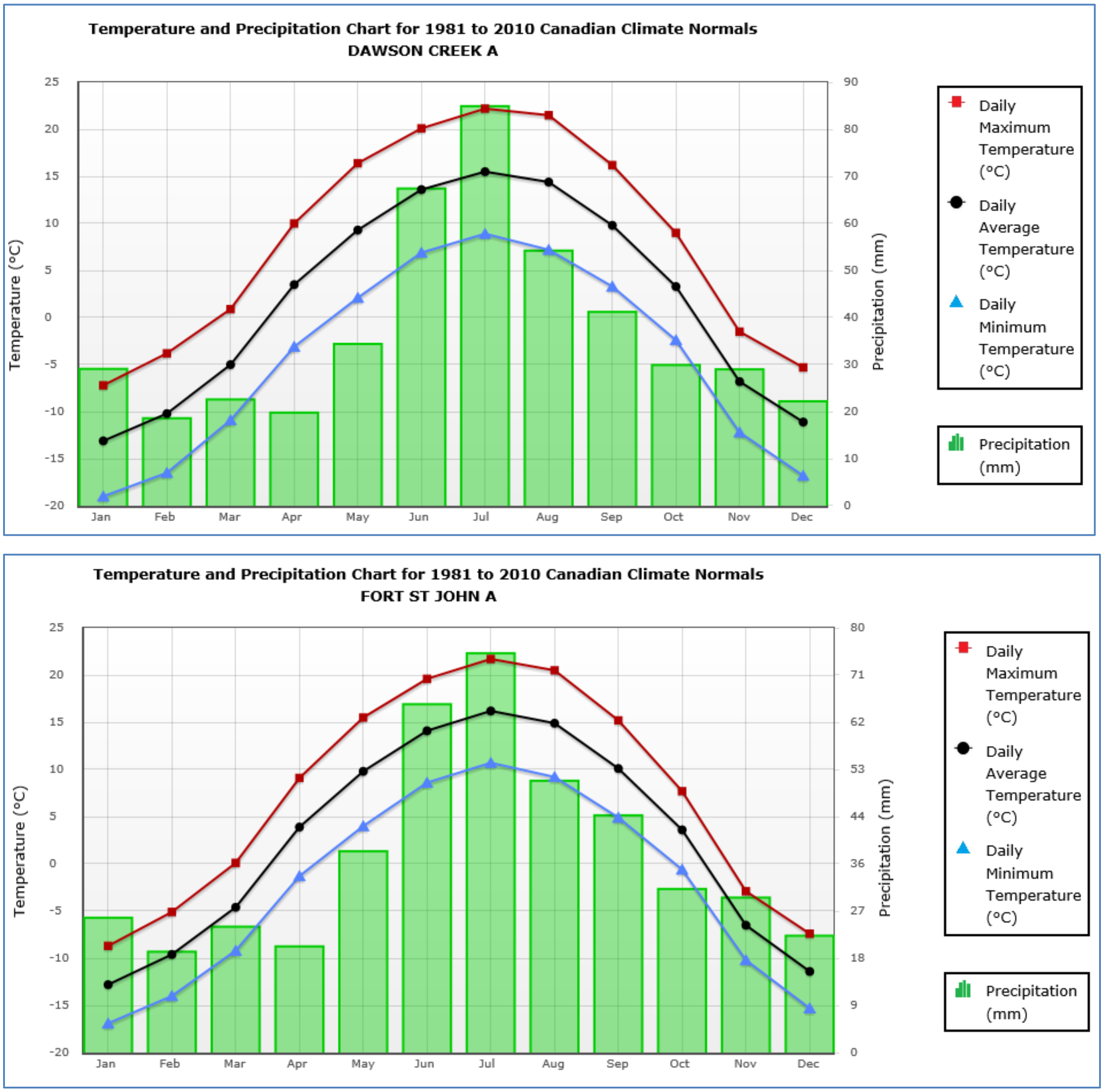


Figure 2 Climate normals (1981-2010) for Dawson Creek and Fort St John Airports

Table 3 Climate normals (1981-2010) for Dawson Creek and Fort St John airports.

	Dawson Creek Airport ID: 1182285	Fort St John Airport ID: 1183000
Mean Annual Temperature (°C)	1.9	2.3
Mean January Temperature (°C)	-13.2	-12.8
Mean July Temperature (°C)	15.5	16.2
Mean Annual Precipitation (mm)	453	447
Rain (mm)	307	292
Snow (mm)	146	155
Summer Precipitation (Jun-Aug) (mm)	207	192
Winter Precipitation (Dec-Mar) (mm)	93	90

Mean annual temperature is about 2°C, varying from a low of -13°C in January to a high of +16°C in July (http://climate.weather.gc.ca/climate_normals/index_e.html). Mean annual precipitation is approximately 450 mm, of which two-thirds occurs as rain and one-third occurs as snow. Summer is the wettest season, with 45 percent the mean annual precipitation occurring in June, July and August. Summer precipitation tends to be convectional, with occasional large rainstorms associated with low pressure systems pushing into the Peace area from Alberta, producing widespread rainfall. Winters are typically arid, with about 20 percent (90 mm) of the mean annual precipitation occurring during the December-March period. However, this winter precipitation is stored as snow and is released during the spring freshet period, usually from early April to early June.

2.2.2 Hydrology

The study area contains a number of watersheds, including the Pouce Coupe River, Kiskatinaw River, and smaller basins draining into the Peace River. The North East Water Tool (NEWT) (http://geoweb.bcogc.ca/apps/newt/newt.html) provides a useful tool to evaluate the hydrology in the vicinity of the study area. Surface water hydrology in the study area is manifested by seasonally high stream flows in late April, May and June, as the accumulated winter snow melts; steady recession into summer low flows (August, September) following the end of the freshet; and a continual decline of stream flows in the autumn and winter, with the annual low flows occurring usually in December, January and February, when precipitation is being stored as snow and water inflow to streams is very low. There is considerable variability of stream flows within and between years, depending on the amount of water stored in the winter snowpack, and the weather conditions during the freshet snow melt period. During the open water season of late April to late November, rainfall can occasionally produce large increases in runoff; conversely, summer droughts appear to be common, resulting in very low streamflow during August and September. The Kiskatinaw River provides a good example of local hydrology, based on 70 years of flow measurement (Figure 3). Potential annual evapotranspiration exceeds annual precipitation, resulting in low rates of surface runoff in streams. Local annual runoff in the vicinity of the study varies from about 75 to 100 mm (Pouce Coupe – 75 mm; Kiskatinaw – 91 mm).

2.3 Physiography

The study area is within the Alberta Plateau region of the Interior Plains physiographic subdivision of British Columbia (Church and Ryder, 2006) (Figure 4). The overall study area is of low relief with flat terrain in the north to gently rolling terrain in the south incised by Kiskatinaw River. Ground elevations over the area range from about 400 to 1100 m above mean sea level. The Kiskatinaw River and Pouce Coupe River valleys are deeply incised with over 200 m of relief.

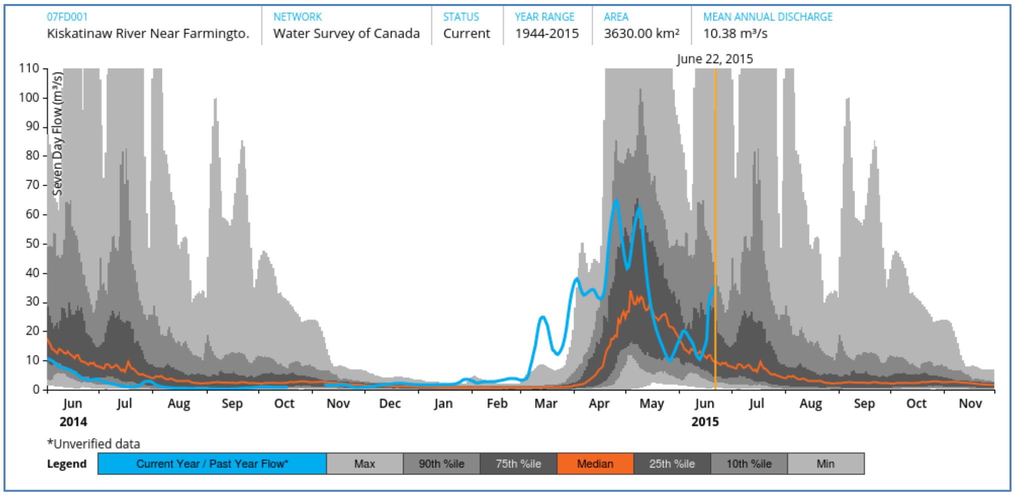


Figure 3 Kiskatinaw River flow measurement (near Farmington). The daily measurements for all years is statistically presented to show the quartiles (grey tones) with median value in red. The blue line truncating at the orange date represents the measurement for the year to date.

Figure 4 Physiographic location of the study area (Church and Ryder, 2006).

2.4 Geology

2.4.1 Regional Surficial Geological Setting

The study area is characterized by unconsolidated (or surficial) deposits consisting of a heterogeneous assortment of clay to boulder size material of pre-glacial, glacial, interglacial and/or postglacial origin overlying the bedrock (Lowen, 2011).

Potential unconsolidated aquifers in the study area are likely to be associated with the following geologic units from youngest to oldest (Lowen, 2011) (Figure 5):

- Sand and gravel deposits at or near present channels associated with modern alluvium along major creeks and rivers;
- Glaciofluvial deposits at or near surface formed by glacial melt waters at the end of the last glaciation; and
- 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.

Age	**Unit (Mattews, 1963)**	**Descriptions (Mattews, 1963)**
Youngest	Postglacial deposits	Stream and terrace gravels, alluvial fan deposits, pond silts, peat and swamp deposits, cliff- head and parabolic dunes
	Late glacial deposits	Lacustrine clay and silt, near shore sand and gravel, and in the west sand and till (?) attributable to the Cordilleran ice sheet; related to retreating stages of the Laurentide ice sheet when ice-dammed lakes persisted
	Glacial Till	Till attributable to the last major ice advance, massive and clay rich
	Interglacial and early Wisconsin(?) river and lake deposits	River and lake deposits relating to stream transport, aggradation, and ponding, consisting of gravel with minor sand, overlain conformably by silt and clay
	Old glacial till	Till attributable to an early advance of Laurentide ice
Oldest	Early interglacial or preglacial river and lake deposits	Buried gravels and sands, silt and clays exposed along the north wall of the Peace River overlying Cretaceous shale southeast of Tea Creek

Figure 5 Unconsolidated deposits in the study area (Source: Lowen, 2011).

2.4.2 Regional Bedrock Geological Setting

Most of northeast British Columbia is underlain at the surface and shallow subsurface (i.e., less than 600 m depth) by Cretaceous layered sedimentary rocks that were deposited along the western margin of the Western Canadian Sedimentary Basin (Riddell, 2012) (Figure 6). Bedrock in the study area is predominantly comprised of shale and sandstone from the Smokey Group and Dunvegan Formation of the Upper Cretaceous Period of the Mesozoic Era (McMechan, 1994) (Figure 7). Permeable zones within the Dunvegan Formation and overlying Smokey group are dominated by competent sandstone strata such as the Kaskapau Formation, which comprise the main bedrock aquifers in the study area (Lowen, 2011). On the plains of northeast British Columbia, the structural geology consists of near-horizontal sedimentary strata. In the Rocky Mountain Foothills, the pre-Cretaceous rocks occur at the surface as a result of uplift, folding and faulting along the deformation front.

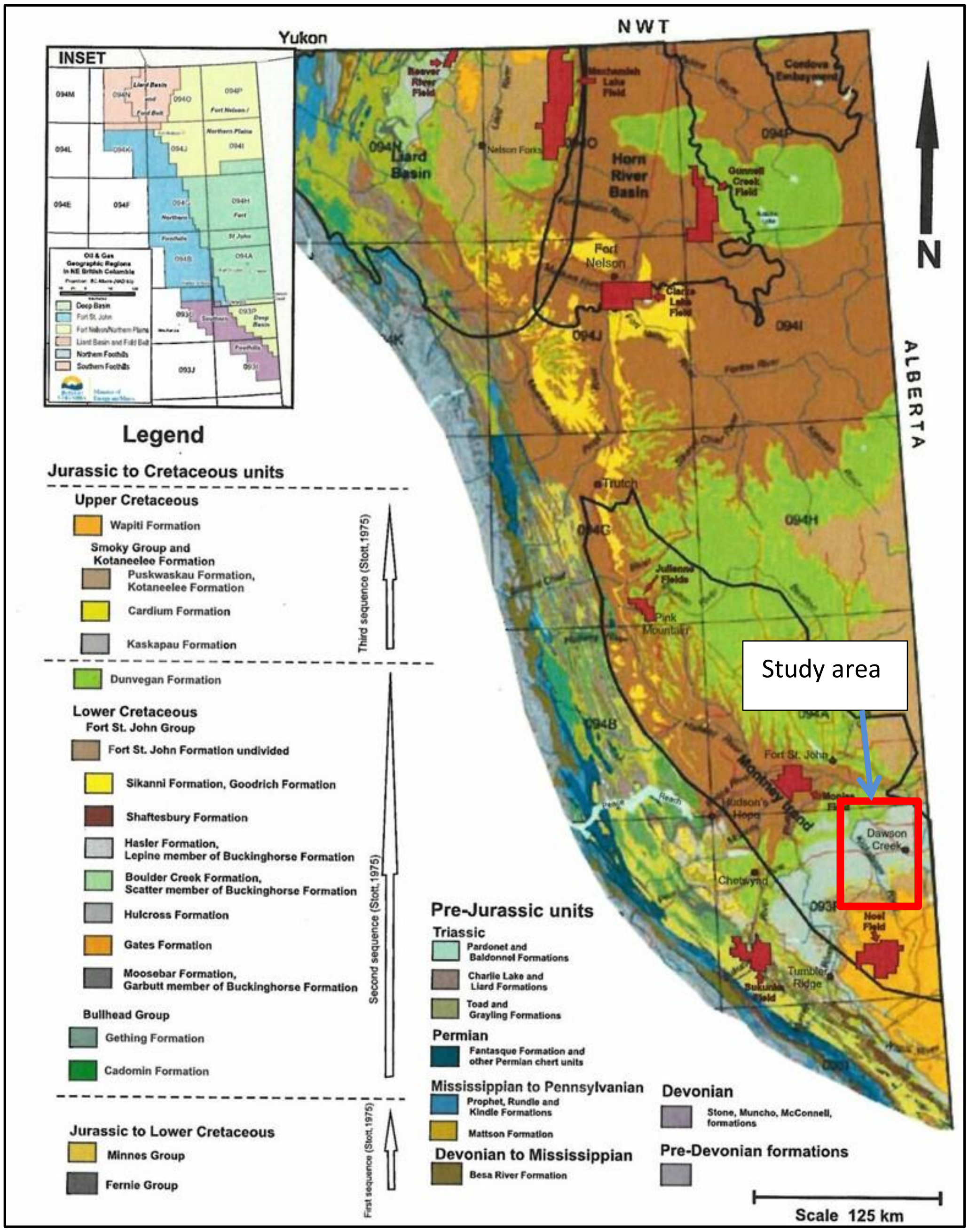


Figure 6 Lithology of surface and shallow subsurface bedrock units of northeast British Columbia (Riddell, 2012).

At a regional scale, coarse clastic (e.g., sandstone) regressive sequences[1] (Bullhead Group, Dunvegan and Wapiti Formations) can be viewed as potential aquifers and the marine shale units (Fort St. John Group, Kaskapau, Puskwaskau and Kotaneelee Formations) as aquitards. Generalizations about aquifer characteristics at the formation scale, however, are not sufficiently accurate for groundwater exploration purposes because none of the Cretaceous formations are lithologically homogeneous.

---

[1] Regressive sequences are associated with sediments deposited during the retreat of the ocean (or lake) from the land over time. From a stratigraphic perspective, this is reflected in a gradual coarsening of sediments from deeper depths to shallower depths (e.g., clay grading upward to sand and gravel).

Period	Group	Formation	Description (from Scott, 1982 except where noted)
Upper Cretaceous	Smokey	Wapiti	Sandstone, mudstone, coal
		Puskwaskau-Kotaneelee	Dark Marine shale and siltstone
		Badheart Marshbank	Fine-grained sandstone Sandstone, Carbonaceous shale (McMechan, 1994)
		Muskiki	Dark marine shale
		Cardium	Fine-grained, grey sandstone
		Kaskapau including Pouce Coupe and Doe Creek sandstone members	Dark Marine shale Shale and sandstone (Cowen, 1998)
	Dunvegan Formation		Carbonaceous sandstone, massive conglomerate, dark shale, siltstone
Lower Cretaceous	Fort St John	Sulley (north of Peace River) Shaftesbury (south of Peace River)	Dark Grey, sideritic shale , dark marine shale and siltstone

Figure 7 Bedrock stratigraphy of the study area (Source: Lowen, 2011).

Within the three major, basin-wide regressive-transgressive[2] cycles (Fernie–Minnes; Bullhead–Fort St. John–Dunvegan and Smoky Group-Kotaneelee Formation) many minor and spatially constrained cycles occurred. All of the coarse clastic formations contain shale members, and all of the shale formations contain continuous or lensoid coarse clastic members which might be potential local aquifers. In addition, fracture enhancement of secondary porosity is seen in both shale and coarse clastic formations, producing local aquifers (Riddell, 2012).

The Dunvegan Formation is a widespread coarse clastic unit (e.g., sandstone) in northeastern British Columbia (Figure 6) and northwestern Alberta, where it is the host for many classified bedrock aquifers. The Dunvegan Formation is dominant within the study are, and is the most used bedrock aquifer host because it underlies the relatively populated Peace River valley and has supplied water for agriculture, communities and conventional oil and gas operations (Riddell, 2012).

2.5 Land Use

Agriculture, including crop and livestock production, is the dominant land use over much of the study area, particularly in the northern and northeastern portions of the study area (Figure 8). Forest cover and timber harvesting are prevalent in the central and southern portions and in the northwest corner. Oil and gas development is prominent throughout the study area. Dawson Creek and Pouce Coupe are the major urban centers.

---

[2] Trangressive sequences are associated with sediments deposited during the landward advance of the ocean or lake. From a stratigraphic perspective, this is reflected in a gradual fining of sediments from deeper depths to shallower depths (e.g., sand and gravel grading upward to clay).

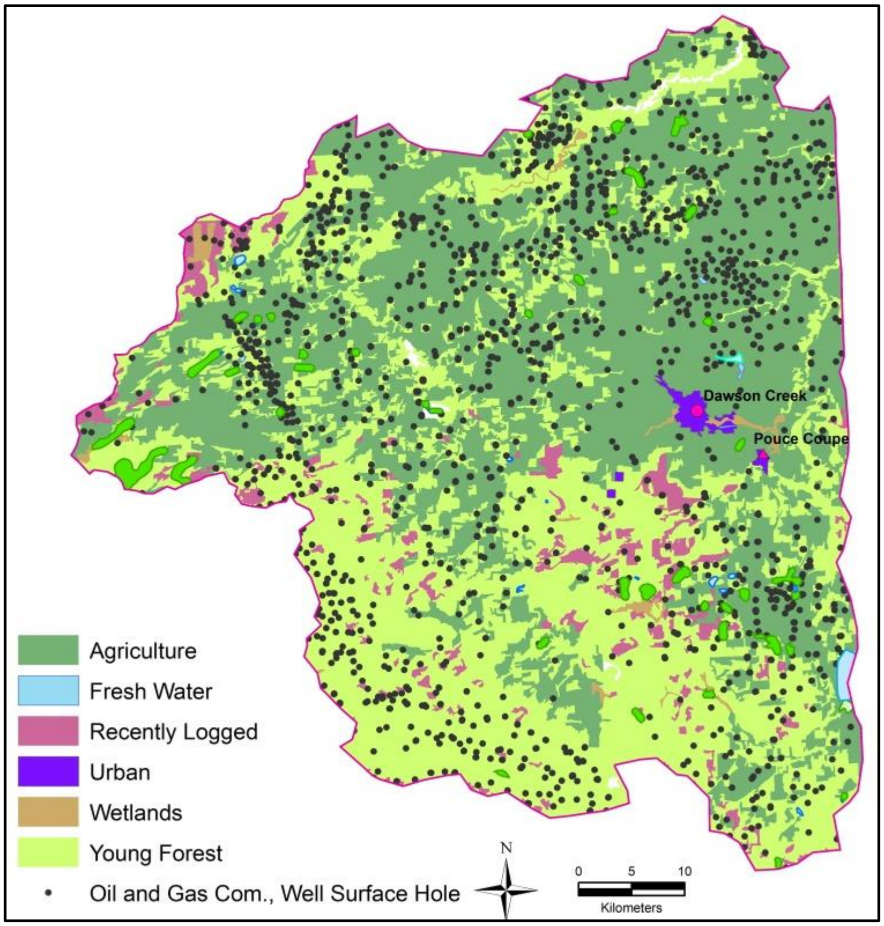


Figure 8   Study area land use (Source: Geoscience BC Montney Water Project report 2013-1).

2.6 Groundwater Development and Water Use

Information on groundwater development and use in the study area is inferred from voluntarily submitted well records in the ENV WELLS database. Based on these records, groundwater development in the study area is low, with less than four wells per square kilometer (based on criteria established in Berardinucci and Ronneseth, 2002). Available well records are more concentrated in the northwestern portion of the study area, and in the rural agricultural areas to the northwest, north, and south of Dawson Creek and Pouce Coupe (Figure 9). Groundwater development is sparse in the southwest portion of the study area.

The majority of wells in the WELLS database were constructed between the 1970s and 1990s, with a moderate level of ongoing well construction since 2000. Water use was interpreted from the well records and from the private wells survey. Of the 478 well records in the study area, a majority of wells are used for private domestic water supply (261 wells). There are also a large number of well records (171 wells) listed with unknown water use; however, it is likely that many of these wells are also used for private domestic water supply. Very few groundwater supply systems were identified in the study area during the Northeast B.C. Source Area (capture zone) delineation for groundwater supply systems (Western Water Associates, 2012). Nine wells are identified in ENV database as water source wells for water supply systems. Seven wells are listed as observation wells and five wells are listed for commercial and industrial water supply wells. However, many of the wells sampled by the private well survey program aren't in the database and many that are in the database don't appear to exist on the ground during the field visit.

Although the WELLS database does not record the total volume of the groundwater that is being diverted, it is expected that the groundwater use does not exceed the aquifer recharge at this time given that all the observation wells show relatively stable groundwater levels as described in Section 4.3. Improved understanding of groundwater use in the study area will be aided by the licensing of non-domestic groundwater use under the Water Sustainability Act, which came into force on February 29, 2016.

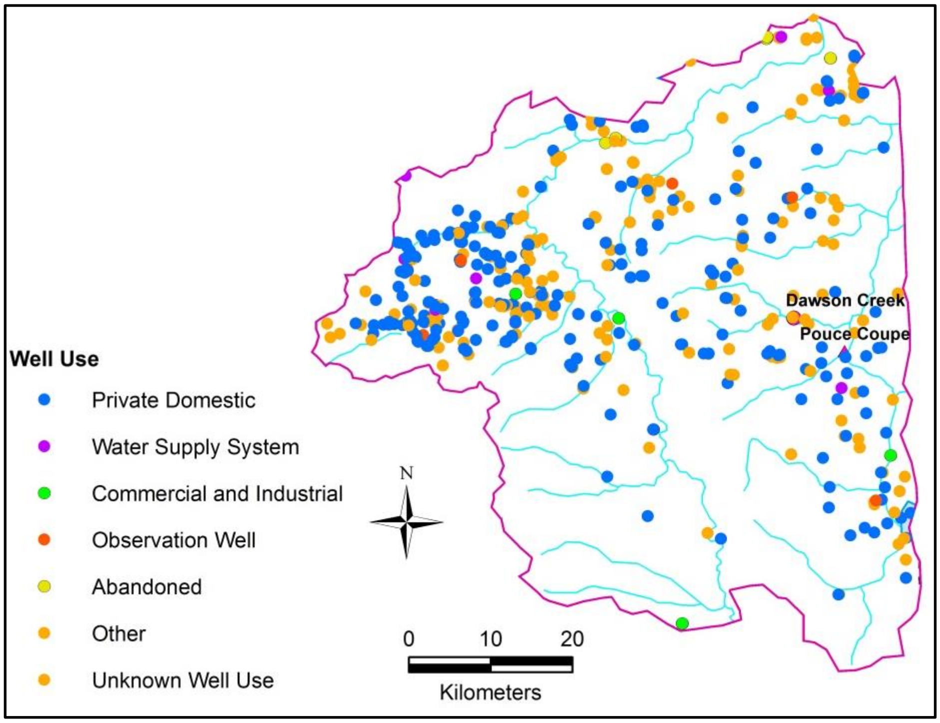


Figure 9 Groundwater development and water use in the study area (inferred from well drillers' logs in WELLS and from the well survey).

3. DESCRIPTION OF HYDROSTRATIGRAPHIC UNITS

3.1 Hydrogeological Setting of the Study Area

The study area is in the Western Plains Hydrogeological Region, which is characterized by a wide basin of low-relief, sub-horizontal sedimentary rocks, overlying extensive glacial deposits and ancient buried valleys (paleovalleys) (Cowen, 1998). Incised post-glacial valleys (Kiskatinaw River and Pouce Coupe River valleys) provide local relief (Geological Survey of Canada, 2008). The Groundbirch paleovalley in the study area is incised into Cretaceous bedrock (Hickin and Best, 2013).

3.2 Hydrostratigraphy of the Study Area

A lithostratigraphic unit is a geological unit that is defined on the basis of its lithologic properties or combination of lithologic properties and stratigraphic relations. A hydrostratigraphic unit is a unit distinguished and characterized principally by common hydraulic properties (porosity, permeability, specific storage) with respect to the occurrence and flow of groundwater (Maxey, 1964). A single hydrostratigraphic unit may therefore include a formation, part of a formation, or a group of formations/lithologies. For example in the study area, the permeable sandstone in the Wapiti Formation and the older Dunvegan Formation may form the same hydrostratigraphic unit if the two sandstones occur adjacent to one another, even though they are different lithostratigraphic units.

3.2.1 Data Sources

There are numerous water wells available in the study area from the provincial WELLS database (https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp). Well records in WELLS contain basic information at the time of drilling such as date of construction, location of the well, driller's name, well depth, lithology, estimated well yield, and static water level. The actual number of wells that have historically been drilled in the area is likely more than what is recorded in WELLS because the submission of well records to government has been voluntary.

The lithological descriptions in the WELLS database do not contain sufficient detailed lithologic information to allow many of the wells to be positively correlated to geological units of the study area. The correlation/interpolation of the lithology between wells is also challenging partly due to the fact that water wells are not evenly distributed over the study area and lithological descriptions recorded by the driller in the well record is frequently generalized. Water wells are denser in settled areas, spotty in sparsely populated areas and lacking in remote areas, particularly in the southern part of the study area (Figure 9).

Significant effort has been made in this project to standardize the driller's lithologic description. A data set is organized from different sources for plotting and hydrostratigraphic interpretations. Four hundred and sixteen (416) well records were selected from the provincial WELLS database and standardized using the SFU standardized well lithology (Toews, 2007 unpublished report). Forty (40) additional well records were also included in the data set from the Geoscience BC database (Figure 10, Appendix A).

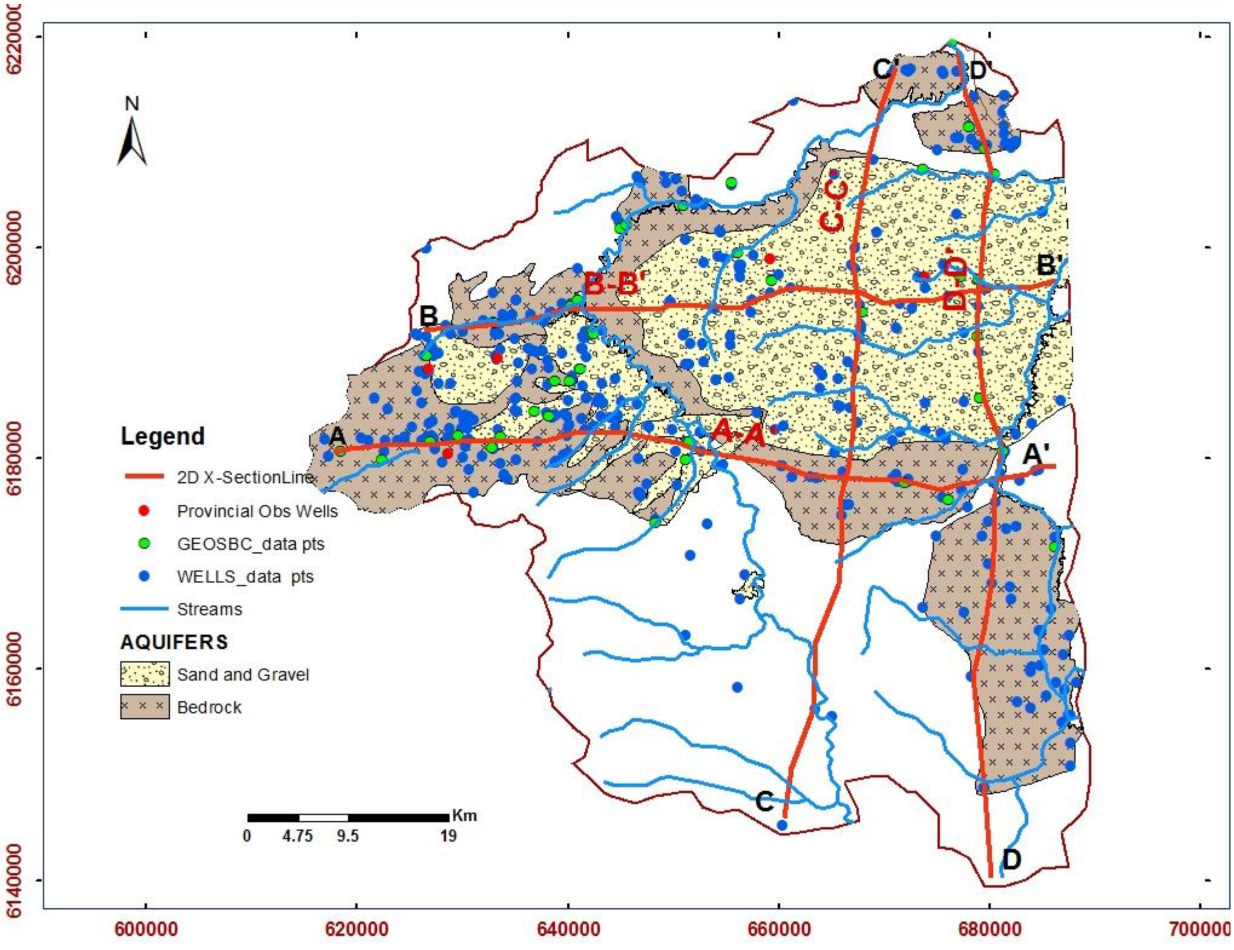


Figure 10 Well lithology data points, aquifers and 2D cross section lines.

3.2.2 Data Conversion and Interpretation

Lithologic descriptions in the well records from the WELLS and Geosciences BC databases were used to establish the lithologic and hydrostratigraphic relationships between wells and across the study area. Lithologic description data are recorded by well drillers but not according to specific protocols. As a result there is ambiguity and variability in the lithologic descriptions recorded by drillers. The lithology interpretation carried out in this project took into consideration the limitations of well log data information and driller practice in recording lithology. Significant effort was made to convert driller lithology descriptions into standard lithology codes. Lithostratigraphic units were grouped into hydrostratigraphic units either as aquifer (permeable sand and gravel or bedrock formations), semi aquifer or aquitard, and aquifer strata (intercalations of less permeable clay, till, silt with lenses of sand and/or gravel formations) or aquitard material. During the interpretation, the lithological records were checked for lithologic descriptions that could not be interpreted because of non-lithological phrases (e.g., hard pan, water bearing formation/rock, etc.), gaps in the lithologic record, the appearance of glacial lithology in a bedrock section of the well log, or no lithological descriptions resulted in excluding the well record from the interpretation.

Each well log was interpreted, assigned a standard lithology code, and regrouped into major hydrostratigraphic units (Table 4shows example interpretations and Table 5 shows the hydrostratigraphic units alongside the colour symbology used to represent the different lithologies). Four hundred and sixteen (416) well lithology records from WELLS and 40 additional records from Geosciences BC database were used for the lithology and hydrostratigraphic interpretations.

Table 4 Examples of interpreting hydrostratigraphy from driller's lithologic descriptions.

Well Tag Number	Depth from (m)	Depth to (m)	Original WELLS database lithology description	Interpreted Lithostratigraphic Unit	Interpreted Hydrostratigraphic Unit
1047	0.0	3.4	Clay med grey/brown	Clay	Aquitard
	3.4	38.4	Silty sandy clay	Clay	Aquitard
	38.4	55.8	Med grey shale	Shale	Bedrock Aquifer
	55.8	73.1	Dark grey shale	Shale	Bedrock Aquifer
11930	0.0	42.7	Clay and gumbo	Clay	Aquitard
	42.7	43.0	Weathered shale	Shale	Bedrock Aquifer
14512	0.0	1.2	Blue clay	Clay	Aquitard
	1.2	51.8	Silt	Silt	Aquitard
	51.8	54.3	Gravel	Gravel	Unconsolidated Aquifer
	54.3	54.9	Sand	Sand	Unconsolidated Aquifer
18789	0.0	1.2	Silt	Silt	Aquitard
	1.2	3.4	Silty clay	Clay	Aquitard
	3.4	5.2	Silty sand	Sand	Unconsolidated Aquifer
	5.2	14.9	Sticky silty clay	Clay	Aquitard
	14.9	29.3	Silty clay - lenses of sand	Clay with S&G layers	Aquitard/ Aquifer strata
	29.3	30.5	Silty clay - layers of fine sand	Clay with S&G layers	Aquitard/ Aquifer strata
	30.5	34.4	Fine sand layers of clay	Clay with S&G layers	Aquitard/ Aquifer strata
	34.4	39.6	Silty clay, lenses of fine sand	Clay with S&G layers	Aquitard/ Aquifer strata

Table 5 Interpreted hydrostratigraphic unit descriptions.

Hydrostratigraphic unit	Descriptions	Lithological symbology in the cross sections
Unconsolidated Aquitard	Units with significant less permeable fine-textured unconsolidated units (e.g., clay, till and/or silt)	🟥
Unconsolidated Aquitard /Aquifer strata	Less permeable unconsolidated units interbedded with lenses of permeable materials that can yield groundwater to wells	🟧
Unconsolidated aquifer	Permeable sand and / or gravel units	🟨
Bedrock aquifer	Bedrock with sufficient permeability to yield groundwater to wells	🟩

3.2.3 2D Cross Sections

The local litho/hydro stratigraphic relationship was interpolated using two West–East (AA'; BB', Figure 11) and South–North 2D cross sections (CC'; DD', Figure 12).

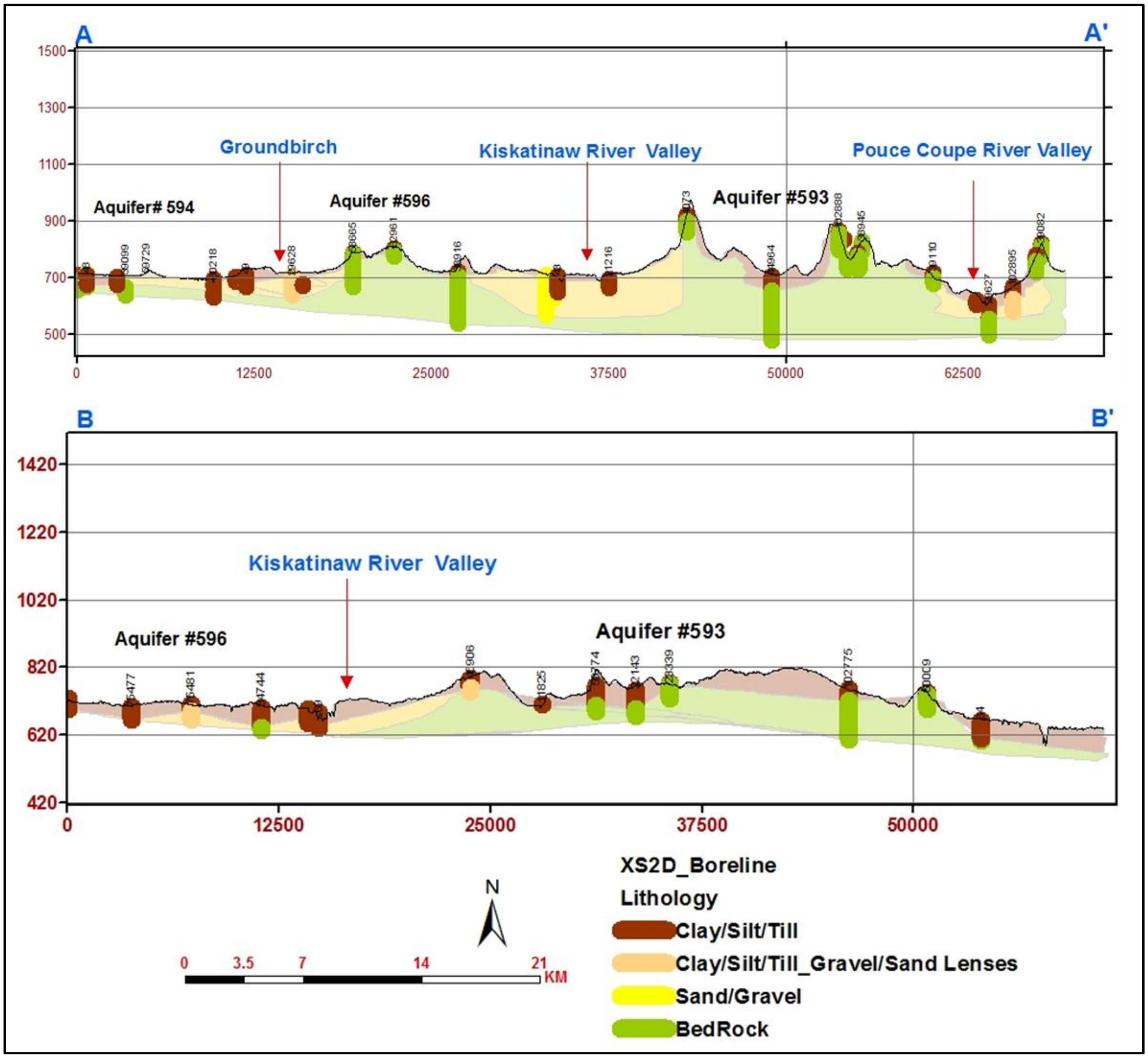


Figure 11 West–East 2D cross sections.

The unconsolidated sand and gravel aquifers are spotty in nature and seem to be associated with major river valleys and low lying areas (Figure 12). The aquifers in most of the areas along the cross section lines are overlain by clay/till deposits of variable thickness creating a confined condition in both bedrock and unconsolidated aquifers. Relatively thick unconsolidated sand and gravel aquifers are intercepted in the west central part of the study area around Groundbirch, which reflect the buried channel Groundbirch paleovalley aquifers. The topographic lows of the Kiskatinaw River valley in the western part of the study area and Pouce Coupe River valley in the eastern part of the study areas are also covered by patches of unconsolidated sand and gravel aquifers. Bedrock aquifers underlie the entire study area with variable depth ranging from surface out crop to more than 100 meters at places.

With respect to driller's well log lithology descriptions in the WELLS database, there is not enough distinction of the different bedrock types (shale, sandstone, mudstone, etc.). As a result, the bedrock hydrostratigraphy is lumped as one bedrock unit.

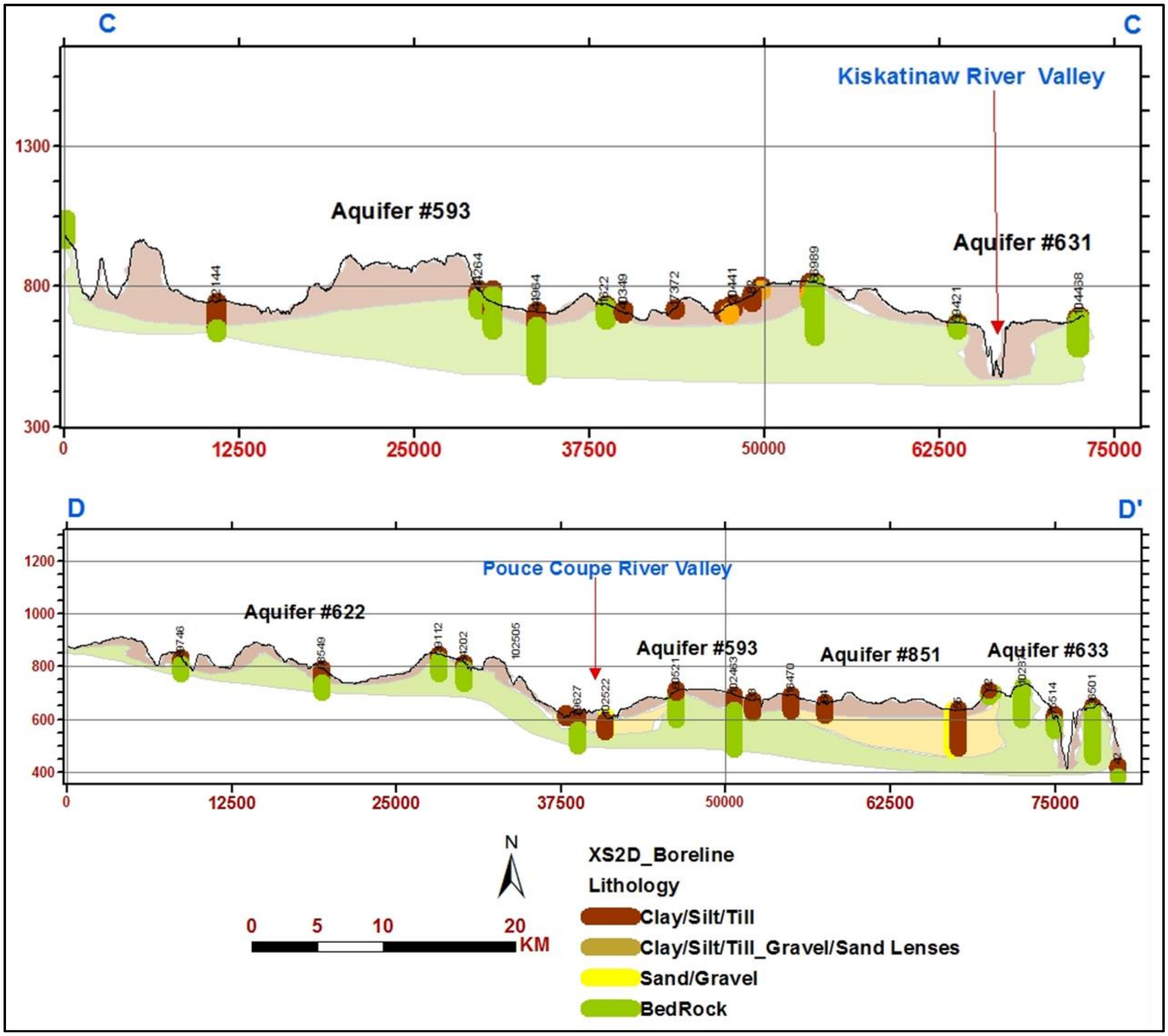


Figure 12 South–North 2D cross sections.

3.2.4 Buried Valley (Paleovalley) Stratigraphy

Buried paleovalleys are common in northeast British Columbia (Hickin, 2011). Three provincial observation wells are located in the Groundbirch area where a paleovalley is believed to trend east-northeast from the Kiskatinaw River to the Pine-Murray River confluence (Hickin et al., 2016). Hickin (2013) investigated the stratigraphy of the paleovalley and concluded that the Quaternary valley fill above the bedrock mainly consists of three units: advance phase/ fining upward glaciolacustrine sediments (glacial Lake Mathews), glacial tills, retreat phase/ coarsening upward glaciolacustrine sediments (glacial Lake Peace). Among all these three units the upper and lower lake deposits are potential aquifers separated by clay rich glacial tills.

In order to characterize the Groundbirch paleovalley, two exposed sections (Figure 13), representing the upper and lower succession of the valley fill, were investigated. In addition, five exploration wells were drilled in 2015 within the extent of the paleovalley to further investigate the spatial distribution of the three major units.

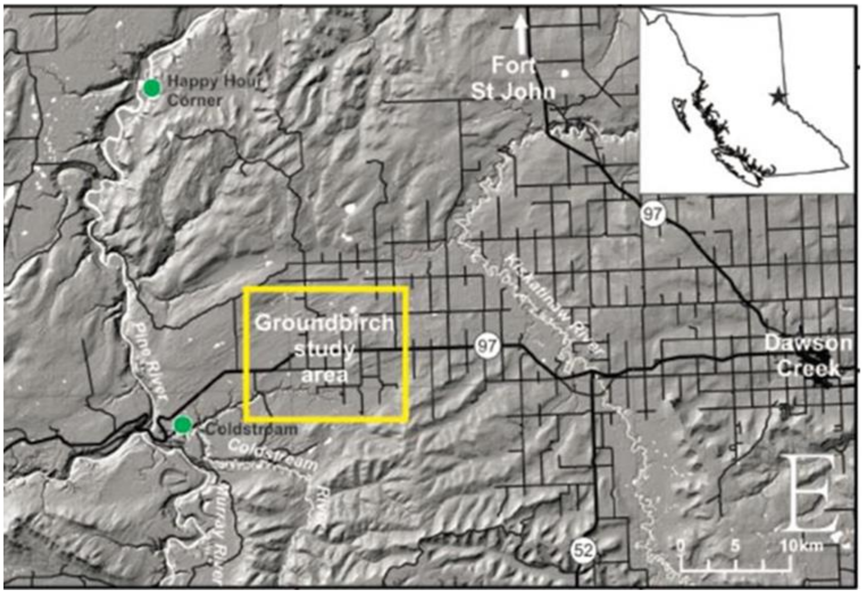


Figure 13 Topograpghy and general location of the Goundbirch paleovalley (Source: Hickin et al., 2016).

Detailed descriptions of the exposures and the well logs can be found in Hickin et al. (2016). A summary of the findings are reported in this section with the permission of the lead author.

The Happy Hour Corner section (Figure 13) has over 200 m of unconsolidated sediments deposited above bedrock. The majority of the exposed section is the glaciolacustrine deposits (advance phase, fining upward glacial sequence, Lake Mathews) characterized by sand, silt, clay with dropstones and diamicton lens. The major section of this exposure is interpreted as subglacial fluvial and glaciolacustrine (retreat phase coarsening upward glacial sequence, Lake Peace) deposits. Unlike the thicker and more homogenous sand, silt and clay in the Happy Hour Corner section, the retreat phase glaciolacustrine deposits at this section has relatively coarser sand and gravel layers.

At the Coldstream River section, the overall unconsolidated sediments are thinner and less exposed. It consists of pre-glacial/interglacial fluvial sand and gravel at the bottom overlain by 12-20 m glacial till. The major section of this exposure is interpreted as subglacial fluvial and glaciolucstrine (retreat phase, Lake Peace) deposits. The topmost section is the post glacial silty sand. Unlike the thicker and more homogenous sand, silt and clay in the Happy Hour Corner section, the retreat phase glaciolacustrine deposits at the Coldstream River section has relatively coarser sand and gravel layers.

In 2015, five exploration wells were drilled west of Dawson Creek at the Groundbirch area (Figure 14) to supply the ground based information to an earlier electromagnetic (EM) survey (Hickin et al., 2016). The detailed glacial lithologic description of the exploratory borehole data was regrouped into simplified litho/hydro stratigraphic units for the purpose of this report.

- GB-1 was drilled on the north flank of the Groundbirch paleovalley. The drilling encountered bedrock at 81 m (shown in green in Figure 15). From the bottom to the ground level the unconsolidated sediments consist of diamicton (gray), gravel/sandy gravel (gold), sand/silty sand (yellow) and clay (shown in brown in Figure 15).
- GB-2 was drilled approximately 800 m south of GB-1. The drilling stopped at 146 m and the bedrock was not encountered. The unconsolidated sediments can be generally compared to the sediments in GB-1 but with significant differences in thickness.
- GB-3 is located roughly 3 km east of the previous two wells. The bedrock in this location is relatively shallower at 53.6 m. Overlying the bedrock is a silty to silty clay diamicton which can be interpreted as glacial till. Above this unit are the fine sand/silty sand and clay respectively (Figure 15).
- GB-4 is approximately 2.6 km south of GB-2 which is at the south flank of the paleovalley. The shell bedrock is at a depth of 69.1 m. From the bottom to the ground level the unconsolidated sediments consist, diamicton, fine sand/silty sand and clay respectively.
- GB-5 was drilled in between GB-3 and GB-4, a little more towards the south flank of the paleovalley valley. No bedrock was encountered up to 118 m. Here the glaciolacustrine deposits are characterized by fine sand/silty sand and clay, from bottom to top.

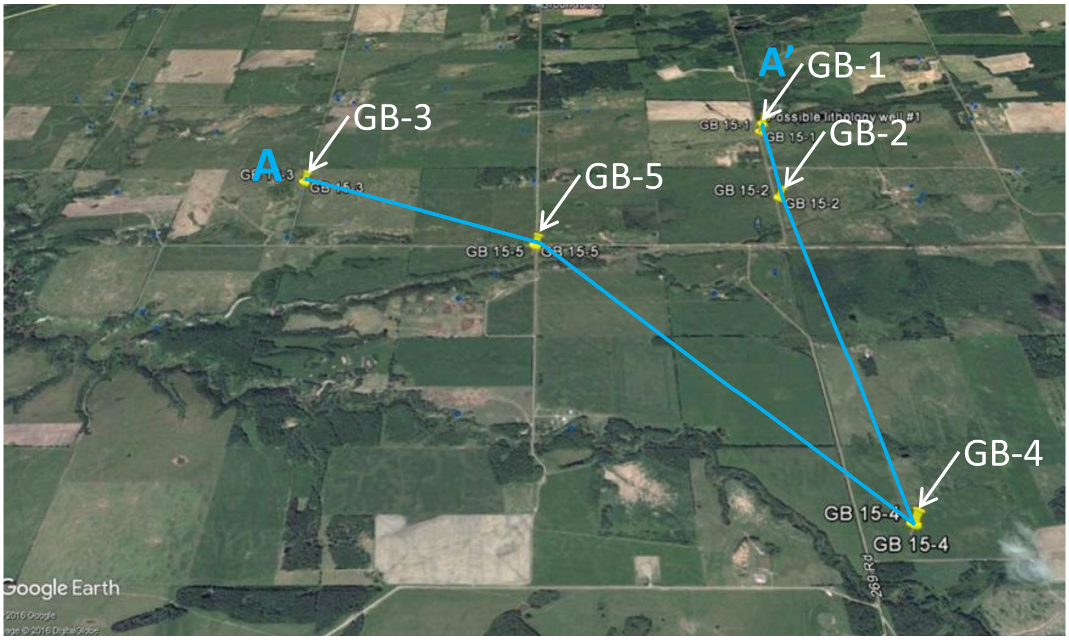


Figure 14 Location of exploration wells in the Goundbirch paleovalley study area (Source: Hickin et al., 2016).

A simplified 2D litho-hydrostratigraphy cross section was plotted using the five exploratory boreholes data (Figure 15). The valley fill material can be observed to thicken towards the middle of the valley. The bedrock appears to be shallower at the northeast and southwest flank. Although sand and gravel deposits are good aquifer materials, the layers are not continuous and can only be seen in two wells (GB-2 and GB-4).

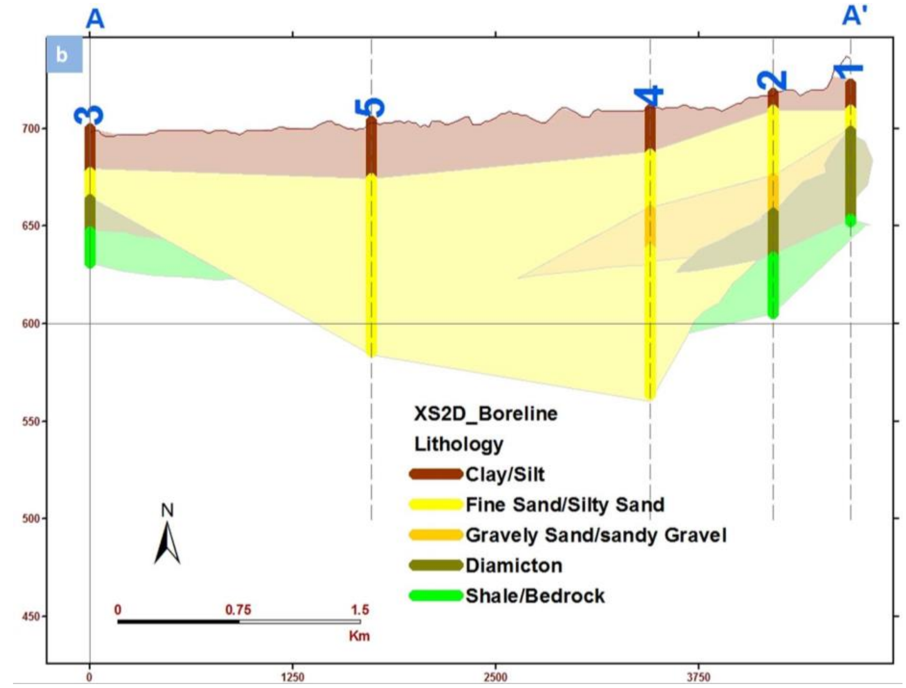


Figure 15 2D cross-section of the Groundbirch paleovalley exploratory wells.

3.3 Study Area Classified/Mapped Aquifers

Prior to this study, ENV has delineated and classified 17 aquifers within the study area (Figure 16). Nine of the classified aquifers are unconsolidated sand and/or gravel (Table 6) and eight are consolidated sedimentary bedrock aquifers (Table 7). The aquifers range in size from 3.2 km^2 to 1146.2 km^2. Because this aquifer mapping was mainly based on the well log information recorded in the provincial WELLS database, the aquifer boundaries and the understanding of connectivity between aquifers is uncertain and is subject to change as more information becomes available in the future. For an explanation of the BC Aquifer Classification System, see Kreye and Wei (1994) and Berardinucci and Ronneseth (2002).

Based on the provincial aquifer classification inventory, most of the aquifers in the area are characterized by moderate productivity, low vulnerability to surface contamination and multiple water use (Table 8).

3.3.1 Unconsolidated Aquifers

The aquifer boundaries are delineated on the basis of water well records available in the WELLS database, surficial geologic maps, and topographic features. In well lithology, the unconsolidated aquifers were described by well drillers either as fine sand, sand and/or gravel. Based on well drillers' estimates, unconsolidated aquifers are generally more productive and have shallower static water level (SWL) compared to the bedrock aquifers (Table 6, Table 7). The unconsolidated aquifers in the study area are variable in nature. The majority of the unconsolidated aquifers (i.e., 590, 592, 596, and 598) seem to be associated with river valleys and low lying areas. Others (i.e., 851) are mapped as discrete units but the water bearing sand and gravel zones do not occur everywhere and may not be continuous. As indicated by Kelly and Janicki (2011), the selection of the provincial observation well locations aimed, for the most part, to intercept both the overlying unconsolidated and underlying bedrock aquifers in the area. However, five of the wells were completed in bedrock aquifers 591 (Obs wells 416 & 417) and 593 (Obs wells 418, 419 & 420) without intercepting any water-bearing sand and gravel zones within the boundary of the mapped overlying unconsolidated aquifers (590, 592 or 851), while two other wells (Obs well 421 and 445) were successfully drilled into unconsolidated, water-bearing sand and gravel in aquifer 590. Drilling of the observation wells and interpretation of the hydrostratigraphy of the study area reveals that the aquifer 851 is not as aerially extensive or continuous as implied by the aquifer polygon. Aquifer 851 can be viewed as an aquifer with apparently discontinuous water-bearing zones. Hence, the authors of this report strongly recommend a review of aquifer 851.

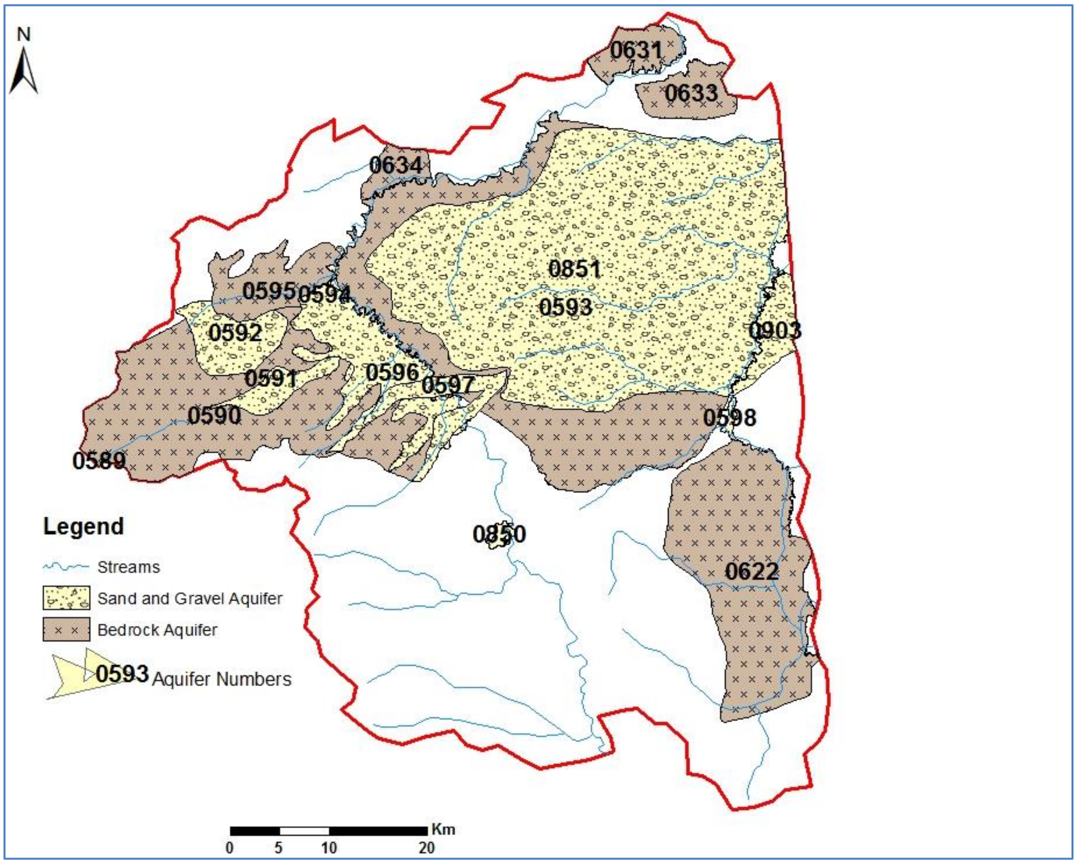


Figure 16 Mapped and classified aquifers in the study area.

Table 6   Summary properties of unconsolidated aquifers.

Statistic	Aquifer Number								
	590	**592**	**594**	**596**	**597**	**598**	**850**	**851**	**903**
Well depth (m)									
n	28	23	26	21	5	4	2	42	3
min	21.9	5.5	13.7	6.7	98.8	44.2	85.3	3.7	7.3
max	91.4	46.6	118.3	65.5	140.2	112.8	123.4	61.0	36.6
mean	50.3	26.2	68.0	33.5	117.0	72.8	104.5	21.0	23.8
Depth to static water level (m)									
n	16	17	15	13	4	1	1	28	3
min	2.4	1.2	12.2	3.4	4.6	0.6	21.3	1.2	3.0
max	30.5	16.8	47.2	36.9	42.7	0.6	21.3	57.9	30.5
mean	20.7	6.1	29.6	18.3	18.6	0.6	21.3	11.9	18.3
Reported well yield (m^3/day)									
n	13	11	16	7	3	3	2	10	-
min	5.5	27.3	21.8	27.3	98.1	163.5	54.5	Dry	-
max	327.1	218.0	109.0	408.8	408.8	872.2	272.6	163.5	-
mean	92.7	81.8	65.4	163.5	212.6	397.9	163.5	60.0	-

Table 7 Summary properties of bedrock aquifers.

Statistic	Aquifer Number						
	591	593	595	622	631	633	634
Well depth (m)							
n	107	86	18	39	7	22	8
min	8.2	4.9	22.3	27.4	27.4	12.0	30.5
max	182.9	195.1	128.0	140.2	115.8	91.4	158.5
mean	64.9	56.7	54.9	66.8	63.7	41.5	106.1
Depth to static water level (m)							
n	63	46	6	22	-	15	3
min	0.6	0.0	8.2	1.2	-	6.0	6.7
max	50.6	59.1	25.9	89.0	-	76.8	85.3
mean	20.4	21.9	15.2	26.2	-	30.8	38.7
Reported well yield (m^3/day)							
n	80	53	17	31	7	13	5
min	5.5	Dry	5.5	5.5	16.4	Dry	5.5
max	272.6	479.7	125.4	545.1	136.3	43.6	163.5
mean	70.9	60.0	60.0	92.7	92.7	21.8	54.5

Table 8 Mapped aquifers in the study area (Lowen, 2011).

Aquifer number, classification (ranking)	Aquifer material	Aquifer type	Aquifer productivity	Aquifer vulnerability	Aquifer size (km^2)	Type of water use	Observation well numbers
589 IIC (7)	Bedrock	5a	Low	Low	19.1	Domestic	
590 IIIC (11)	Sand & gravel	4b	Moderate	Low	49.3	Multiple	445
591 IIIC (12)	Bedrock	5a	Moderate	Low	519.7	Multiple	416, 417
592 IIIC (11)	Sand & gravel	4b	Moderate	Low	63.9	Multiple	
593 IIIB (9)	Bedrock	5a	Low	Moderate	1146.2	Domestic	418, 419, 420
594 IIIC (10)	Sand & gravel	4b	Moderate	Low	53.8	Multiple	
595 IIIC (10)	Bedrock	5a	Moderate	Low	69.6	Multiple	
596 IIIC (14)	Sand & gravel	4b	Moderate	Low	125.2	Multiple	
597 IIIC (10)	Sand & gravel	4b	Moderate	Low	40.5	Multiple	
598 IIIA (10)	Sand & gravel	2	High	High	3.2	Domestic	
622 IIIC (12)	Bedrock	5a	Moderate	Low	280.2	Multiple	
631 IIIC (10)	Bedrock	5a	Moderate	Low	43.7	Multiple	
633 IIIC (9)	Bedrock	5a	Moderate	Low	44.9	Domestic	
634 IIIC (9)	Bedrock	5a	Moderate	Low	83.8	Domestic	
850 IIC (6)	Sand & gravel	4b	Moderate	Low	4.1	Potential Domestic	
851 IIC (10)	Sand & gravel	4a	Moderate	Low	866.4	Multiple	
903 IIB (9)	Sand & gravel	4b	Low	Moderate	33.9	Domestic	

3.3.2 Bedrock Aquifers

Similar to the unconsolidated aquifers, the bedrock aquifer boundaries are delineated on the basis of water well records, bedrock geologic maps, and topographic features. In most cases the bedrock lithology is described as shale and/or sandstone by well drillers and interpreted as shale and/or sandstone of the Kaskapau or Dunvegan formations by the authors. Based on well drillers' estimates, bedrock aquifers are generally less productive and have deeper static water levels compared to the unconsolidated aquifers in the study area (Table 6, Table 7). Most of the wells outside of the river valleys and low lying areas are drilled into bedrock aquifers which are overlain by aquitards (clays, silts, tills) of variable thickness. It appears that the bedrock aquifers in the study area are extensive and regional, but have been mapped as compartmentalized polygons with separate aquifer classification numbers, based on area of development.

4. AQUIFER HYDRODYNAMIC AND HYDRAULIC PROPERTIES

4.1 Potentiometric Surface Distribution and Flow Direction

The static water level (SWL) is the depth of water in a well that is not affected by pumping. The SWL is typically measured as a depth from the ground surface to the water level in a well. If the ground surface elevation at the well is known, the SWL can be converted to a water level elevation or hydraulic head elevation. A contour map of hydraulic head elevation (also known as a potentiometric surface map) can show the likely direction of groundwater flow. The hydraulic gradients, which can be directly derived from the hydraulic head contours, are one of the components (the aquifer's hydraulic conductivity is the other) for calculating the rate of groundwater flow (De Ridder, 1980). The contour lines of a hydraulic head map or a potentiometric surface map are in fact equipotential lines and represent the distribution of hydraulic heads in the study area. Hence the direction of the groundwater flow, typically assumed to be perpendicular to the equipotential lines, can be directly inferred from these maps. Furthermore, locations of groundwater gaining (i.e., influent stream) or losing (i.e., effluent stream) and flowing artesian conditions (where hydraulic head elevation is greater than local ground surface elevation) can be determined using these maps if enough data is available. Thus, a potentiometric map can assist drillers in assessing the potential for encountering flowing artesian conditions from confined aquifers, or for estimating the depth of drilling required to encounter groundwater under unconfined conditions.

The depth to water map is prepared in two steps. The water level data from all the water wells are first converted to water levels below ground surface (bgs) (i.e., transforming any top of casing (TOC) measurement into below ground surface by subtracting the casing length above ground from the SWL top of casing measurement). Then the calculated data are plotted on the topographical base map at each well and lines of equal depth to groundwater are drawn (Figure 17, untransformed SWL data is used in this case). The SWL or depth to groundwater level in the study area generally increases from west to east. Shallow water levels, less than 30 m, are predominantly in the south central portion of the study arear, and deep water level, greater than 80 m, are predominantly in the northeastern portion of the area. Flowing well conditions are also reported in few areas (e.g., WTN 17941 around Willow Brook school in aquifer 593, Obs well # 419/WTN 104710 around 217Rd and Sweetwater Rd in aquifer 591).

Figure 17(a) displays the interpolated depth to static water level (SWL) map of the study area that can be currently achieved on the basis of the available water level data. The prediction of standard error map (Figure 17b) shows that the accuracy of estimates is greater in the north central part of the study area, where most data points cluster. Highest values of prediction errors are found near the borders and southern part of the study area where data points are sparse or lacking. In addition to the interpolation error there may also be other potential sources of error related to measurement. Not all measurements were taken at the same time, so errors resulting from temporal fluctuations are also present and not accounted for in the prediction error map. Measurement is also taken at time of drilling and may be influenced by the well construction, this error is also not accounted for in the error.

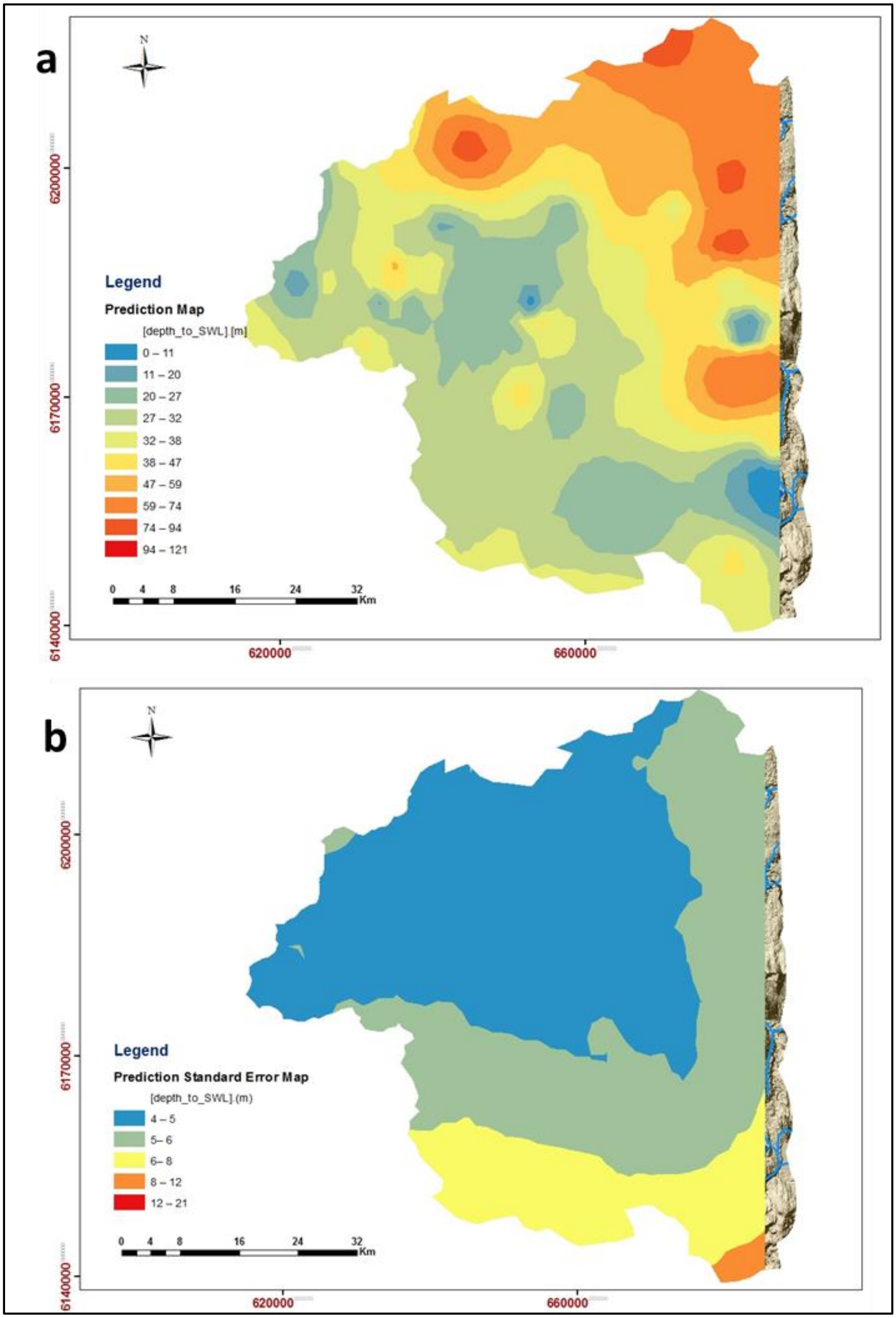


Figure 17 (a) Depth to static water level map (b) Depth to static water level prediction error map.

Figure 18 is a map of the hydraulic head elevation above mean sea level. Groundwater elevation from mean sea level was calculated using the available depth to SWL data and topographic elevation taken from the provincial Trim-25m DEM archive. As the major portion of the study area is overlain by clay and or till deposits of variable thickness which in the most part creates a confined to semi-confined system, all available water level data is used together to show more of a potentiometric surface than a water table. In addition to this, due to lack of data, Figure 18 lumps all the groundwater level elevation data from the unconsolidated or bedrock aquifers and so the contour map reflects a vertically integrated picture of hydraulic head distribution in the study area. Generally, the lateral groundwater flow direction appears to follow the topography, in addition to this local barrier, lithology and structures might also contribute to the complex flow pattern. In the western part of the study area groundwater flow towards the topographic lows of the Kiskatinaw River valley and in the eastern part of the study area groundwater flows towards the topographic lows of the Pouce Coupe River valley. Upland areas would be local recharge areas and low lying areas and river valleys appear to be local discharge areas.

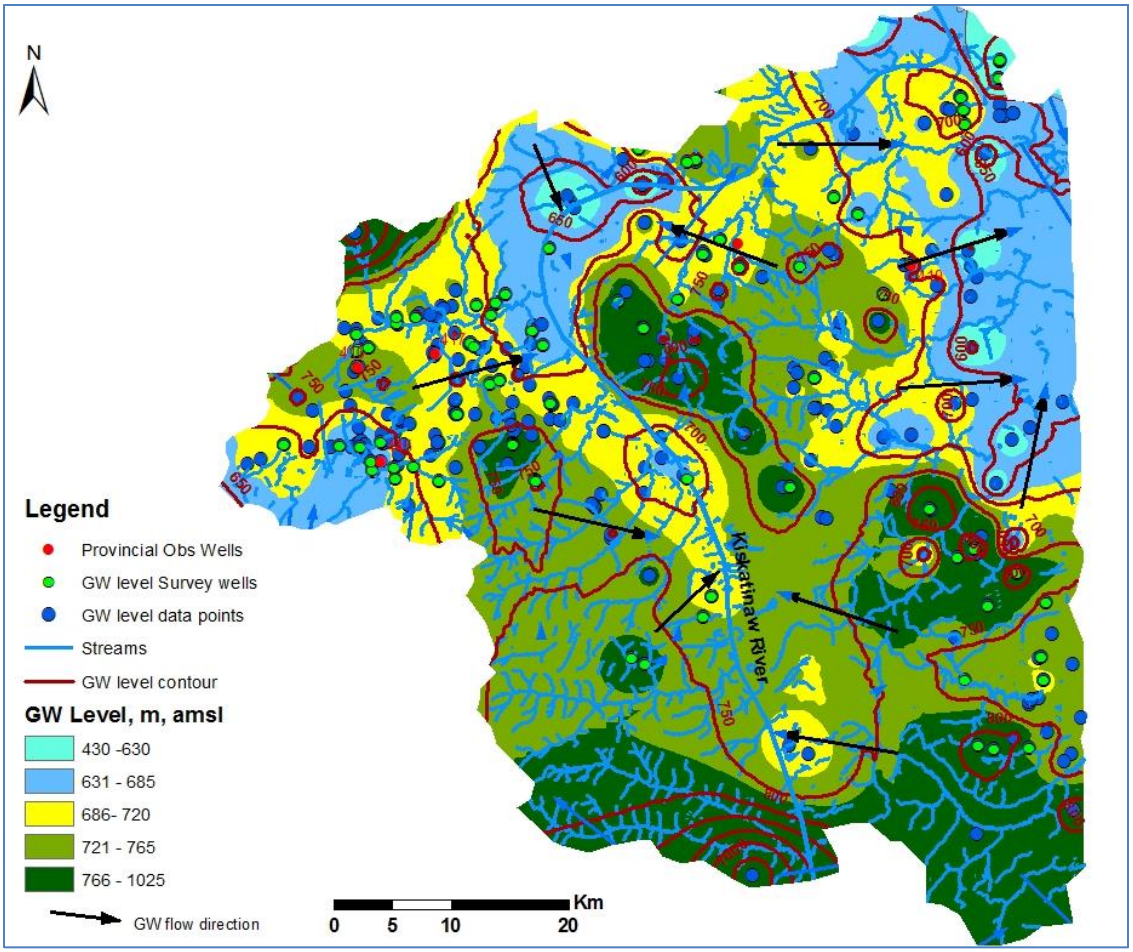


Figure 18 Distribution of potentiometric surface and inferred groundwater flow direction map.

4.2 Groundwater Recharge (by: S. Holding and D.M. Allen, SFU)

Groundwater recharge is the quantity of water that infiltrates and replenishes an aquifer. Recharge is commonly reported as an annual depth value (i.e., mm/year) and is an important component of an aquifer's water budget. Recharge can be estimated using a variety of approaches varying from direct measurements to modelling. Pros and cons for the various methods are discussed elsewhere (Healy, 2010).

In the study area, recharge modelling was conducted using the US Environmental Protection Agency's Hydrologic Evaluation of Landfill Performance (HELP) software program (Schroeder et al., 1994), which calculates recharge through the vadose (unsaturated) zone based on climate and land surface data, and soil and aquifer properties. HELP utilizes a storage routing technique based on hydrological water balance principles to determine soil moisture storage, runoff, interception, and evapotranspiration from climate data. For this study, vertical percolation columns were defined using the standardized lithological descriptions for the well records in WELLS to represent the range of vadose zone and soil properties. The amount of water that percolates to the base of the column represents recharge to the aquifer. HELP uses a stochastic weather generator to generate a time series of daily climate data (temperature, precipitation and solar radiation) for a pre-defined number of years using mean monthly values and a set of statistical parameters based on historical climate data. For this study, mean monthly temperature values were based on Dawson Creek climate normals 1981-2010, the statistical parameters were based on the nearest climate station in the database, Prince George. Mean monthly precipitation normals were varied to represent the different values observed within the study area, as described below. HELP was run for a 100 year simulation time to provide average annual recharge estimates.

4.2.1 Recharge Scenarios

Recharge scenarios were based on unique combinations of the predominant soils and vadose zone materials in study area. Vadose zone materials are predominantly till and glaciolacustrine sediments, with minor areas of glaciofluvial sediments along river valley bottoms. Soils are predominantly loamy sand with smaller areas of mixed (undifferentiated) sandy/silty Loam. Scenarios are labelled as per Table 9. Figure 19 shows the vadose zone and soil material distributions with the study area.

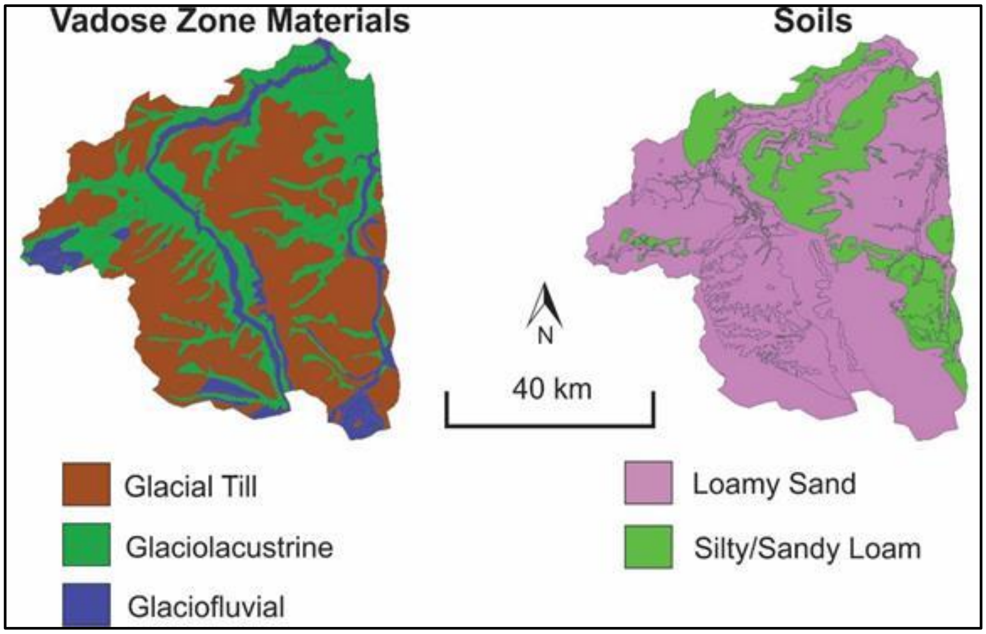


Figure 19 Study area vadose zones and soil distributions used in HELP modeling

4.2.2 Input Parameters

Soils were assigned the default parameters in HELP, including the hydraulic conductivity (K) values for the soil and vadose zone. The vadose zone materials were approximated based on similar materials within the HELP soils database (till was simulated with barrier soils; glaciolacustrine with silty clay; glaciofluvial with fine sand). K values were specified using literature estimates for the materials (same as those used in the DRASTIC assessment by Holding and Allen, 2015).

The soil layer was set at 1 m thick, with the vadose zone 19 m thick. Therefore, the full unsaturated zone was 20 m. This value represents the average depth to water for all wells within the study area.

Table 9 Combinations of vadose zones and surface soil properties used in study area HELP modeling,

Recharge scenarios		**Vadose Zone**		
		Till (K = 8.64x10^{-5}m/d)	**Glaciolacustrine** (K = 4.32x10^{-6} m/d)	**Glaciofluvial** (K = 432 m/d)
Soils	**Loamy Sand** (K = 1.468 m/d)	A	C	E
	Sandy Loam (K = 0.622 m/d)	B	D	F
	Silty Loam (K = 0.164 m/d)	B2	D2	F2

4.2.3 Results

Average monthly precipitation, evapotranspiration, runoff and recharge are provided in Appendix B and results are summarised in Table 10. In general, the soil type does not have a large effect on the recharge results, except for the glaciofluvial vadose materials where the siltier soils result in slightly lower recharge rates (Table 10).

Table 10 HELP model results for average annual recharge in the study area.

Annual average recharge results (mm/year)		**Vadose Zone**		
		Till (K = 8.64x10^{-5}m/d)	**Glaciolacustrine** (K = 4.32x10^{-6} m/d)	**Glaciofluvial** (K = 432 m/d)
Soils	**Loamy Sand** (K = 1.468 m/d)	33	2	68
	Sandy Loam (K = 0.622 m/d)	33	2	57
	Silty Loam (K = 0.164 m/d)	33	2	46

Scenarios of both silty loam and sandy loam soils were modelled. Only the silty loam scenarios (Appendix B: B2, D2 and F2) were carried forward in the mapping as they represent a larger change in results. Therefore, all areas with soil identified as mixed silty/sandy loam were assigned the silty loam results. Figure 20 shows the estimated recharge values for the combinations of vadose zone and soil materials within the study area.

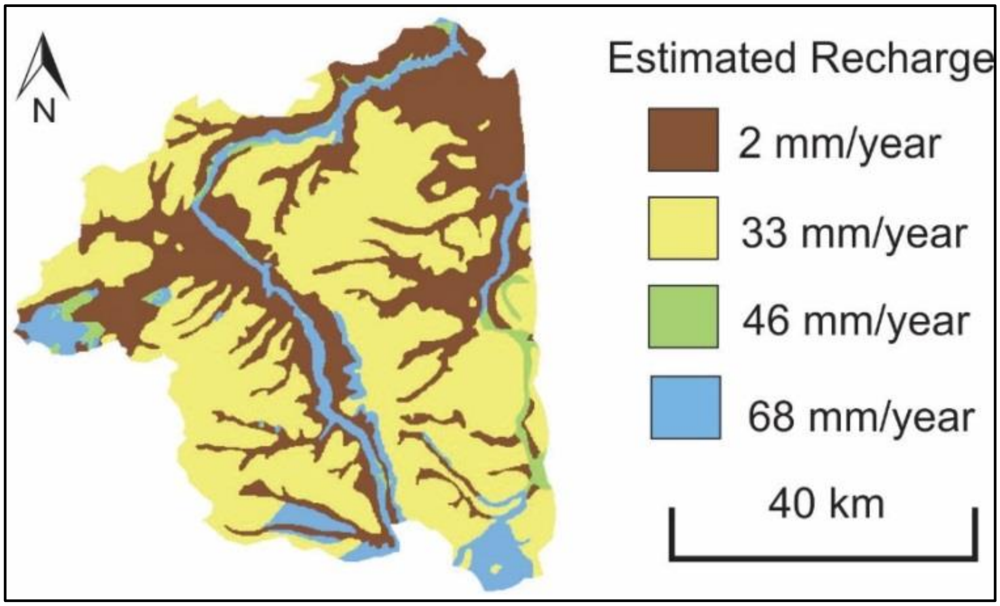
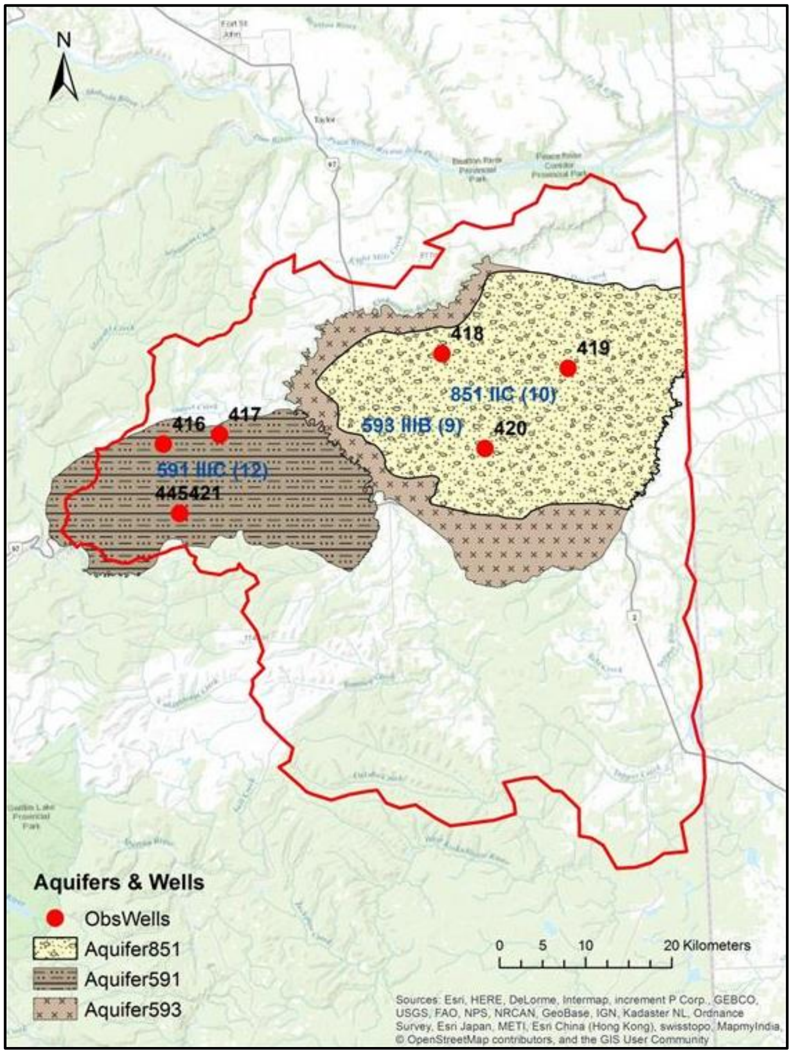


Figure 20 Estimated study area recharge distribution from HELP modeling

The HELP model groundwater recharge results indicate that the vadoze zone influences the recharge rate more than the soil type. The soil type does not have a large effect on the recharge results, except for the glaciofluvial vadose materials where the siltier soils result in slightly lower recharge rates.

4.3 Observation Wells and Groundwater Monitoring

In 2011 and 2012, seven provincial observation wells were drilled into aquifers 590, 591 and 593 to monitor the groundwater level fluctuation over time and to characterize baseline groundwater quality in the aquifers. Observation wells 416 and 417 were drilled into bedrock aquifer 591 west of Dawson Creek (Figure 21). The locations of observation wells 418, 419 and 420 were initially selected to encounter both aquifer 851 which is the overlying sand and gravel aquifer and the underlying bedrock aquifer 593, but none of these wells intercepted the unconsolidated aquifer (Kelly and Janicki, 2011). This shows that aquifer 851 is not continuous implied by the aquifer polygon. Instead, the aquifer is discontinuous, with groundwater zones often identified in well logs as thin sand and gravels lenses, and more commonly encountered around low lying areas and river valleys. Observation well 421 (which was later decommissioned) and 445 were completed in unconsolidated sand and gravel aquifers 590 in the Groundbirch paleovalley. Details of the construction of these observation wells are presented in Kelly and Janicki (2011).



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 21 Locations of observation wells in the Dawson Creek area

Observation well 419 is a flowing artesian well and is not currently monitored. A packer was installed 2.4 m below the ground surface to prevent the well from flowing and freezing during the winter time. All the other observation wells were instrumented with the satellite telemetry system. The hourly water level data is publicly available at the BC observation well interactive map website (http://www.env.gov.bc.ca/wsd/data_searches/obswell/map). Water quality was sampled one or two times every year by regional staff and the results are available in the EMS database. (https://a100.gov.bc.ca/ext/ems/mainmenu.do).

4.3.1 Observation Wells 416 & 417

Provincial observation well 416 is located at Lineham and 275 Road west of Dawson Creek (Figure 21). The well monitors water levels in bedrock aquifer 591. During construction, bedrock was encountered at a relatively shallow depth of approximately 3 m with a thin overburden of clay and rocks. The bedrock is primarily weathered sandstone with intercalations of shale and siltstone. At the time of drilling, the static water level was 18.97 m below the ground surface and the estimated well yield was 1.89 l/s (30 US gpm). Subsequent pumping test analyses estimated the aquifer transmissivity and hydraulic conductivity at 69 m^2/d and 7.7 m/d, respectively (Baye, 2013). The lithology and hydraulic testing indicate a productive fractured sandstone aquifer at this location.

Observation well 417 is located at 267 and 214 Road west of Dawson Creek (Figure 21) and was also installed to monitor water levels in bedrock aquifer 591, similar to observation well 416. However, the lithology encountered during drilling was somewhat different from that observed at observation well 416. The overburden was comparatively thicker consisting of approximately 12 m of clay and till, and the bedrock material was primarily weathered shale and siltstone, compared with sandstone at well 416. The static water level at the time of drilling was at 5.28 m below the ground surface, and the well yield estimated by the driller was 1.26 l/s (20 US gpm). Subsequent pumping test analyses estimated the aquifer transmissivity and hydraulic conductivity at 16 m^2/d and 0.8 m/d, respectively. The lithology and hydraulic testing indicate a fractured shale and siltstone aquifer with low to moderate productivity.

Figure 22 shows measured groundwater hydrographs in wells 416 and 417 from August 2014 to July 2015. Both observation wells show similar seasonal patterns. Groundwater levels rise over a two-month period in late spring following freshet, with peak groundwater levels lagging peak streamflow in the Kiskatinaw River by about one month (Figure 3). Subsequently, groundwater levels gradually diminish over the remainder of the year. The overall change in groundwater levels from recharge following freshet is small in both wells, about 1m. However, the recharge response is about four times greater in well 416 (0.8 m) than in well 417 (0.2 m). This may reflect the greater local recharge due to the thinner overburden thickness at well 416 (3 m) compared to 12 m at well 417, and the greater conductivity of the sandstone formation (~8 m/s) compared to the shale formation (0.8 m/s).

4.3.2 Observation Wells 418 & 420

Observation well 418 is located at Sweetwater and 235 Road north-west of Dawson Creek (Figure 21). The well was drilled to 90 m, which is the deepest of all the seven wells. The well was drilled into shale and siltstone and has a very low well yield of 0.016 l/s (0.25 USgpm) as estimated by the driller. The static water level when the well was drilled was at 57.44 m below the ground surface. Due to the extremely low well yield and deep groundwater table, a pumping test could not be conducted. Less fractured bedrock (and low yield) may also explain the relatively stable groundwater table year round with no apparent response to spring freshet or end of the year recession (Figure 23).

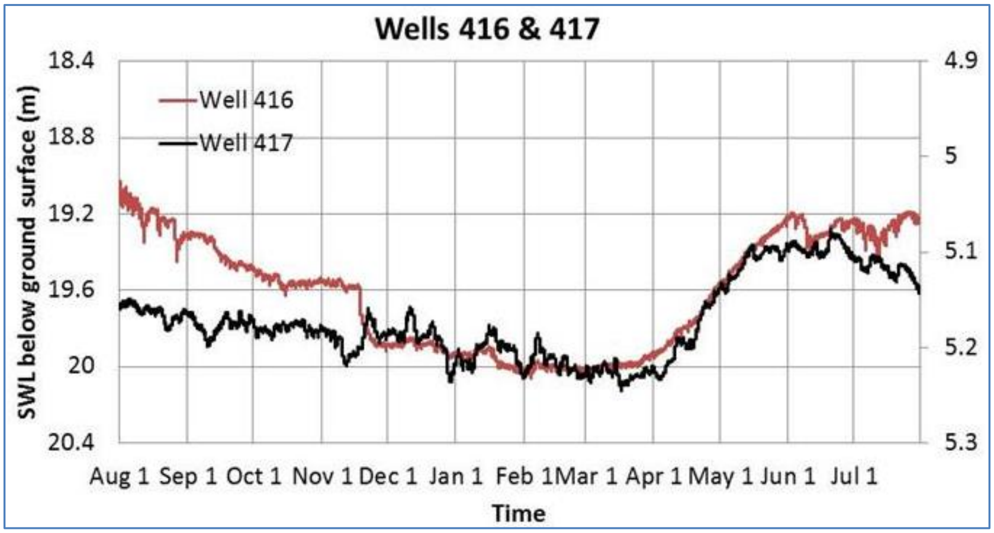


Figure 22. Static water level records for Observation Wells 416 (left y-axis) and 417 (right y-axis) monitoring groundwater levels in bedrock aquifer 591 between August, 2014 and July, 2015.

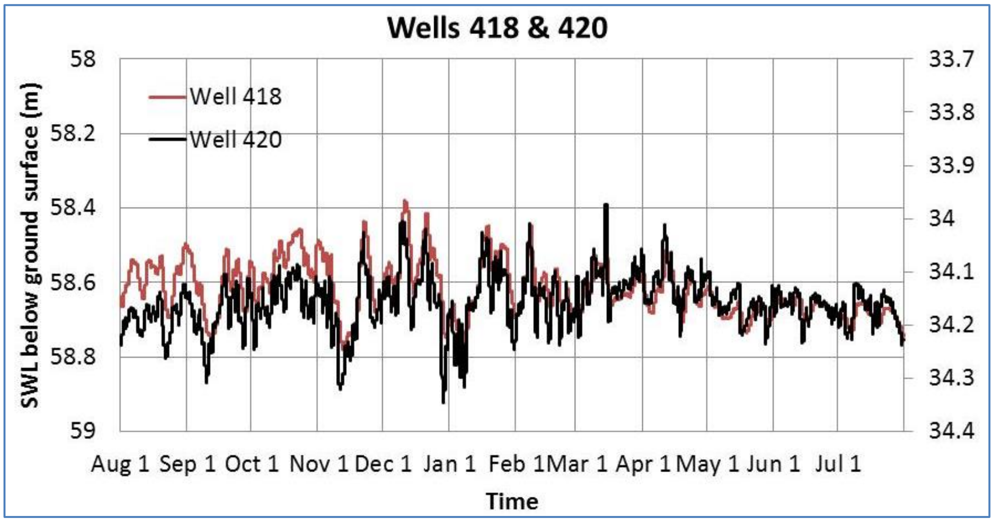


Figure 23. Static Water Level records for Observation Wells 418 (left y-axis) and 420 (right y-axis) monitoring groundwater levels in bedrock aquifer 593between August, 2014 and July, 2015.

Observation well 420 is located at 229 and 212 Road north-west of Dawson Creek (Figure 21). The static water level when the well was drilled was at 33.9 m below the ground surface. The well yield estimated by the driller was 0.32 l/s (5 USgpm). The estimated hydraulic properties (53.9 m^2/d transmissivity; 3.92 m/d hydraulic conductivity) determined from the pumping test is higher than for well 419 (described below). This may be due to the heterogeneity of aquifer 593 caused by different degrees of weathering and fracturing at different locations. Regardless of the fractured conditions, the water level in the well fluctuates at a very similar magnitude with no significant seasonal recharge and recession (Figure 23). The two hydrographs from the wells in aquifer 593 show a different recharge mechanism: unlike aquifer 591, aquifer 593 is in a more confined environment and is less responsive to direct recharge such as snowmelt. It is also evidenced by the relatively thicker confining layer in both obs. well 418 (19.8 m) and 420 (42.7 m) (Kelly and Janicki, 2011). There appears to be less variability in water level from May to July.

4.3.3 Observation Well 419

Observation well 419 is located at Sweetwater and 217 Road (Figure 21). The well encountered weathered shale bedrock shallower than well 418 at a depth of 26 m. Flowing artesian condition was encountered during the drilling. The well yield estimated by the driller was 1.89 l/s (30 USgpm). The pumping test data show similar results to obs well 417 (through the wells are drilled into different aquifers) with a transmissivity of 13.5 m^2/d and a hydraulic conductivity of 0.53 m/d. Due to the flowing condition, no groundwater level data is available for this well. A packer was installed to prevent the flow and keeping the water level below the frost line.

4.3.4 Observation Wells 421 & 445

Observation well 421 was drilled in November, 2011 and subsequently closed in early 2014 because of cross-communication of water between the sand and gravel aquifer 590 and the deeper bedrock aquifer 591. The static water level when the well was drilled was at 22.05 m below the ground surface. Due to the aquifer communications, the pumping test was not successful and the data were not analyzed (Baye, 2013).

Observation well 445 was drilled in 2012 to replace the observation well 421. It is located at 273 and 208 Road west of Dawson Creek (Figure 21). The initial driller's report has an estimated well yield of 0.125 US gallons per min. No static water level was recorded and no pumping test was conducted due to the low reported yield. Groundwater level data recorded in 2014 and 2015 shows slight increase in spring and early summer in 2015, which may reflect the spring recharge period of freshet (Figure 24). The cause of the slight increase water level between Nov. 2014 and Jan. 2015 is as yet unclear.

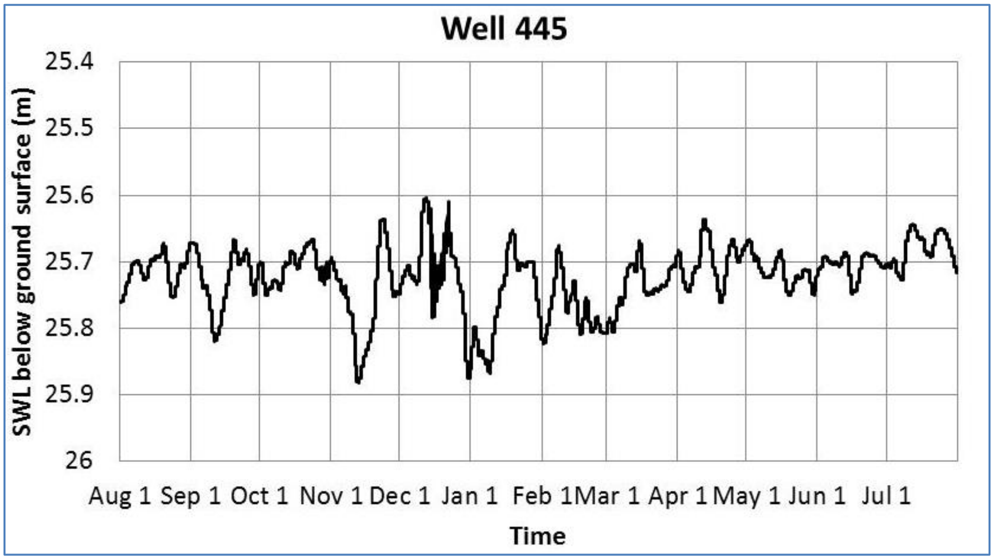


Figure 24 Static Water Level records of Observation Well 445 in sand and gravel aquifer 590 between August 2104 and July 2015.

4.4 Hydraulic Properties of Hydrostratigraphic Units

The aquifer hydraulic parameters were calculated using the time-drawdown data from constant rate pumping and recovery tests conducted on the recently constructed observation wells in bedrock aquifer 593 (Obs well 419 (WTN104710) and Obs well 420 (WTN104711)) and aquifer 591 (Obs well 416 (WTN04707) and Obs well 417 (WTN04708)). Aquifer Test Pro and manual curve matching techniques were used for data analysis. All the pumping tests were conducted with a single pumping well, and all drawdown measurements were observed at the pumping well; no observation wells were available for monitoring. Based on the pumping test procedures (single well test), three pumping test solution methods were used for each well to analyze the field time-drawdown data. Single well test solution methods; Theis, Papadopulos-Cooper and Theis recovery were used for data analysis. Aquifer hydraulic parameters could not be calculated from any of the unconsolidated aquifers in this study because no pumping tests were conducted in wells drilled into unconsolidated aquifers.

Except the borehole storage effect at the beginning of pumping, for the most part, the diagnostic plots of the drawdown derivative of the twenty four hour pumping test data parallels the non-zero slope trend lines depicting a dominant linear flow regime. A longer pumping duration would likely encounter a radial flow regime, which is the regime that governs the aquifer's long term response; a 24-hour pumping test at the pumping rate conducted may not have been sufficient in allowing long-term radial flow response to be observed.

In drilling the observation wells, drilling was not intended to penetrate the full thickness of the aquifers, hence, we do not have enough information on the full aquifer thickness. For the purpose of estimating the hydraulic conductivity (K) of the aquifer, it was assumed that the entire saturated open hole thickness is the aquifer thickness, i.e., the difference of the total well depth and static water level for wells where the steel casing length is above the water level, and the difference between the total well depth and length of the steel casing for wells where the static water level is above the steel casing. The actual aquifer thickness may be greater and the estimate of K may be lower than actual K. Details on data collection, single well test solution methods and data analysis can be found in Baye (2013).

As summarised in Table 11, transmissivity for the bedrock aquifers ranges from 12.4 to 72 m^2/day and hydraulic conductivity ranges from 0.5 to 8 m/d. These values are comparable to those found for similar bedrock aquifers in other portions of the province.

Table 11 Summary of aquifer hydraulic parameters

Aquifer number and type	**Obs well number & WTN**	**Constant Discharge (L/sec)**	**Transmissivity (m^2/day)**			**Hydraulic conductivity (m/d)**		
			Theis	Papadopulos-Cooper	Theis Recovery	Theis	Cooper	Recovery
591- Confined bedrock in Kaskapau Formation	416, 104707	1.89	72	69.2	268	8	7.67	29.7
	417, 104708	1.26	13.5	15.7	15.4	0.7	0.814	0.8
593- Confined bedrock in Kaskapau Formation	419, 104710	1.89	12.4	13.5	16.8	0.49	0.53	0.659
	420, 104711	0.189	42	53.9	56.5	3.05	3.92	4.11
Geo-mean			26.7	29.8	44.5	1.7	1.9	2.8

5. HYDROGEOCHEMISTRY AND WATER QUALITY CHARACTERISTICS

5.1 Synopsis of the Hydrogeochemistry of the Study Area (by: Dirk Kirste, SFU)

Groundwater sampling initiated in November 2011 and is ongoing. To date, a total of 342 groundwater samples have been collected from wells throughout the peace region (larger than current study area) and analyzed for the chemical and isotopic composition (Figure 25) (see Section 1.3.3 for methods and procedures). Of those, 95 are quality assurance and quality control (QA/QC) duplicates or they are repeat samples from the same locations on different dates, 4 are from lakes occurring in the region and 47 are from springs. Hundred sixty four (164) of the groundwater samples included sampling for tritium and 109 for carbon-14 and $\delta^{13}C$ of the dissolved inorganic carbon. Atmospheric monitoring stations were installed in June 2012 and a total of 82 rain and/or snow samples were collected and analyzed for chemical and isotopic composition.

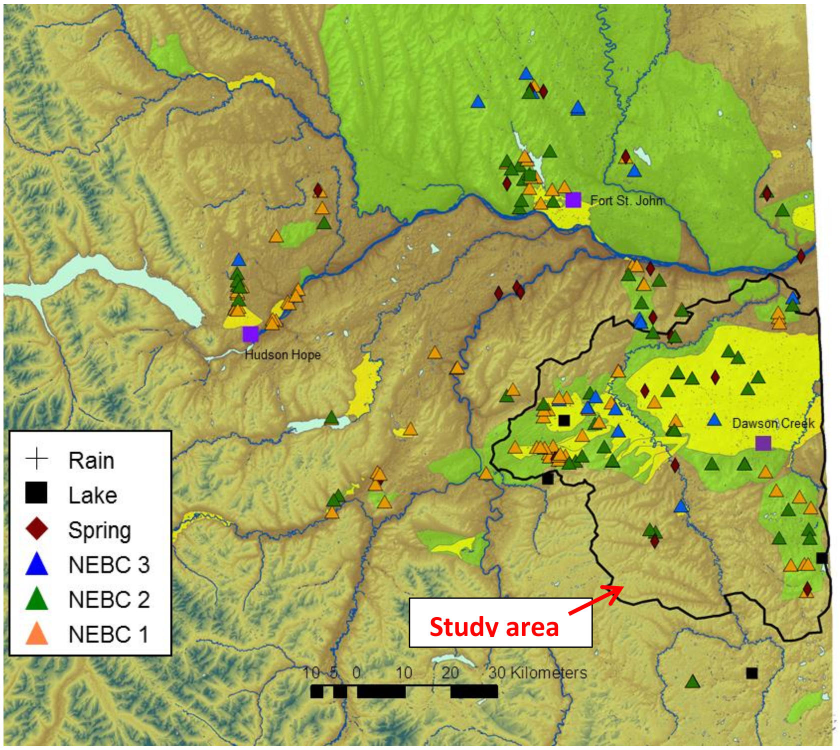


Figure 25 Location map of water samples.

Groundwater chemical composition commonly shows considerable variability. These differences reflect the signatures of one or more of such factors as soil/rock composition, prevailing climatic condition, pH, the residence time of water within the formation and the rate of recharge through the soil/vadose zone (Davis and De Wiest, 1966). Hydrochemistry can be interpreted to gain understanding of the key processes that have occurred during the movement of water through aquifers. The overall implication of this is that the hydrochemical facies of groundwater changes in response to its flow path history.

The groundwater samples are typically of the Ca-Mg-HCO_3 to Na-HCO_3 and Na-SO_4-HCO_3 type (Figure 26). The precipitation has predominantly a Ca-Mg-HCO_3 type composition and very low total dissolved solids (TDS). The lowest TDS groundwaters are the Ca-Mg-HCO_3 type and for the samples collected from wells that are found within the wells database (total 52), they are consistently completed in the Quaternary sediment sand/gravel aquifers. The more Na-rich groundwaters are predominantly sourced from wells that are completed in the bedrock aquifers. In this region, the Cretaceous bedrock formations were deposited as marine to marginal marine sediments. Marine sediments commonly impart elevated sodium content on Ca-Mg-rich fresh groundwater through cation exchange (Hem, 1992). Groundwater, recharging through the Quaternary sediments would undergo a change from being Ca-Mg-rich to Na-rich during transport through the bedrock aquifer. The Quaternary sediments are non-marine so there should be no elevated Na in groundwater that has only followed a flow path through those sediments. This results in the capability to identify groundwater sourced from bedrock versus from the Quaternary sediment aquifers, making it possible to assign a bedrock or Quaternary aquifer marker to each sampled well location to help better define the regional and local groundwater flow systems (Figure 26 symbols).

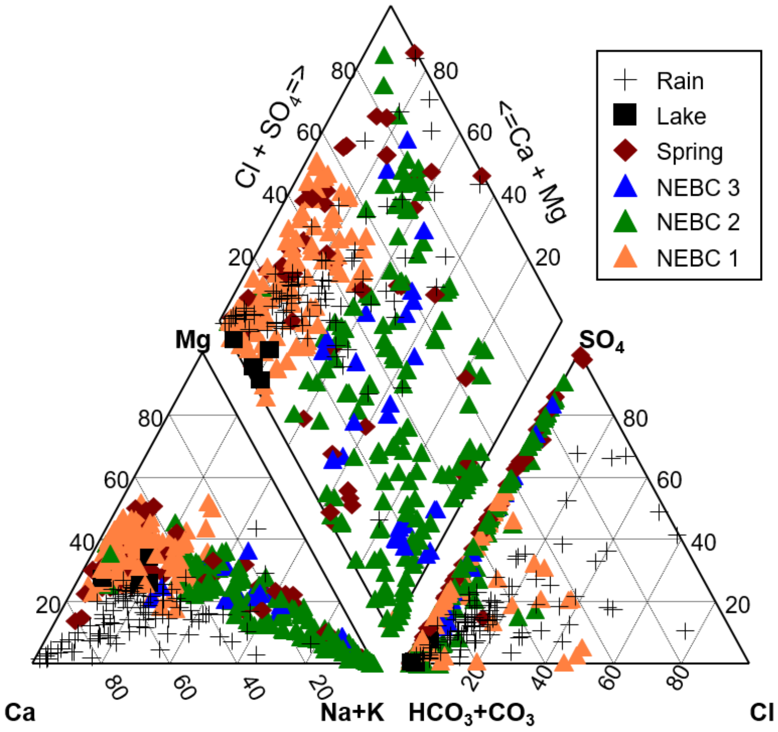


Figure 26. Piper diagram showing the precipitation (rain), groundwater, surface water and spring composition. The groundwater samples were defined as Quaternary (NEBC 1) or bedrock (NEBC 2 and 3) based on the chemical and stable isotopic composition.

The stable isotopic composition of the groundwater ranges from -27 to -18 ‰ (V-SMOW) $\delta^{18}O$ and -207 to -143 ‰ (V-SMOW) $\delta^{2}H$ (Figure 27). The precipitation showed a wider range from -27 to -10 ‰ (V-SMOW) $\delta^{18}O$ and -207 to -83 ‰ (V-SMOW) $\delta^{2}H$. Winter precipitation was the most depleted and summer the most enriched in the heavier isotopes while spring and fall precipitation fell between. The annual amount averaged isotopic composition of the precipitation for the three year collection period was -19.9 ‰ (V-SMOW) $\delta^{18}O$ and -154 ‰ (V-SMOW) $\delta^{2}H$. The lake samples show a clear evaporation trend and show no relation to the groundwater samples indicating that they are not likely to be a source of groundwater recharge. The majority of the groundwater samples identified as originating from the Quaternary aquifers have an isotopic composition with a similar range to those of the spring and fall precipitation. The bedrock sourced groundwater has two different groups identified, that with an isotopic composition similar to the Quaternary (green triangle) and water samples with a more depleted isotopic composition compared to the Quaternary (blue triangle). All of the groundwater data lie on the local meteoric water line defined by the precipitation. The data indicate that the majority of the groundwater was locally sourced and all of the Quaternary and some of the bedrock groundwater was recharged by the spring and/or fall precipitation. Some of the bedrock groundwater appears to either be recharged exclusively from the winter precipitation or from a colder climate.

The tritium content of the precipitation ranges from just under 4 to over 15 tritium units (TU) while the groundwater samples range from 0 to over 15 TU (Figure 28). The winter precipitation tritium content was the lowest and the summer had the highest, spring and fall precipitation fell between. The majority of the Quaternary sourced groundwater had some tritium present while the majority of the bedrock sourced groundwater had no tritium. The springs had variable tritium content some with tritium similar to that of the Quaternary source water and some without tritium, similar to the bedrock. The presence of tritium in the groundwater indicates a mean residence of less than approximately ~50 years. This suggests that most of the groundwater hosted in the Quaternary has a mean residence of less than 50 years or at least some of the groundwater is very young and that this groundwater originates as recent recharge, as indicated by the stable isotopic composition. The bedrock groundwater appears to be much older (calculated ages using carbon-14 range from hundreds to thousands of years).

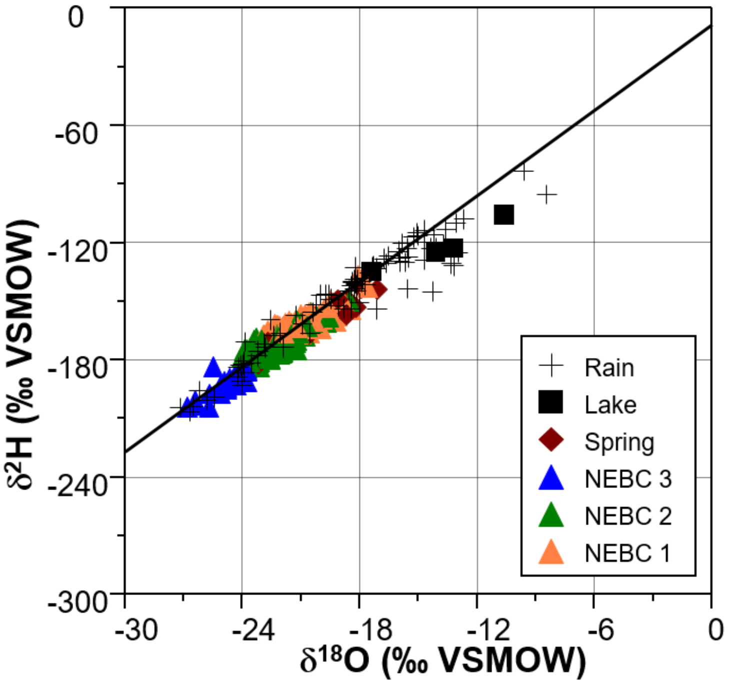


Figure 27   Plot of the stable isotopic composition of the water (δ2H versus δ18O) in ‰ (V-SMOW). The precipitation shows the widest range and defines the local meteoric water line (black line).

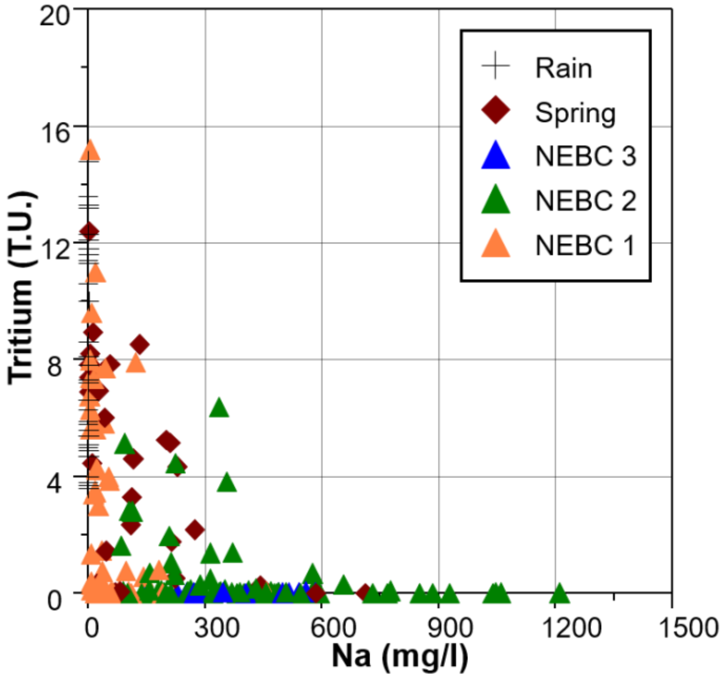


Figure 28   Plot of tritium (TU) versus Na content (mg/L) showing the range in tritium content of the rain and presence of tritium in most of the groundwater identified as Quaternary (low Na) and little to no tritium in the groundwater samples identified as bedrock (high Na) sourced. Springs show a range of tritium and Na content.

5.2 Groundwater Quality Characteristics

Groundwater quality in the study area is characterized through comparisons to the Canadian Drinking Water Guidelines (Health Canada, 2014), and through development of groundwater quality maps. Groundwater quality data for this analysis are combined from two sources: the recent private well survey data collected by FLNRO (Section 1.3.2 and 1.3.3), and historical groundwater quality data available in the WELLS database. The well survey dataset are recent data (since 2011) that span areas outside of the defined study area boundary, and include a range of inorganic constituents and some organic constituents. The WELLS dataset are historical data generally collected at the time of drilling and are limited spatially to the study area boundary. The constituents in the WELLS dataset typically include only iron, hardness, and sometimes sulfate; no minor chemical constituents were available in the historical data. All data used in this analysis are included in a companion Excel file described in Appendix A.

The available groundwater quality data were grouped by aquifer stratigraphy (unconsolidated or bedrock) based on lithology information in the well record. For those wells with no lithology information or no well record, the aquifer stratigraphy was inferred using indirect indications including the well location relative to mapped aquifers, the lithology of neighboring wells, and depth of well screen.

Table 12 shows summary water quality results for inorganic constituents with established drinking water guidelines. The Maximum Allowable Concentration (MAC) is a health-based guideline for protection of human health. The Aesthetic Objectives (AO) are non-health based guidelines that address aesthetic issues such as taste, colour, odour, and water use. In addition to constituents in Table 12, other water quality constituents were measured that do not have established MAC or AO guidelines. These data are presented in Appendix A, but are not discussed further as they pose no significant health or aesthetic based issues of concern.

Summary information in Table 12 shows arsenic is the main health based constituent of concern, with about 30 percent of samples exceeding the MAC guideline. Several constituents have significant exceedances of AO guidelines, including iron, manganese, sodium, sulfate, total dissolved solids, and hardness. The following subsections further discuss these constituents.

5.2.1 Arsenic

Arsenic occurs naturally in groundwater from the weathering of arsenic bearing rocks and minerals. Arsenic is a documented human carcinogen and ingestion of high levels of arsenic through drinking water or food poses human health risks (Health Canada, 2014). It is not possible to detect arsenic by taste or smell.

The Health Canada guideline establishes a maximum acceptable concentration (MAC) for arsenic in drinking water at 0.010 mg/L. This guideline is based on limitations of municipal- and residential-scale treatment achievability. The MAC is higher than the level associated with an “essentially negligible” risk. Consequently, Health Canada states that every effort should be made to maintain arsenic levels in drinking water as low as reasonably achievable.

Results from the private well sampling study show arsenic levels in groundwater exceed the MAC in about one-third of the samples (Table 12). More than half of the samples had arsenic concentrations greater than 0.005 mg/L. It should be noted that the private well sampling protocol included field filtration of groundwater samples (Section 1.3.2). Higher arsenic levels potentially occur in unfiltered groundwater, which may exceed the Health Canada MAC. Additional information is available from Health Canada (2014) and the B.C. Ministry of Environment (2007).

Table 12 Summary information for groundwater quality data

Parameter (mg/L)	Formation	No. of samples	Range	Median	DW Guidelines[1]		Exceedances	
					MAC[2]	AO[3].	No.	%
Arsenic (As)	Unconsolidated	52	0.001 - 0.021	0.007	0.01	-	16	31%
	Bedrock	71	0.001 - 0.048	0.007			22	31%
Barium (Ba)	Unconsolidated	51	0.004 - 0.73	0.029	1	-	0	0%
	Bedrock	50	0.001 - 0.59	0.015			0	0%
Boron (B)	Unconsolidated	52	0.001 - 0.98	0.11	5	-	0	0%
	Bedrock	67	0.021 - 1.4	0.30			0	0%
Chloride (Cl)	Unconsolidated	52	0.18 - 150	0.78	-	250	0	0%
	Bedrock	71	0.12 - 160	3.2			0	0%
Fluoride (F)	Unconsolidated	46	0.05 -2.0	0.34	1.5	-	2	4%
	Bedrock	58	0.06 -2.2	0.40			1	2%
Hardness ($CaCO_3$)	Unconsolidated	79	30 - 2800	500	-	120*	74	94%
	Bedrock	85	4 – 2300	500			69	81%
Iron (Fe)	Unconsolidated	79	0.002 – 48	1.4	-	0.3	55	70%
	Bedrock	83	0.001 – 19	0.43			46	55%
Manganese (Mn)	Unconsolidated	52	0.001 – 7.2	0.13	-	0.05	35	67%
	Bedrock	70	0.001 – 2.6	0.092			40	57%
Nitrate (NO_3)	Unconsolidated	20	0.067 – 4.3	0.88	45	-	0	0%
	Bedrock	21	0.01 – 14	1.4			0	0%
Sodium (Na)	Unconsolidated	53	3.4 – 960	40	-	200	16	40%
	Bedrock	71	6.4 – 1000	220			40	56%
Sulfate (SO_4)	Unconsolidated	57	3.8 – 2900	110	-	500	8	14%
	Bedrock	72	0.20 – 2100	280			22	31%
Total dissolved solids (TDS)	Unconsolidated	53	45 – 5200	650	-	500	38	72%
	Bedrock	72	120 – 3500	1100			67	93%
Zinc (Zn)	Unconsolidated	47	0.001 – 1.9	0.01	-	5	0	0%
	Bedrock	44	0.001 – 0.23	0.0055			0	0%

[1] Health Canada Drinking Water Guidelines

[2] MAC = Maximum acceptable concentration. This guidelines addresses human health concerns

[3] AO = Aesthetic objective. This guideline addresses non-health based issues such as taste, colour, and odour.

* There is no established AO for hardness because public tolerance of hardness varies greatly. It is included in this table because hardness can pose significant aesthetic issues. A total hardness above 120 mg/L is the level where treatment may be desirable.

Figure 29 shows the location of measured arsenic concentration ranges. Visual inspection indicates groundwater samples with arsenic concentrations above the MAC do not occur more frequently in any area or aquifer type. High levels of arsenic occur about equally in unconsolidated (sand and gravel) aquifers and bedrock aquifers (Table 12) and visual observation of arsenic levels do not suggest a dominant area of elevated arsenic (Figure 29). The risk of elevated arsenic in groundwater appears to be relatively uniform throughout the study area.

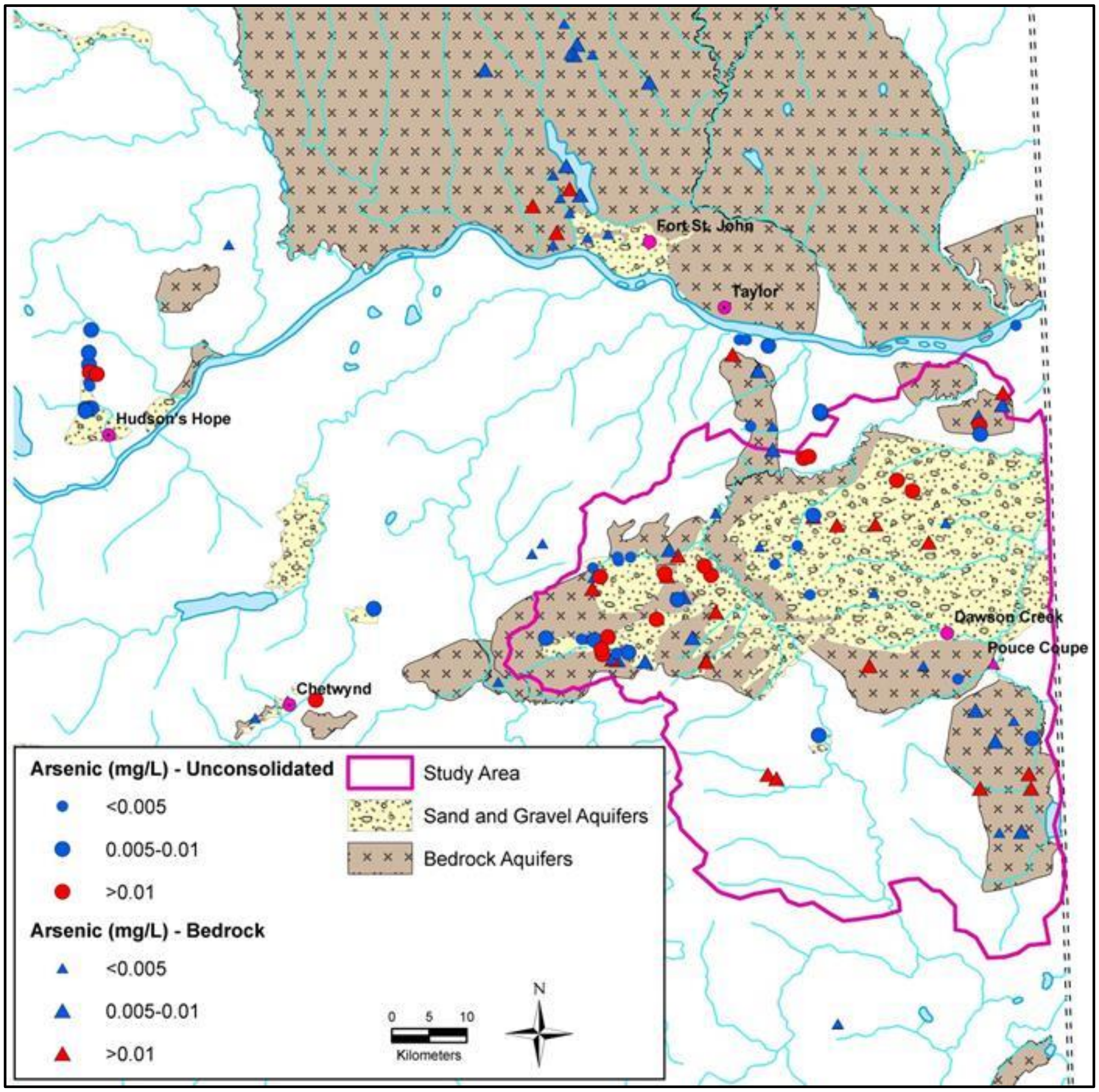


Figure 29 Occurrence of arsenic in groundwater samples collected in the FLNRO private well survey.

5.2.2 Total Dissolved Solids

Total dissolved solids (TDS) is a measure of inorganic salts and small amounts of organic matter that are dissolved in water. Dissolved salts occur naturally in groundwater from contact with soils, sediments, and bedrock. In other areas, human activities can also influence salt levels in groundwater.

High levels of TDS affect the taste and palatability of water and can affect the suitability of water for irrigation supply and stock watering. High TDS can also cause encrustation and corrosion in water distribution systems. The Health Canada Guidelines sets an AO for TDS in drinking water of ≤ 500 mg/L. There is no health-based guideline for TDS. The effect of TDS on the palatability of drinking is rated as follows (Health Canada, 2014):

- Excellent – TDS less than 300 mg/L;
- Good – TDS between 300 to 600 mg/L;
- Fair – TDS between 600 to 900 mg/L;
- Poor – TDS between 900 to 1200 mg/L; and
- Unacceptable – TDS greater than 1200 mg/L.

For stock watering (cattle), TDS concentrations between 1000-3000 mg/L are considered generally safe, and TDS concentrations between 3000-5000 mg/L are considered poor or marginally safe (Alberta Government, 2007). B.C. has established working aesthetic objectives for TDS (B.C. Ministry of Environment, 2015). For stock watering the B.C. aesthetic objective is 1000-3000 mg/L, and for irrigation the aesthetic objective ranges from <500 to 3500 mg/L depending on crop salt tolerance.

The TDS concentration in groundwater samples from the private well survey was calculated by summing the measured concentrations of principal cations and anions. TDS levels are also related to electrical conductivity, which was measured in the field during the private well survey. The correlation in Figure 30 indicates TDS concentration in the study area can be approximately estimated as 70% (~0.7) of measured electrical conductivity (Figure 30).

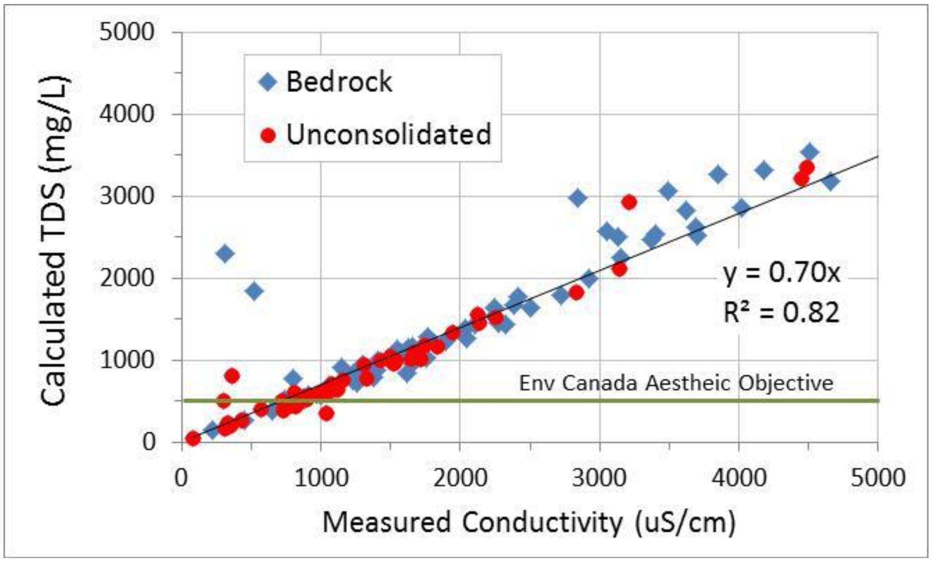


Figure 30 The relationship between conductivity and total dissolved solids for private well groundwater samples.

Groundwater TDS levels in the study area are high. About 85% of all groundwater samples had a TDS concentration exceeding the drinking water aesthetic objective (500 mg/L; Table 12). Bedrock wells are moderately more likely to exceed the aesthetic objective (92%) than wells in unconsolidated aquifers (73%).

About half of all groundwater samples exceeded the aesthetic objective (500 mg/L), but had TDS levels within the potable range of 500 to 1200 mg/L (fair to poor palatability). About one-third of all samples had a TDS concentration exceeding 1200 mg/L (unacceptable palatability), and 6% of all samples had a TDS concentration exceeding 3000 mg/L, the B.C. stock watering AO.

Figure 31 shows the location of TDS ranges in the study area. Although TDS levels exceeding 1200 mg/L occur throughout the region, visual inspection suggests several areas where TDS levels in the potable range (<1200 mg/L) appear more concentrated. These are wells in unconsolidated aquifers in the western and north-central portions of the study area, and a scattering of bedrock wells in the southeastern portion of the study area.

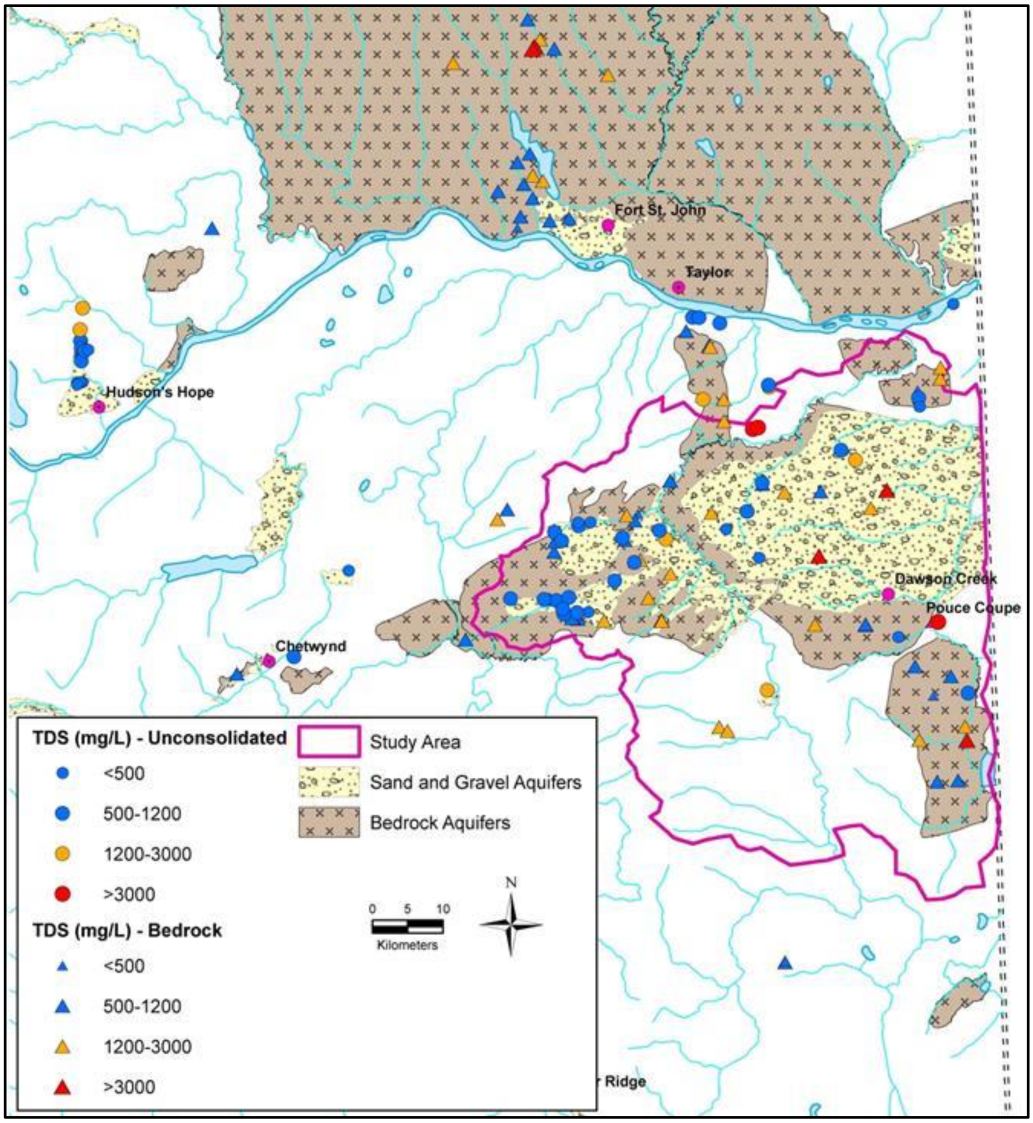


Figure 31 Occurrence of TDS in groundwater samples.

5.2.3 Hardness

Water hardness is a traditional measure of the capacity of water to react with soap. Hard water requires more soap to produce a lather. Water hardness is caused by the presence of calcium and magnesium salts, which are primarily dissolved from geologic deposits through which groundwater travels.

Water hardness is an aesthetic issue of concern for several reasons. Hard water can have unpleasant taste, it causes scale formation in pipes and on plumbing fixtures, and it can leave water spots on glassware and dishes. It can also feel unpleasant on the skin and can reduce the life of washable fabrics. Especially relevant for groundwater users is that hard water can promote early encrustation of well screens that can affect well supply through inefficiency.

There are no health-based objectives for water hardness in the Health Canada drinking water guidelines, which states calcium and magnesium ions are not of direct public health concern (Health Canada, 2014). There is also no aesthetic objective for water hardness in the guidelines because public acceptance of hardness can vary considerably according to the local conditions. The Health Canada drinking water guidelines classifies water hardness in terms of an equivalent concentration of calcium carbonate ($CaCO_3$) (carbonate hardness):

Hardness Category	Equivalent Concentration of $CaCO_3$ (mg/L)
Soft	< 60
Medium hard	60 to < 120
Hard	120 to < 180
Very hard	180 mg/L or greater

Water hardness greater than 200 mg/L is considered poor in most regions of the province but can be tolerated by users. Water hardness greater than 500 mg/L is normally considered unacceptable for domestic purposes (B.C. Ministry of Environment, 2007b).

Groundwater hardness in the study area is predominantly hard to extremely hard, reflecting aquifers with high concentrations of dissolved solids. More than half of all groundwater samples (55%) had hard to very hard water, ranging from 120 to 600 mg/L. About 30% of the samples had extremely hard water greater than 600 mg/L, considered unacceptable for domestic use. Less than 15% of samples are classified as soft to medium hard (<120 mg/L). Figure 32 shows the location of hardness ranges in the study area. Visual inspection suggests hard to very hard groundwater is prevalent in unconsolidated aquifers in the western portion of the study area, and extremely hard groundwater is somewhat more prevalent in central and eastern portions of the study area.

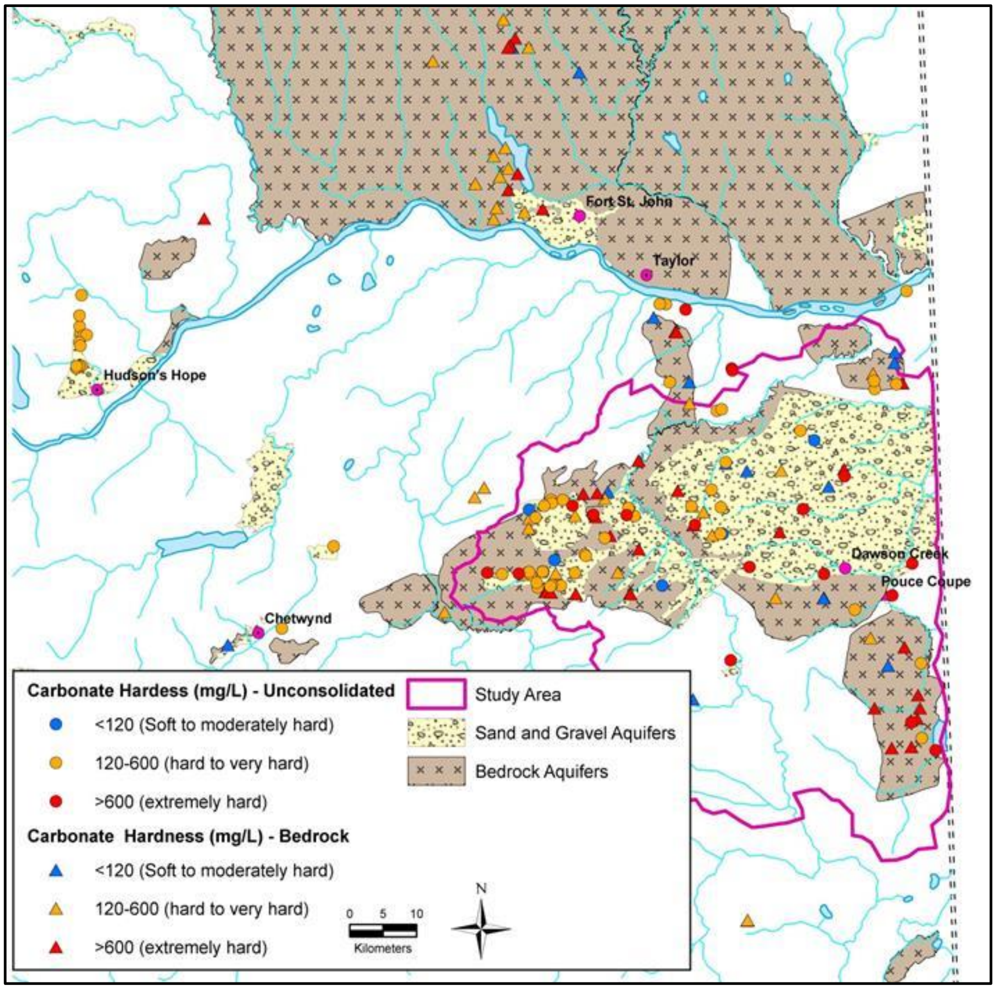


Figure 32 Occurrence of hardness in groundwater samples.

5.2.4 Iron

Iron occurs naturally in groundwater from the weathering of iron bearing minerals. The concentrations in groundwater are often greater than in surface waters.

Health Canada has not set a health-based objective for iron in drinking water, as iron levels commonly found in drinking water do not pose a hazard to human health (Health Canada, 2014). However, excessive iron in drinking water does have aesthetic issues. High levels of iron can cause staining of clothes and plumbing fixtures, and can have unpleasant taste and colour. Iron solids that precipitate from solution can collect and block pipes and fixtures. High iron levels can also promote growth of bacteria that form a slimy coating in water pipes and clog well screens. The Health Canada aesthetic objective (AO) for iron is 0.3 mg/L.

Summary results in Table 12 show the majority of groundwater samples exceed the AO for iron. Wells in unconsolidated aquifers show slightly more exceedances (70%) than bedrock aquifers (55%). About 10% of the wells had very high iron levels in excess of 5 mg/L.

Figure 33 shows groundwater iron concentrations exceeding the AO occur throughout the study area and appear to be prevalent in unconsolidated aquifers in the western portions of the study area. Visual inspection suggests areas with low iron levels are more likely in north central and northeastern regions of the study areas.

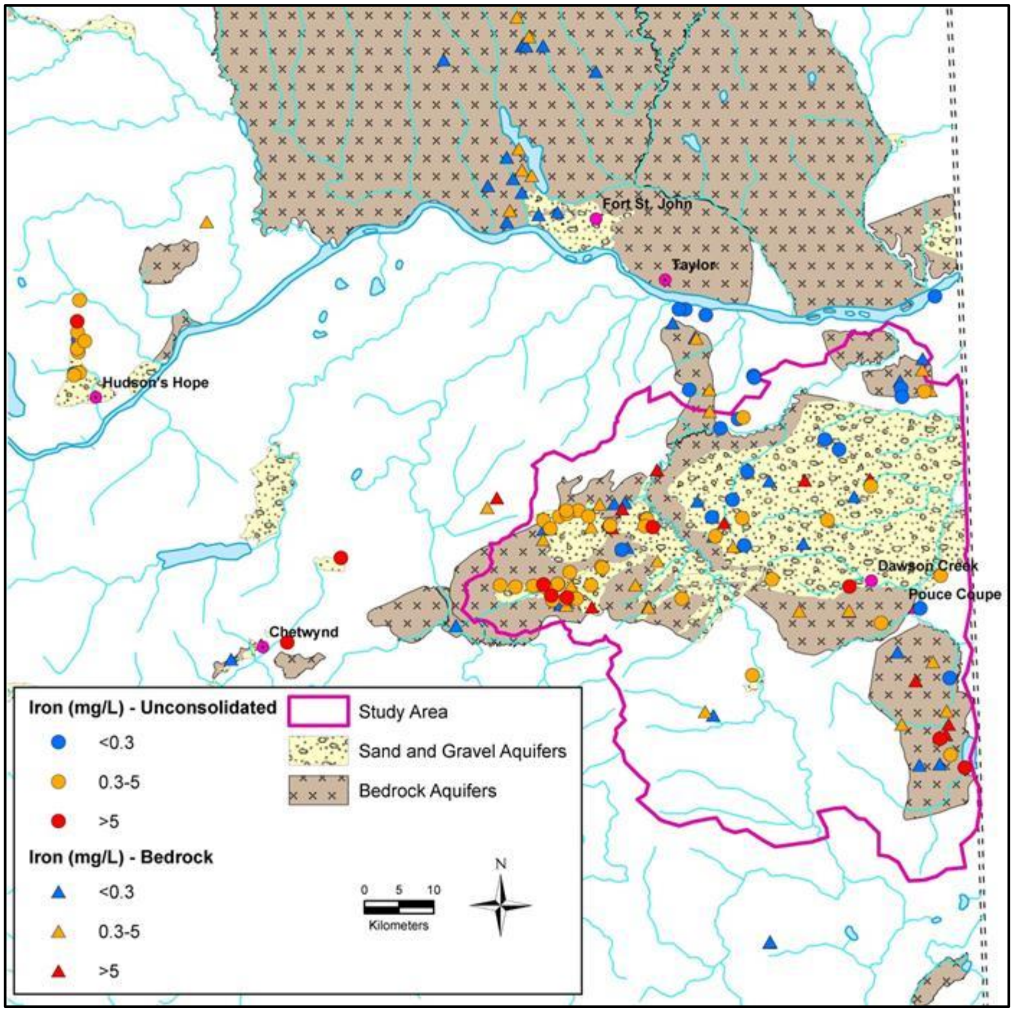


Figure 33 Occurrence of iron in groundwater samples.

5.2.5 Manganese

Manganese occurs naturally in groundwater that is low in oxygen due to the weathering or geologic materials. Health and aesthetic concerns related to manganese are similar to iron. Health Canada has not established a health-based objective for manganese. The World Health Organization (WHO 2004b) established a health based value of 0.4 mg/L. However, WHO further states that this health-based value is well above concentrations of manganese normally found in drinking water, and therefore it is not considered necessary to derive a formal guideline value.

High levels of manganese in drinking water do cause aesthetic issues. At concentrations exceeding 0.15 mg/L, manganese stains plumbing fixtures and laundry and causes undesirable tastes in beverages. At concentrations of approximately 0.02 mg/L, manganese can form coatings on water distribution pipes that may slough off as black precipitates, which can collect and block pipes and fixtures, and can clog well screens. Manganese can also support growth of "manganese" bacteria, which may give rise to taste, odour and turbidity problems (Health Canada, 2014).

Health Canada has set an aesthetic objective (AO) for manganese at 0.05 mg/L based on treatability limitations. Manganese at this recommended limit is not considered to represent a threat to health, and drinking water with much higher concentrations has been safely consumed (Health Canada, 2014).

Summary results in Table 12 show the majority of groundwater samples exceed the AO for manganese. Similar to iron, wells in unconsolidated aquifers show slightly more exceedances (67%) compared with wells in bedrock aquifers (57%). About 40% of the wells had high to very high manganese levels in excess of 0.15 mg/L. The distribution of manganese in the study area is similar to iron. Manganese concentration in excess of the AO occurs throughout the study area, but is somewhat more prevalent in the western portions of the study area (Figure 34). Manganese levels below the AO appear more prevalent in the northern and eastern regions of the study area.

5.2.6 Sulfate

Sulfate is the oxidized form of sulfur comprised of comprised of sulfur and oxygen atoms (SO_4^{2-}). Sulfate is widely occurring in the environment from natural and manmade sources. Sulfate occurs naturally in groundwater from the weathering of soluble sulfate minerals such as gypsum barite, and epsomite. Sulfate occurs as a dissolved ion, and therefore it is mobile with groundwater. If oxygen levels in groundwater are low, sulfur may be present as hydrogen sulfide (H_2S), which can impart a strong odour.

Many industries use or dispose of sulfur containing compounds, including oil and gas production, fertilizer production, mining and smelting operations, pulp and paper mills, textile mills and tanneries. High levels of sulphate in groundwater may occur from such industrial sources when sulfur containing compounds are improperly stored or discharged to the environment.

Health Canada has not established a health-based objective for sulfate in drinking water as existing data do not identify a level of sulfate in drinking water that is likely to cause adverse human health effects (Health Canada, 2014). Sulfate in drinking water at concentration between 1000-1200 mg/L are associated with a laxative effect, but with no increase in diarrhoea, dehydration or weight loss (WHO, 2004). Lower concentrations may affect bottle-fed infants and adults who have just been introduced to the water.

The presence of sulphate in drinking water can also result in a noticeable taste. Taste threshold concentrations for various sulphate salts are at or above 500 mg/L for the general population, but sensitive individuals may find the taste objectionable at lower sulphate concentrations (Health Canada, 2014).

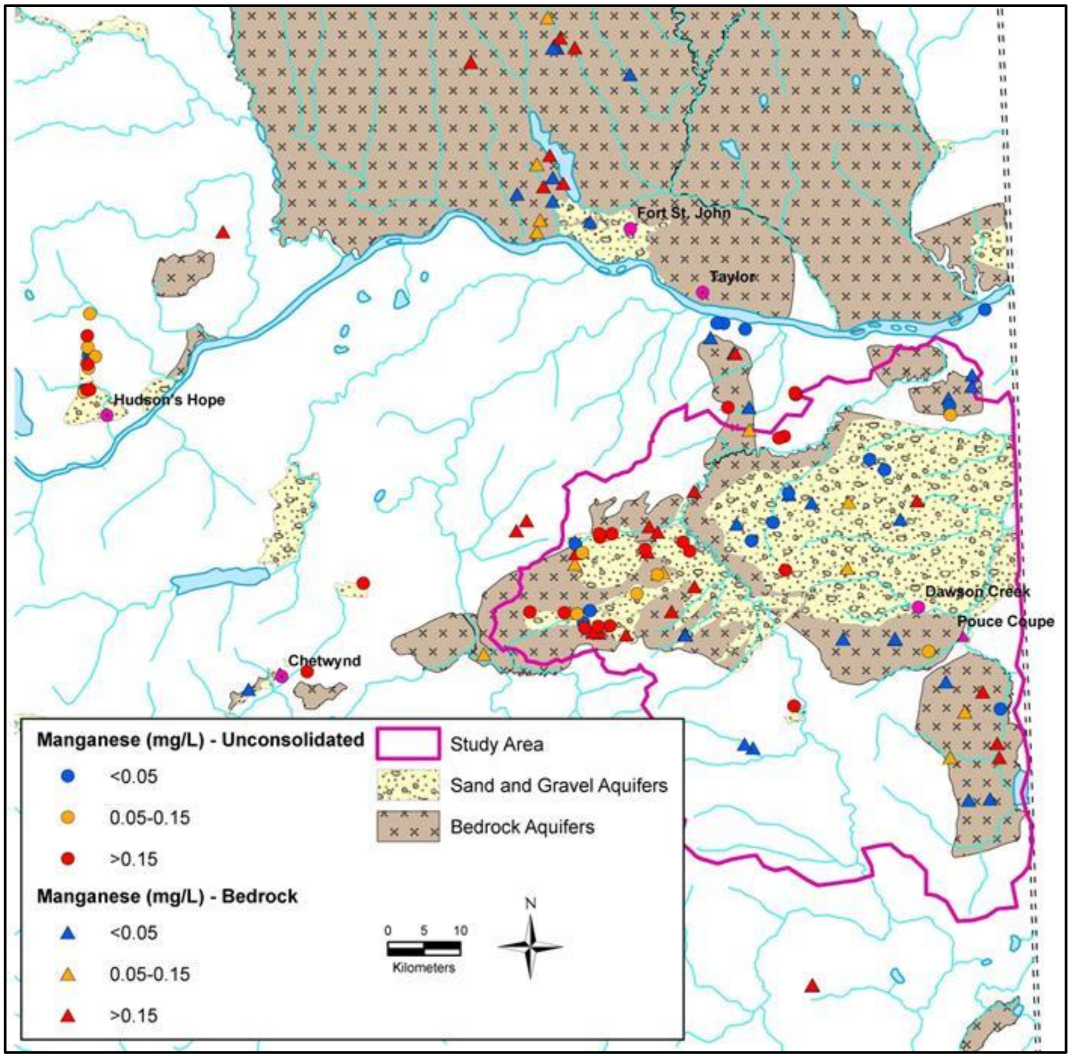


Figure 34 Occurrence of manganese in groundwater samples.

Health Canada has set an aesthetic objective for sulfate of 500 mg/L based on taste. However, because of the possibility of adverse physiological effects (laxative effect) at higher concentrations, Health Canada also recommends that health authorities be notified of sources of drinking water that contain sulphate concentrations in excess of 500 mg/L.

B.C. has established an aesthetic objective of 1000 mg/L for stock watering (B.C. Ministry of Environment, 2015).

Summary results in Table 12 show the majority of wells have sulfate concentrations below the Health Canada AO. About 25% of the wells had measured sulfate level above the AO, with some very high level above 2000 mg/L. Bedrock wells had about three times as many exceedances as unconsolidated wells. Lower sulfate levels appear more prevalent in unconsolidated aquifers in the western portions of the study area, and high sulfate level above the AO appear more prevalent in bedrock wells in the northcentral and northeastern portions of the study area (Figure 35).

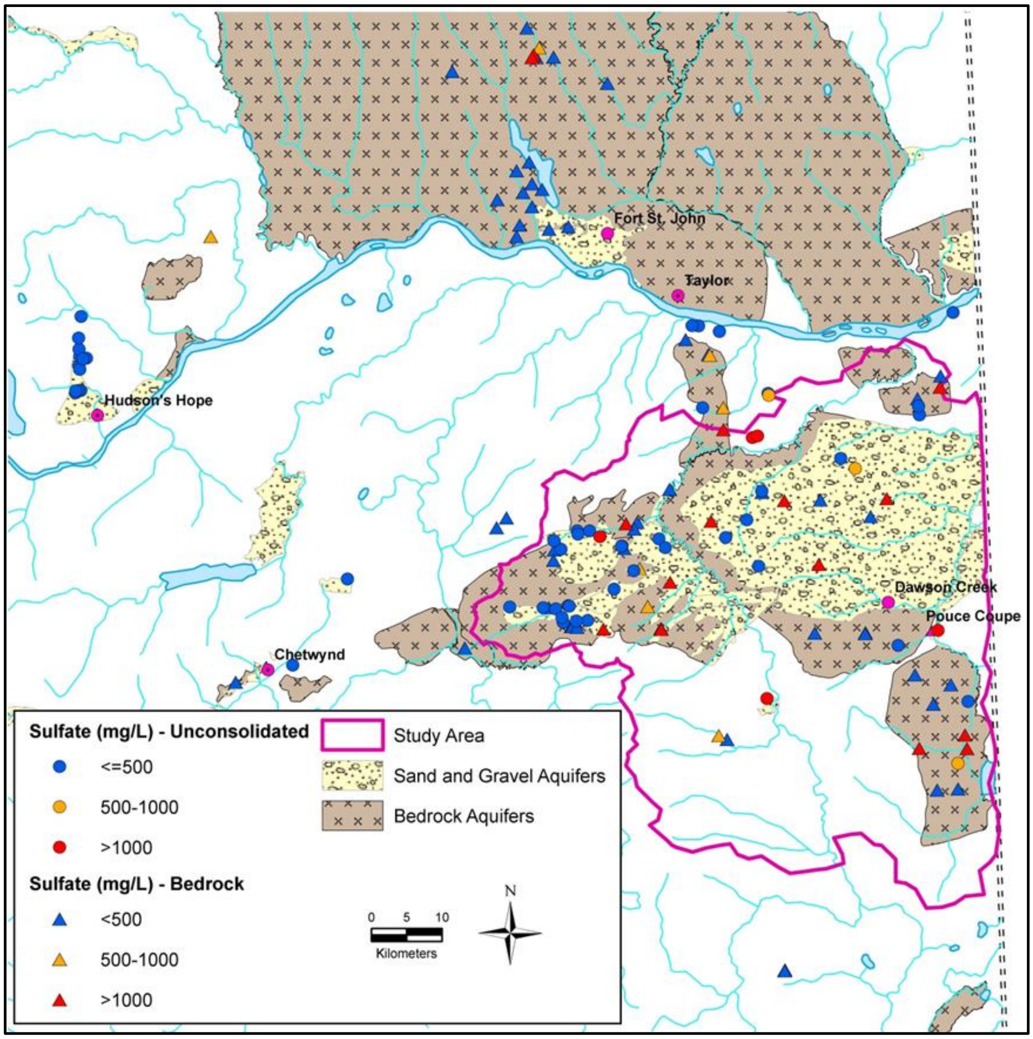


Figure 35 Occurrence of sulfate in groundwater samples.

6. SYNTHESIS AND CONCEPTUAL MODEL OF AQUIFERS IN THE STUDY AREA

A conceptual model is a pictorial representation of the groundwater flow system, commonly in the form of a simplified diagram or hydrogeological cross section. The conceptualization of how and where water originates in the groundwater flow system and how and where it leaves the system is the basis for the development of any subsequent mathematical or numerical model. The following hydrogeological conceptual model of the study area is a synthesis of information presented in the previous sections of this report; e.g., geology, lithology, geological structures, hydrology, hydrochemistry, isotope hydrology, etc. (Winkler et al., 2003).

A conceptual model of hydrogeological conditions in the study area is represented by the generalized west-east cross section shown in Figure 36. Based on the results of various study components, the groundwater occurrence and flow in the study area can be conceptualized as shown in Figure 37.

The paleovalley area in the west central part of the study area around Groundbirch is characterized by interlayers of less permeable silty clay/till and more permeable sand/gravel deposits. The major river valleys are dominated by unconfined fluvial sand and/or gravel aquifers; these aquifers are likely to be hydraulically connected to local streams. The eastern part of the study area is dominated by thick deposits of till/silty clay with thin lenses of sand which can produce sufficient groundwater to support private domestic wells.

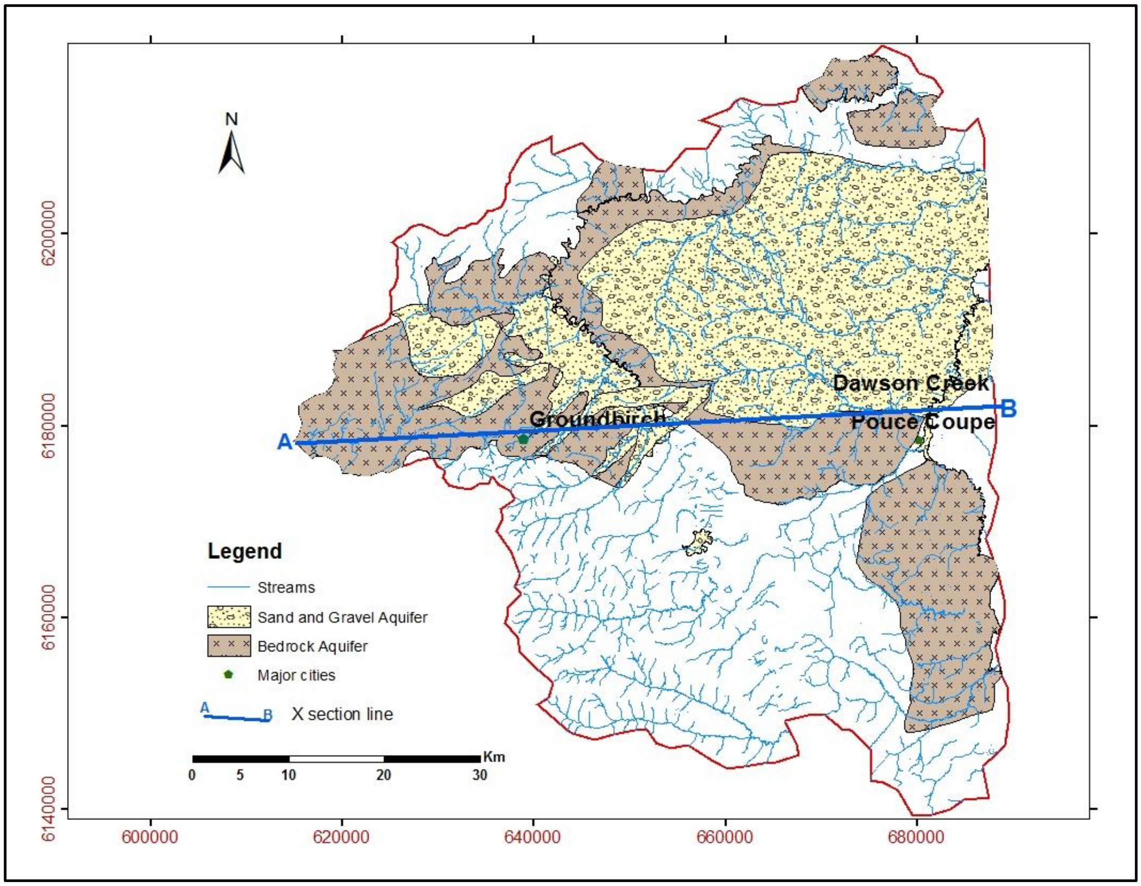


Figure 36 West-East schematic cross section general direction (A-B)

The vast majority of the study area is underlain by bedrock aquifers that are confined by clay/till deposits of variable thickness. Transmissivity of the bedrock aquifers, based on limited pumping tests, appear to be in the range of 20-50 m^2/day.

Direct recharge to aquifers is generally limited to unconfined fluvial deposits in the major river valleys. In addition to this, at high flows, rivers could provide river bank recharge to connected aquifers which could create local systems of circulation which drain back out into the river at low flow. The HELP modelling also suggests recharge occurs in the upland areas with precipitation seeping through the tills; this is supported by monitoring of groundwater levels in some of the observation wells (e.g., observation wells 416 and 417). Due to the relatively smaller physical extent of the study area and due to the fact that most of the area is overlain by clay/till deposits of variable thickness, the source of the recharge and flow pathways for the regional bedrock aquifer is currently unclear. More regional studies along the Rocky Mountain-Foothill-Plateau transect could help in understanding the regional groundwater occurrence and flow.

Generally, groundwater flow appears to follow the topographic gradient. In the western part of the study area groundwater generally flows toward the topographic lows of the Kiskatinaw River valley. Similarly, in the eastern part of the study area groundwater flows towards the topographic lows of the Pouce Coupe River valley.

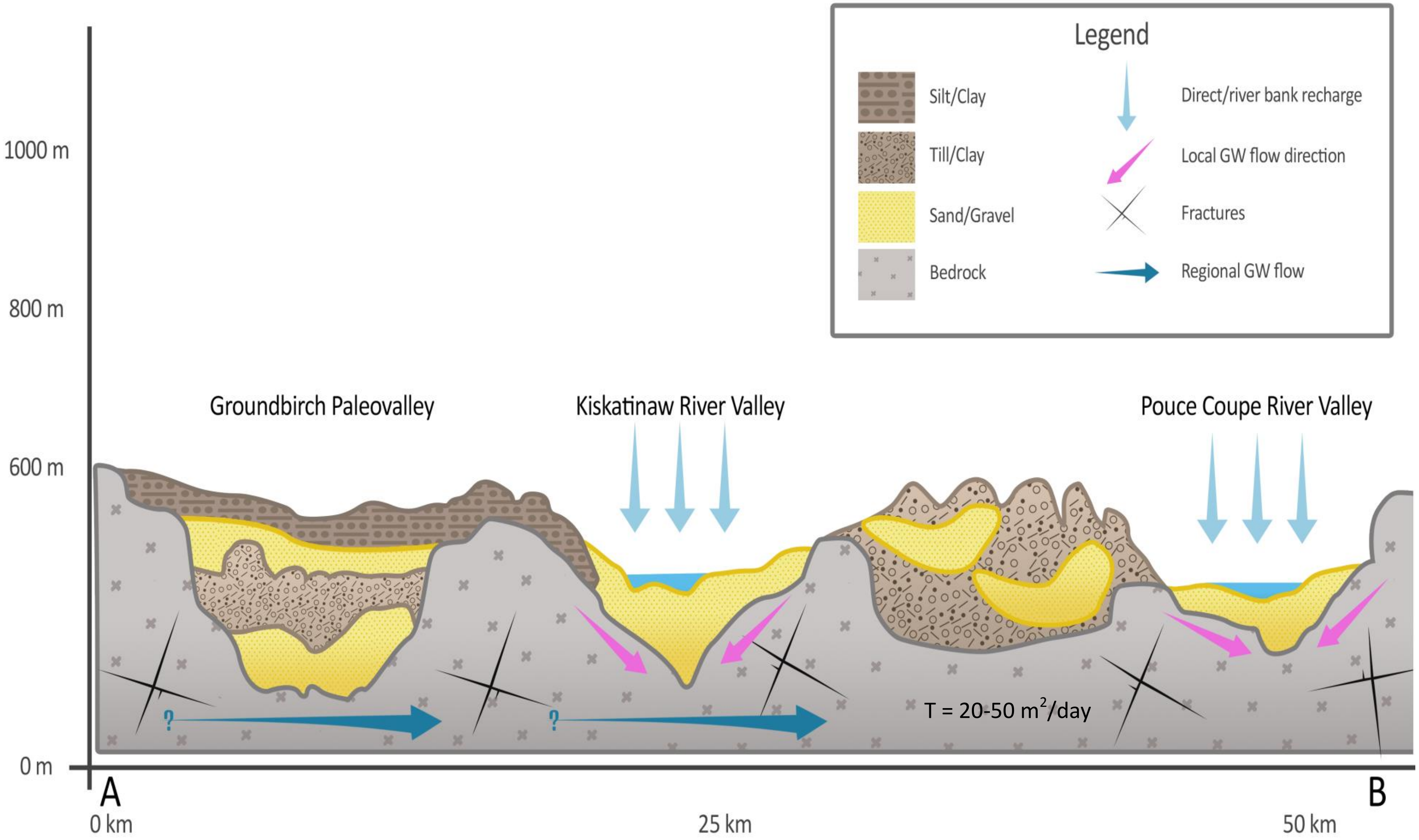


Figure 37 Generalized schematic west-east cross section illustrating groundwater occurrence and flow directions in the study area. The location of the cross section line is shown in Figure 36.

7. RECOMMENDATIONS

Based on the synthesis of the results of the aquifer characterization project around Dawson Creek-Groundbirch area, the following recommendations are made to better understand the groundwater occurrence and flow in the region.

- Well owners diverting groundwater for domestic and waterworks purposes should routinely test for arsenic, given the prevalence of this chemical in groundwater in the study area and the potential health effects associated with arsenic.
- As the province authorizes the use of groundwater under the *Water Sustainability Act*, new information on transmissivity of aquifers will be submitted by applicants for authorizations. This new data should be entered into the ENV WELLS database with the well record to build a dataset of aquifer parameters over time to facilitate modelling of groundwater availability.
- Based on evidence from the provincial observation well drilling and litho-hydrostratigraphic interpretations, aquifer # 851 is not a continuous extensive aquifer as implied by the aquifer polygon. The delineation and description for aquifer 851 to be reviewed.
- Longer term 72-hour pumping test is recommended to assess the aquifer's long term response and implication to water supply for wells drilled into bedrock aquifers.
- Groundwater monitoring is restricted to a very small portion of the region and mostly in bedrock aquifers. It is recommended that the monitoring be expanded in other parts of the region and include unconsolidated aquifers so as to understand the groundwater occurrence and flow in these potential aquifers.
- The current observation wells should be reviewed in 1-3 years' time to assess whether all of them are needed. For example, observation wells 416 and 417 monitor the same bedrock aquifer and show a very similar hydrograph (Figure 22).
- A plan should be developed for flowing observation well 419 to either equip the well for monitoring or to decommission the well.
- Results of water chemistry and isotope sampling indicate that groundwater in bedrock aquifers in the study area appears to be hundreds to thousands of years older than groundwater in unconsolidated valley fill, suggesting a different, most likely a colder climate recharge regime. A study along a more regional Rocky Mountain-foothill-plateau transect could help in understanding the regional groundwater occurrence and flow and ultimate recharge areas for groundwater in the bedrock aquifers.
- Good quality lithology data is limited. It is recommended future aquifer characterization initiatives to consider generating new properly described borehole lithology data by drilling exploratory wells to ground truth existing information.

REFERENCES

Baye, A. (2013). Pumping test and water chemistry analysis report on provincial observation wells around Dawson Creek, Ministry of Forests Lands and Natural Resources Operations. Prince George, BC.

B.C. Ministry of Environment (2007). Arsenic in Groundwater, Water Stewardship Information Series, February 2007, http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-wells/as020715_fin3.pdf

B.C. Ministry of Environment (2015). Working water quality guidelines, http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/waterqualityguidesobjs/final_2015_wwqgs_26_nov_2015.pdf

B.C. Ministry of Environment (2007b). Hardness in Groundwater, Water Stewardship Information Series, February 2007, http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-wells/hardness020715_fin2.pdf

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.

Callan, D.M.(1970). An investigation of a buried channel deposit in the Groundbirch area of northeastern British Columbia: Report No. 3 of 1969 Peace River Rotary Drilling Programme, British Columbia Ministry of Environment, Groundwater Division.

Catto, N.R. (1999). Quaternary Geology and Landforms of the Peace River Region, northeastern British Columbia: Implications for Water Supply. Report to Prairie Farm Rehabilitation Agency, Agriculture Canada, Edmonton, Alberta.

Chebotarev, I. J. (1955). Metamorphism of natural water in the crust of weathering. Geochem. Cosmochim. Acta. 8, 22-212.

Church, M. and J.M. Ryder (2006). Physiographic regions of British Columbia.

Cowen, A. (1998). BC Peace Region Groundwater Initiative Interim Report 1998; Prairie Farm Rehabilitation Administration, 25p.

Davis, S.N. and De Wiest, R.J.M. (1966). *Hydrology*. Wiley, New York.

Geological Survey of Canada (2008). Hydrogeological Regions of Canada, open file 5893.

Hem, D. J. (1992). Study and interpretation of the chemical characteristics of natural water. Third edition, US geological survey water supply paper 2254, United States government printing office, Washington, 264pp.

Health Canada (2014). Guidelines for Canadian Drinking Water Quality - Technical Documents, online at http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/index-eng.php#tech_doc

Healy, R.W.(2010). Estimating groundwater recharge. Cambridge University Press, United Kingdom.

Hickin, A.S., (2011). Preliminary bedrock topography and drift thickness of the Montney Play area: British Columbia Ministry of Energy and Mines, Energy Open File 2011-1.

Hickin A., and Best, M. (2013). Mapping the Geometry and Lithostratigraphy of a Paleovalley with a Time-domain Electromagnetic Technique in an Area with Small Resistivity Contrasts, Groundbirch, British Columbia, Canada, J. Environ. Eng. Geophys., doi:10.2113/JEEG18.2.119., v. 18(2), p.119-135.

Hickin, A.S., Best, M.E., and Pugin, A. (2016). Geometry and valley-fill stratigraphic framework for aquifers in the Groundbirch paleovalley assessed through shallow seismic and ground-based electromagnetic surveys. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 2016-5, 46p.

Holding, S. and Allen, D.M. (2015). Shallow Groundwater Intrinsic Vulnerability Mapping in Northeast British Columbia, Simon Fraser University, Burnaby, BC.

Holland, S.S. (1964). Landforms of British Columbia, A Physiographic Outline; British Columbia Department of Mines and Petroleum Resources, Bulletin 48.

Kelly, J. and Janick, E.i (2011). Drilling and Construction of Observation Wells in the Montney Play Area, Dawson Creek, British Columbia.

Kruseman, G.P. and De Ridder, N.A. (1990). Analysis and evaluation of pumping test data. Ilri pub Ser: No 47, 377p.

Levson, V. (2014). NE BC Aquifer Characterization Project – Gamma Ray Interpretation

Lowen Hydrogeology Consulting Ltd (2004). Aquifer Classification Mapping in the Peace River Region, B.C. Ministry of Water, Land and Air Protection, contract No. WAC-05-039, Victoria, BC.

Lowen, D. (2011). Aquifer classification mapping in the Peace River region for the Montney Water Project: Geoscience BC,., File 1026, Victoria, BC.

Mathews, W.H. (1955). Ground-water possibilities of the Peace River Block, British Columbia. British Columbia Department of Mines, Ground-water Paper No. 3, 7 pp.

Maxey, G.B. 1964, Hydrostratigraphic units: Journal of Hydology, 2, pp. 124-129.

McMechan, M.E. (1994). Geology and structure cross section, Dawson Creek, British Columbia. Geological Survey of Canada, Map 1858A, scale 1:250,000. Ottawa, ON.

Province of Alberta (2007). Water Analysis Interpretation for Livestock, Agri-Facts http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex718/$file/400_716-2.pdf?OpenElement

Riddell, J. (2012): Potential for freshwater bedrock aquifers in northeast British Columbia: regional distribution and lithology of surface and shallow subsurface bedrock units (NTS 093I, O, P; 094A, B, G, H, I, J, N, O, P); in Geoscience Reports 2012, British Columbia., Ministry of Energy and Mines, pages 65-78.

Saha, G.C., Paul, S.S., Li, J., Hirshfield, F. and Sui, J. (2013): Investigation of land-use change and groundwater–surface water interaction in the Kiskatinaw River watershed, northeastern British Columbia (parts of NTS 093P/01, /02, /07–/10); *in* Geoscience BC Summary of Activities 2012, Geoscience BC, Report 2013-1, p. 139–148.

Schroeder, P.R., Dozier, T.S. Zappi, P.A., McEnroe, B.M. Sjostrom, J.W. and Peyton, R.L. (1994) The Hydrologic Evaluation of Landfill Performance (HELP) model: Engineering documentation for Version 3, Rep. EPA/600/R-94/168b, U.S. Environmental Protection Agency, Washington, D.C., USA.

Shlumberger Water Services (2012). Aquifer test pro (Pumping Test & Slug Test Analysis) Software version 2011.1, Ontario, Canada.

Toews, W.M. (2007). Lithology editing scripts for WELLS database. Simon Frazer University.

Western Water Associates LTD. (2012). Northeast BC Source Area Delineation for Groundwater Supply Systems, Ministry of Environment, Victoria, BC.

Winkler, G., Reichl, P. and Strobl, E. (2003). Hydrogeological conceptual model. Materials and Environment, Vol. 50, no. 1, 417-420.

APPENDIX A: WELL DATA AND WATER QUALITY RESULTS

Data compiled and collected in conjunction with the study are assembled in an Excel workbook called ‘Montney Well and WQ Data.xlsx is included as a companion electronic file to this report.

The workbook contains the following spreadsheets:

1) Study area wells: Provide basic well information including location and construction details for the study area wells. This information is compiled from three sources: the Ministry of Environment WELLS database, the Geoscience BC Montney Water Project database, and well information gathered in the FLNRO private well survey. Wells are cross-referenced among the three data sources.
2) Lithology comparison: Lists available lithology from the WELLS database and provides a comparison of stratigraphic interpretations and the SFU standardized lithology.
3) Groundwater Quality data: A compilation of water quality data collected in the private well survey and water quality information in the WELLS database.

APPENDIX B: HELP MODEL SCENARIOS AND RECHARGE ESTIMATES

Scenario A: Soil = Loamy Sand; Vadose Zone Material = Till

(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.6	5.4	19.7	11.2	4.8	0.0	0.0	0.0	0.0	0.0	0.5	0.6	43
Evaporation	10.3	9.3	11.2	10.4	40.4	79.8	79.6	56.3	35.7	23.5	12.7	9.8	379
Recharge	2.8	2.5	2.8	2.7	2.8	2.7	2.8	2.8	2.7	2.8	2.7	2.8	33

Scenario B: Soil = Sandy Loam; Vadose Zone Material = Till

(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.6	5.7	20.4	11.8	5.1	0.0	0.0	0.0	0.0	0.0	0.5	0.5	45
Evaporation	10.3	9.3	11.2	10.8	50.1	67.9	78.8	56.5	36.5	24.0	12.7	9.8	378
Recharge	2.8	2.5	2.8	2.7	2.8	2.7	2.8	2.8	2.7	2.8	2.7	2.8	33

Scenario B2: Soil = Silty Loam; Vadose Zone Material = Till

(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.7	6.0	21.1	12.2	5.2	0.0	0.0	0.0	0.0	0.0	0.6	0.6	46
Evaporation	10.3	9.3	11.3	11.0	50.5	66.1	79.6	57.0	35.9	23.2	12.6	9.8	377
Recharge	2.8	2.5	2.8	2.7	2.8	2.7	2.8	2.8	2.7	2.8	2.7	2.8	33

Scenario C: Soil = Loamy Sand; Vadose Zone Material = Glaciolacustrine

(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.6	5.7	20.4	11.8	5.2	0.5	0.0	0.0	0.0	0.1	0.5	0.6	45
Evaporation	10.3	9.3	11.2	10.4	41.2	95.9	90.0	57.5	36.1	23.3	12.7	9.8	408
Recharge	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6

Scenario D: Soil = Sandy Loam; Vadose Zone Material = Glaciolacustrine

(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.7	6.0	21.2	12.4	5.5	0.0	0.0	0.0	0.0	0.0	0.5	0.6	47
Evaporation	10.3	9.3	11.2	11.0	56.8	86.3	81.6	57.5	36.6	23.6	12.7	9.8	407
Recharge	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6

Scenario D2: Soil = Silty Loam; Vadose Zone Material = Glaciolacustrine													
(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.7	6.2	21.8	12.7	5.6	0.0	0.0	0.0	0.0	0.0	0.6	0.7	48
Evaporation	10.3	9.3	11.3	11.1	59.7	84.0	81.0	57.7	35.9	23.0	12.5	9.8	406
Recharge	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6

Scenario E: Soil = Loamy Sand; Vadose Zone Material = Glaciofluvial													
(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.6	5.3	19.0	10.9	4.5	0.0	0.0	0.0	0.0	0.0	0.5	0.5	41
Evaporation	10.3	9.3	11.2	9.8	32.5	63.8	74.2	54.0	35.8	24.0	12.7	9.8	347
Recharge	7.1	6.7	7.6	7.4	6.7	1.4	2.2	3.7	4.5	6.0	6.9	7.5	68

Scenario F: Soil = Sandy Loam; Vadose Zone Material = Glaciofluvial													
(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.6	5.6	19.9	11.5	4.8	0.0	0.0	0.0	0.0	0.0	0.5	0.5	44
Evaporation	10.3	9.3	11.2	10.3	37.7	63.2	75.8	55.0	36.2	24.2	12.8	9.8	356
Recharge	7.0	6.3	7.1	6.5	4.9	0.6	1.6	2.4	3.1	4.7	6.3	7.0	57

Scenario F2: Soil = Silty Loam; Vadose Zone Material = Glaciofluvial													
(mm/yr)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Precip	28.5	21.4	22.9	20.9	32.5	67.6	82.7	55.5	43.2	31.8	28.7	21.4	457
Runoff	0.7	5.9	20.7	12.1	5.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	46
Evaporation	10.3	9.3	11.3	10.7	43.7	64.0	78.3	56.1	35.8	23.4	12.6	9.8	365
Recharge	4.1	2.9	2.0	0.9	0.6	0.4	4.0	6.4	6.8	7.1	6.1	5.1	46