GIS-based Approach to Spring Occurrence and Spring Source Areas in Northeast British Columbia

By Ismena Bystron, Dirk Kirste and Diana M. Allen

Department of Earth Sciences, Simon Fraser University,
Burnaby, British Columbia. V5A 1S6

For British Columbia Oil and Gas Research and Innovation Society
(BC OGRIS)

July 31 2017

EXECUTIVE SUMMARY

In the Peace River Regional District (PRRD) of Northeast British Columbia (NEBC), there are nearly 200 documented spring locations. The groundwater discharging from these springs is an important resource for potable drinking water, and agricultural and industrial needs. The dependence of landholders on springs as their primary source of fresh water makes pertinent the understanding of where they occur and the extent of the catchments sourcing water vital for resource evaluation and protection.

Identifying the physical and hydrogeological controls on spring occurrence was undertaken using statistical analysis of data from 191 known spring locations in NEBC of which 121 occur within the study area. Field work was conducted to sample and analyze the groundwater from 36 springs to identify the groundwater source (Quaternary or bedrock aquifer). These data were evaluated by applying a multi-criteria decision analysis (MCDA) in GIS to produce maps of the potential for springs to occur in the study area. By combining the results of the statistical analysis with the groundwater source information, maps identifying the regions that are most likely to have springs discharging groundwater from local Quaternary unconsolidated sediment aquifers and regional bedrock aquifers were produced.

The MCDA framework incorporates the following spring-related factors: slope, curvature, proximity to hydrological features, topographic wetness index, surficial geology, and drift thickness. The data for each factor was statistically analyzed for trends to better understand the characteristics of springs in the PRRD. During this step, drift thickness was found to be statistically significant for determining Quaternary and Bedrock-sourced spring types.

A linear equation with the spring-related factors weighted according relative importance was derived for both Bedrock and Quaternary MCDAs. Weights were derived using the pairwise comparison method, by determining the relative importance of every spring-related factor combination. The weighting process reflects the conceptual ideas and hypothesized controls on spring occurrence. Terrain factors are believed to be the most influential for Quaternary-sourced springs, with curvature being the most important, whereas hydrogeology, in particular exposed bedrock, is most influential for Bedrock sourced springs.

The MCDA generated two maps with scores ranging from 0-100 for Likelihood of Occurrence for Bedrock or Quaternary Springs. The maps were classified into intervals of very low (0-25), low (25-50), moderate (50-75), high (75-90) and very high likelihood (90-100) of occurrence for

springs. Across the study area, 5.8% and 9.5% of the area scored in the highest likelihood category for potential Bedrock and Quaternary sourced spring occurrence, respectively. The Likelihood score from both maps for each spring location was compared, and the higher of the two is interpreted to represent the groundwater type feeding the spring. Of the 121 springs in the study area, 58 scored higher in the Bedrock MCDA than the Quaternary MCDA. The median Likelihood score for those potentially Bedrock sourced springs was 82.8, compared to 82.3 for the potentially Quaternary sourced springs indicating that the method was effective for identifying the potential for springs and their source.

A spring's source area is the land area receiving recharge for the groundwater system that feeds the spring(s). Spring source areas (SSAs) were delineated for the 36 sampled springs, according to Kreye et al.'s (1996) methodology. A GIS-based approach was tested by utilizing the Watershed tool to generate spring source areas. In this report, five spring case studies are presented and their SSAs ranging from 0.008 to 3.6 km^2. There are uncertainties regarding each of the SSA's due to assumptions in the methodology and poor resolution or quality of hydrogeological data, thus a high degree of confidence could not be achieved. The GIS-based SSA are approximate extents derived based on topography and should be refined when additional geological or hydrogeological information is obtained.

The springs database, LOQ and LOB GIS data and SSA shapefiles are available on the SFU database RADAR

https://researchdata.sfu.ca/islandora/object/sfu%3A124

TABLE OF CONTENTS

List of Tables

List of Figures

Glossary

Terminology	Description
Spring	A surface feature where groundwater discharges onto the land surface naturally.
Spring source area (SSA)	The land area receiving recharge (the fraction of precipitation that seeps into the ground and reaches the groundwater system) that provides groundwater to the spring(s).
Multi-criteria decision analysis (MCDA)	A decision-making framework that breaks down a problem into smaller, more understandable parts, evaluates each part and integrates the parts together to achieve a decision or solve a problem. There are many ways these factors can be evaluated, but for this project, a weighted linear equation was developed to rank spring-related factors in terms of influence on spring occurrence. This framework can be completed in the GIS to produce a map with the final scores.
Slope	The gradient of a terrain, expressed as degrees or percent. In GIS, the slope factor represents the rate of change in elevation between two cells.
Curvature	Curvature is the amount of derivation from a flat or straight plane. In GIS, each cell is calculated from the surrounding eight cells to describe the shape of the terrain (concave, flat or convex).
Topographic Wetness Index (TWI)	A secondary terrain factor that can be calculated in the GIS to estimate the soil wetness in any particular cell. It is based on the area uphill from the point and the local slope.
Drift thickness	The thickness of the sediments between the ground surface and the top of Bedrock material.
Digital elevation model (DEM)	A gridded file where every cell contains a number representing the elevation of the ground surface.
Bedrock	Consolidated sediments that form rocks such as sandstone, siltstone or shale.
Quaternary	The time period from 2.58 million years ago to the present time, in this study it is assigned to represent the unconsolidated sediments.
Likelihood score	The output of the MCDA is a map, with a value in each cell representing the Likelihood of Occurrence for Springs
Spring related factor	The physical trait or characteristic of a spring, and the individual data layer that represents a physical trait or characteristic in the GIS.
Standardization	The process of manipulating data so that it can be in a common format (i.e., same units or range of values, etc.) for ease of comparison.
Standardization score	The new values that were used to normalize the attribute data. The new values reflect the ranges of data or categories which are common for springs.
Analytical Hierarchy Process	It is a technique for organizing and analyzing complex decisions. This technique includes developing a hierarchy for the decision or goal with several options or factors that contribute to the decision or goal.
Pairwise comparison matrix	A method that compares all pairs of factors, to determine which factor is most suitable. In this project, this method was used to calculate the

weights for the spring-related factors for the MCDA linear equation, based on the relative importance of a factor in influencing spring occurrence. For example, Factor A has a stronger influence on spring occurrence than Factor B.

1 BACKGROUND

This report summarizes the results of a springs study in the Peace River Regional District (PRRD) of Northeast British Columbia. For this study, a spring is defined as a feature where groundwater discharges at the ground surface, and a spring's source area is the land area receiving recharge, which percolates into the groundwater system that feeds the spring(s) (Bryan, 1919; Government of British Columbia, 2010; Kreye, et al., 1996; Meinzer, 1923). The purpose of the study was to use GIS-based methodologies to identify: i) zones in the region with a high likelihood of occurrence for springs; and ii) spring source areas for a selected number of springs. The project compiles and analyzes information available on known springs in addition to determining what factors influence a greater likelihood of occurrence for springs, the spring's potential groundwater aquifer source, and individual spring source areas. The outcomes of this project can be used for evaluating the vulnerability of spring water resources to development in the region. Funding for the project was provided by the British Columbia Oil and Gas Research and Innovation Society (BC OGRIS) and the Ministry of Forestry, Lands and Natural Resource Operations (FLNRO).

The research project is part of a collaborative effort between the Department of Earth Sciences at Simon Fraser University (SFU) and the Research Institute for Humanity and Nature in Kyoto to further scientific research regarding the Water-Energy-Food Nexus in NEBC.

1.1 PROJECT OBJECTIVES

The overall goal of this project was to compile and analyze data toward enhancing the understanding of springs in the Peace River Regional District in NEBC.

The specific objectives for this project were:

- To identify the locations of springs within the defined study area, collect and compile spring physical characteristics, flow measurements, and spring water chemistry data at selected spring locations;

- To determine terrain, hydrological and hydrogeological factors potentially influencing Quaternary or Bedrock-sourced spring occurrence and compile associated spatial data for those factors;
- To conduct an analysis of the potential influencing factors to develop preliminary maps to predict the likelihood of occurrence for springs;
- To develop a GIS-based method that may be useful for delineating spring source areas;
- To generate a comprehensive database of documented spring locations and attribute data across the study area;
- To produce a report describing the research methods and main results.

The work addresses the research questions and deliverables outlined in the proposal entitled "Understanding the controls on the distribution and flow pathways of springs in Northeast BC", in OGRIS agreement letter dated August 25, 2015.

1.2 STUDY AREA

The Peace River Regional District (PRRD) is the largest district in British Columbia, with an area of 120,000 km^2. The region is bound by the Canadian Rocky Mountains to the west and southwest, the Alberta provincial border to the east, and the 58^{th} parallel to the north (Figure 1). The larger towns in the study region are Fort St. John, Dawson Creek, Hudson's Hope and Chetwynd. Agricultural and oil and gas activities are distributed throughout the study region.

Terrain

The terrain of this region is flat to gently rolling with low relief. The Rocky Mountain foothills are to the west, where the terrain is more mountainous with relatively greater relief (Lowen, 2011). The surface topography mainly reflects the structure of the underlying bedrock (Stott, 1982). Within the study region, the total elevation ranges from 377 m to 1664 m (Figure 2). The Peace River and its major tributaries cut through the study region and coincide with topographic lows. The major tributaries of the Peace River are the Beatton River, Halfway River, Halfway River and Kiskatinaw River (Figure 2).

Geology

The Peace River Region has a complex glacial history, which has resulted in diverse Quaternary glacial sediments overlying the bedrock (Figure 3; Catto, 1991; Catto & Thistle, 1993; Hartman & Clague, 2008). Till is the most common sediment, ranging in thickness from thin veneers to up to 500 m thick deposits (Figure 3; Hickin, 2011). Glaciolacustrine and glaciofluvial sediments make up the majority of the remaining materials. The bedrock consists of Lower Cretaceous (Fort St. John Group) and Upper Cretaceous (Dunvegan, Smokey and Wapiti Formations) sedimentary rocks (Figure 4; Bellefontaine, et al., 1995; MacIntyre, et al., 1995). The Dunvegan Formation is a non-marine carbonaceous sandstone overlying a transgressive sequence of marine shales in the Fort St. John Group (Stott, 1982; Riddell, 2012). The Smokey Group is comprised of mainly marine-shale dominated transgressive/regressive sequences, whereas, the Wapiti Formation a continentally derived sandstone, shale and coal (Stott, 1975; Riddell, 2012).

The study area boundary aligns with the modelled bedrock topography map by Hickin (2011). The bedrock topography map was created at a 100 m resolution using ~1500 subsurface data records from water well data, literature, logged geological exposures along river valleys, and over 500 field surface observations (Figure 5). In the study region, palleovalleys trend with modern river systems, such as the Peace, Pine, Murray and Kiskatinaw Rivers (Figure 5; Hickin, 2011).

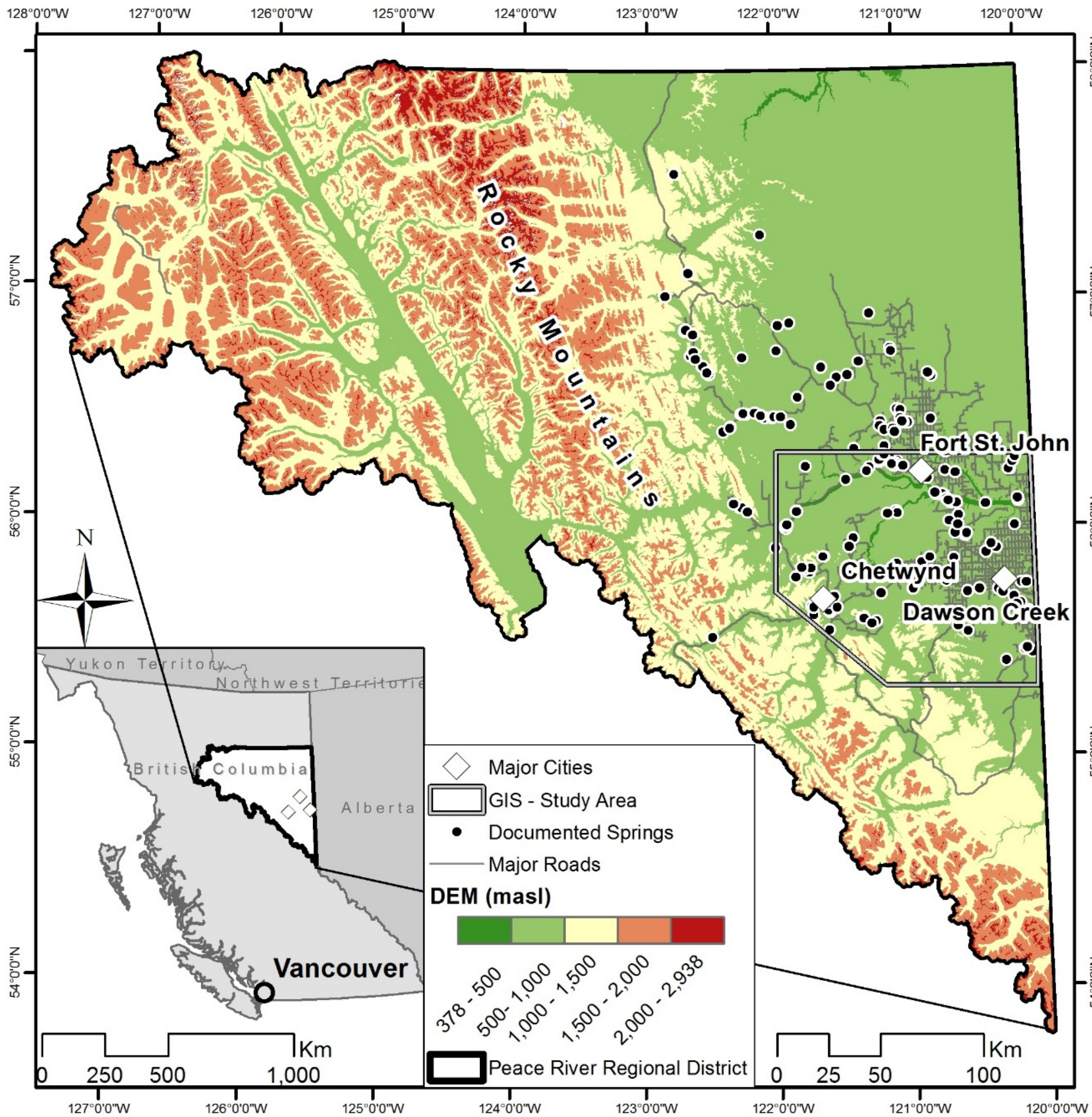

Figure 1. Peace River Regional District in British Columbia with GIS analysis boundary and locations of known springs.

Source: USGS Earth Explorer for DEM, BC Data Catalogue for BC Geographical names, Licensed Springs and Roads, Geobase for Canadian Geopolitical Boundaries.

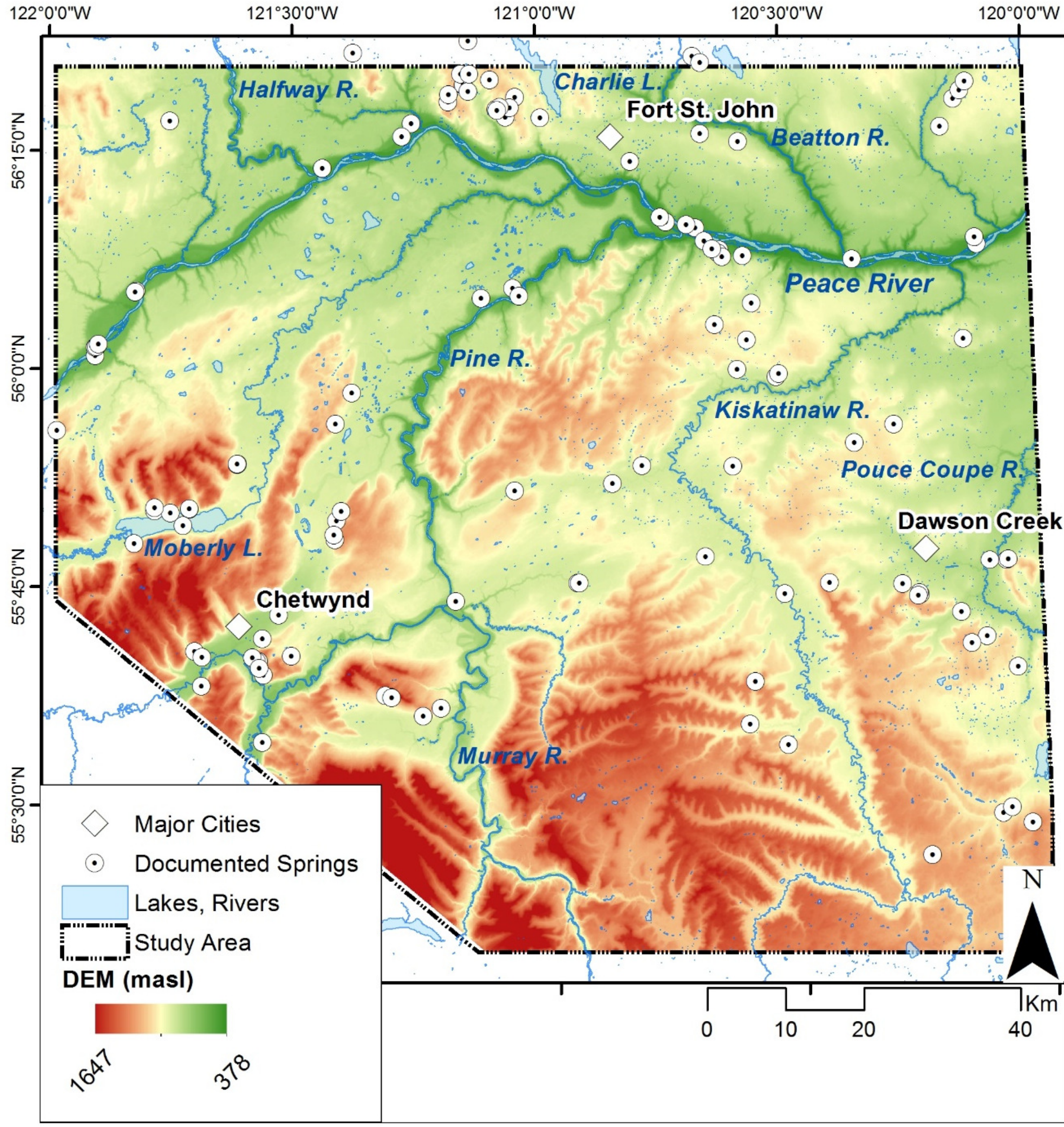

Figure 2. **A digital elevation model (DEM) of the terrain in the GIS spatial analysis boundary with springs in the study area shown.**

Source: USGS Earth Explorer for DEM, BC Data catalogue for BC Geographical names, BC Freshwater Atlas, and Licensed Springs

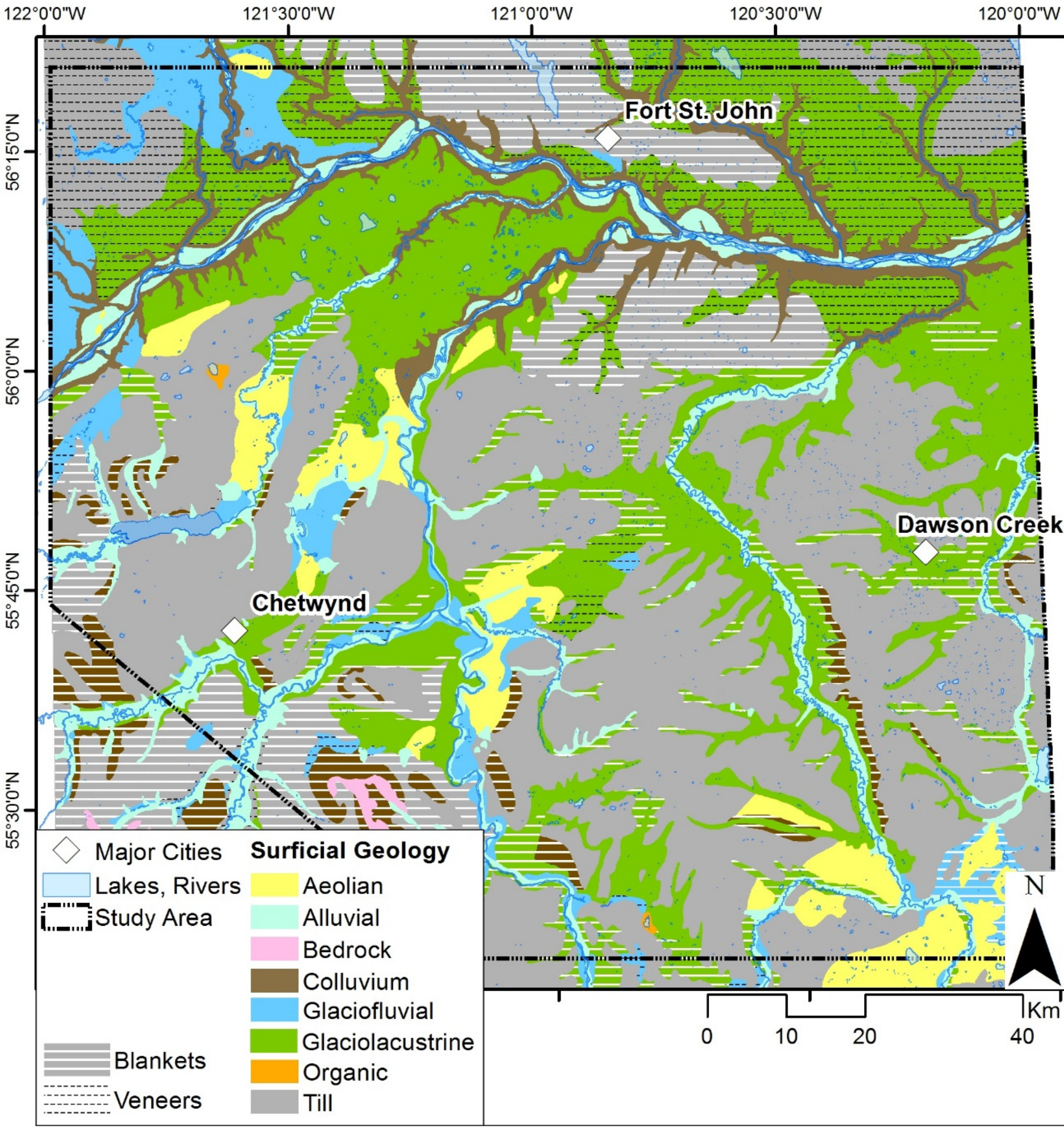

Figure 3. Surficial geology (1:20,000) map in the study area.
Topographic features such as fans, plains, ridges or hummocks are not shown.
Source: BC Data Catalogue for BC Geographical Names and BC Freshwater Atlas; Natural Resources Canda for digitized surficial geology maps (Catto, 1991, Catto & Thirstle, 1993).

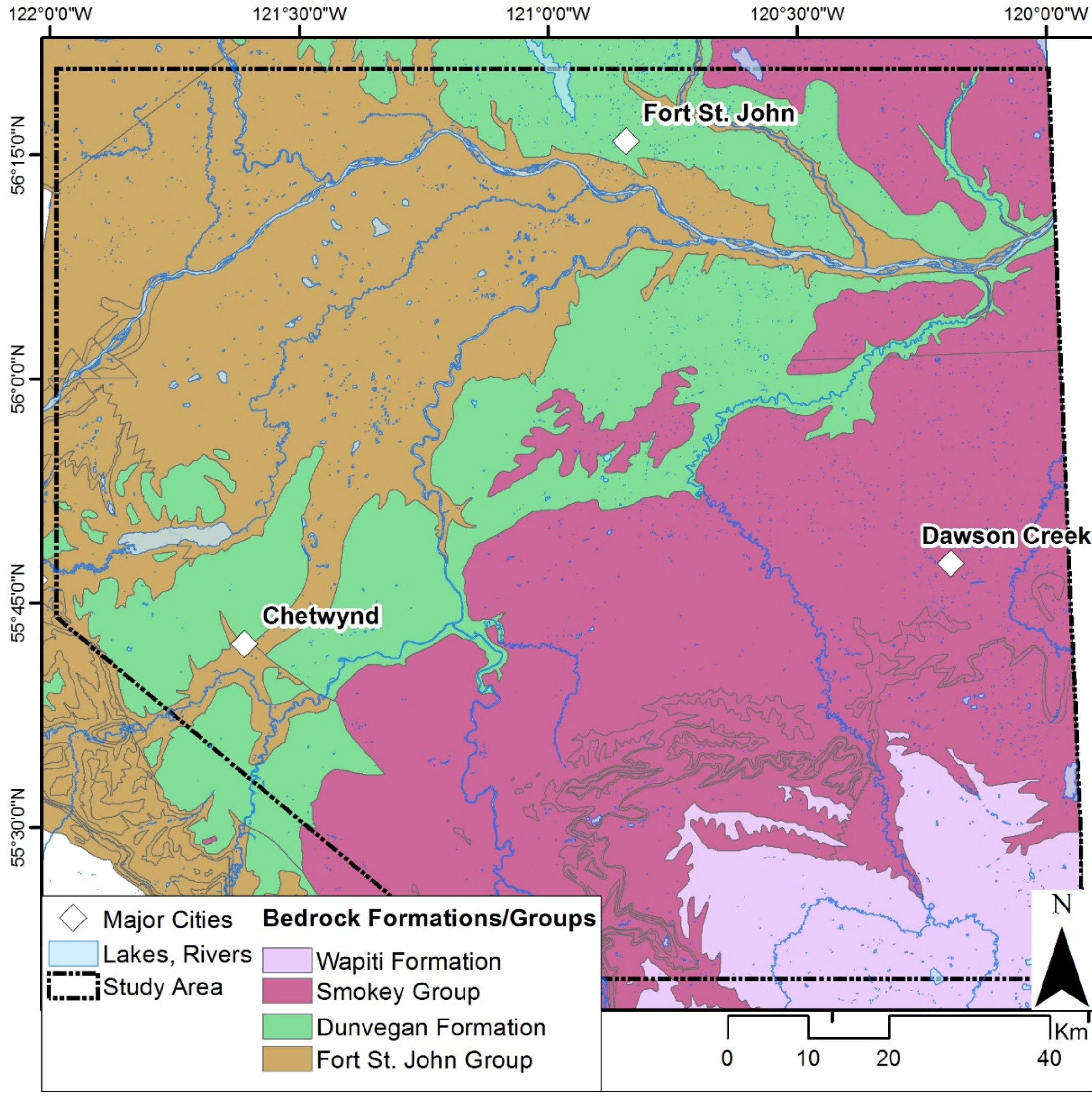

Figure 4. **Bedrock Formations or Groups within the study area.**
Source: BC Data Catalogue for BC Geographical Names and BC Freshwater Atlas; BC Geological Survey for digitized bedrock geology (Bellefontaine et al., 1995 and MacIntyre et al., 1995).

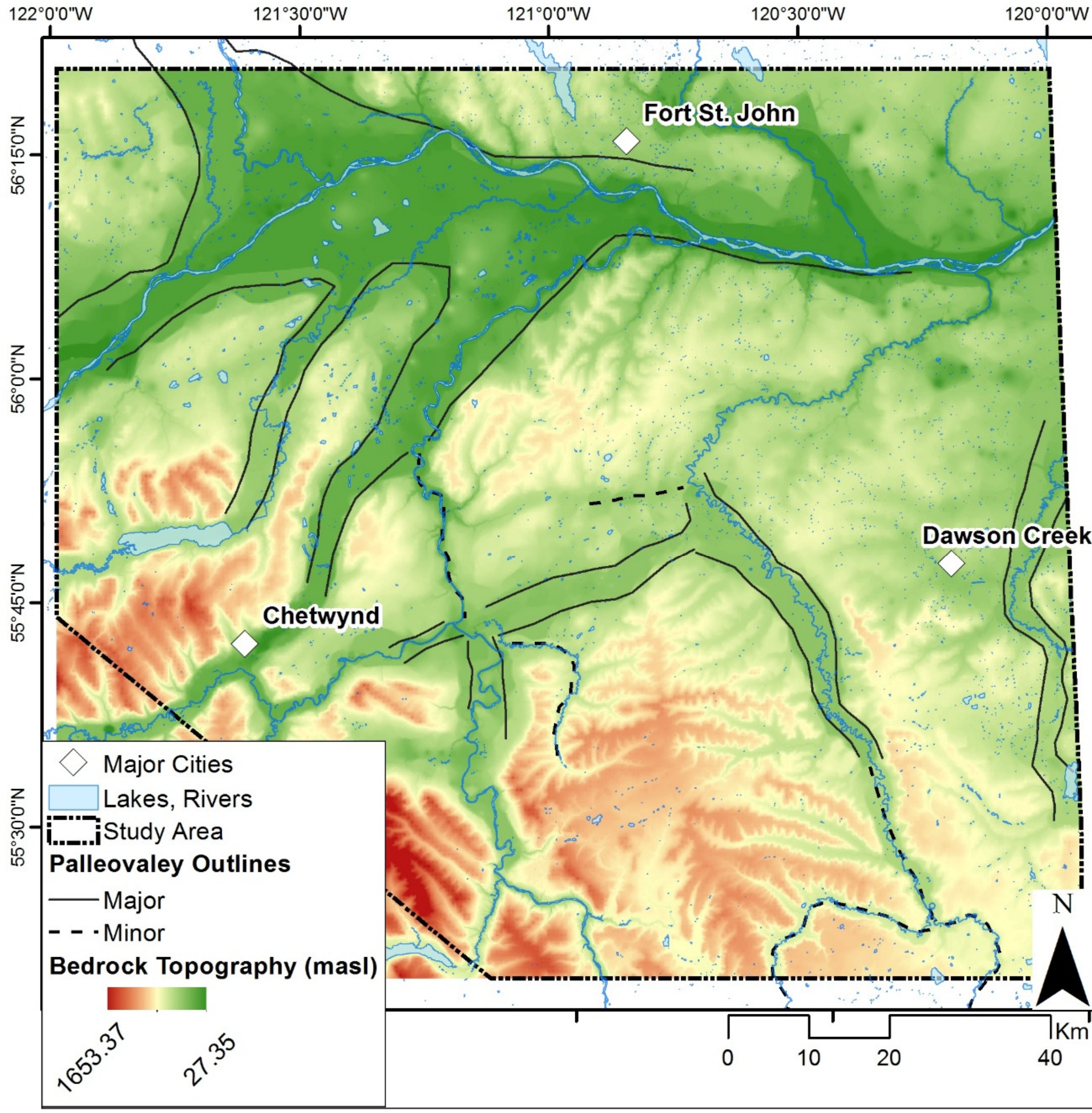

Figure 5. **Modelled bedrock topography in the study area (Hickin, 2011), with paleovalley outlines.**

Source: BC Data Catalogue for BC Geographical Names and BC Freshwater Atlas, and Hickin (2011) for Palleovalleys and Bedrock Topography.

Hydrogeology

The Ministry of Environment has mapped some aquifers in the study area, based on locations of water well records that provide sufficient data to support aquifer mapping (Figure 6; Berardinucci & Ronneseth, 2002; Lowen, 2011; Riddell, 2013); however, aquifer characterization has not been completed across most of the study area. Many of the Quaternary unconsolidated aquifers are comprised of glaciofluvial gravels and/or sands, and sandy tills. The major regional bedrock aquifers are in the Dunvegan Formation. The Wapiti Formation is also known to host an irregular distribution of aquifers (Jones, 1966; Lowen, 2011). The upper surface of the bedrock can act as an aquifer regardless of Formation due to weathering and fracturing, which increases permeability. The groundwater flow direction is inferred to be from high to low elevation, such as the plateaus to stream valleys (Lowen, 2011). Although the regional flow direction is west to east from limited data availability (Baye, et al., 2016).

Springs

There are 167 licensed springs in the NEBC region (Figure 6) in the Government of British Columbia water license database. And an additional 24 non-licensed springs were identified from the Northeast British Columbia Aquifer Study (NEBCAS) (Baye et al., 2016; Wilford et al., 2012). Few studies have provided additional information or characterization regarding springs in NEBC. Mathews (1950) observed spring discharge directly from bedrock in the Kaskapau Formation north of Dawson Creek. Agriculture and Agri-Food Canada conducted evaluations of two water supply springs, Fey and Romedo Springs (Lebedin, 1990). In 2003, these two springs were re-evaluated to determine the groundwater source areas (Cowen, 2003).

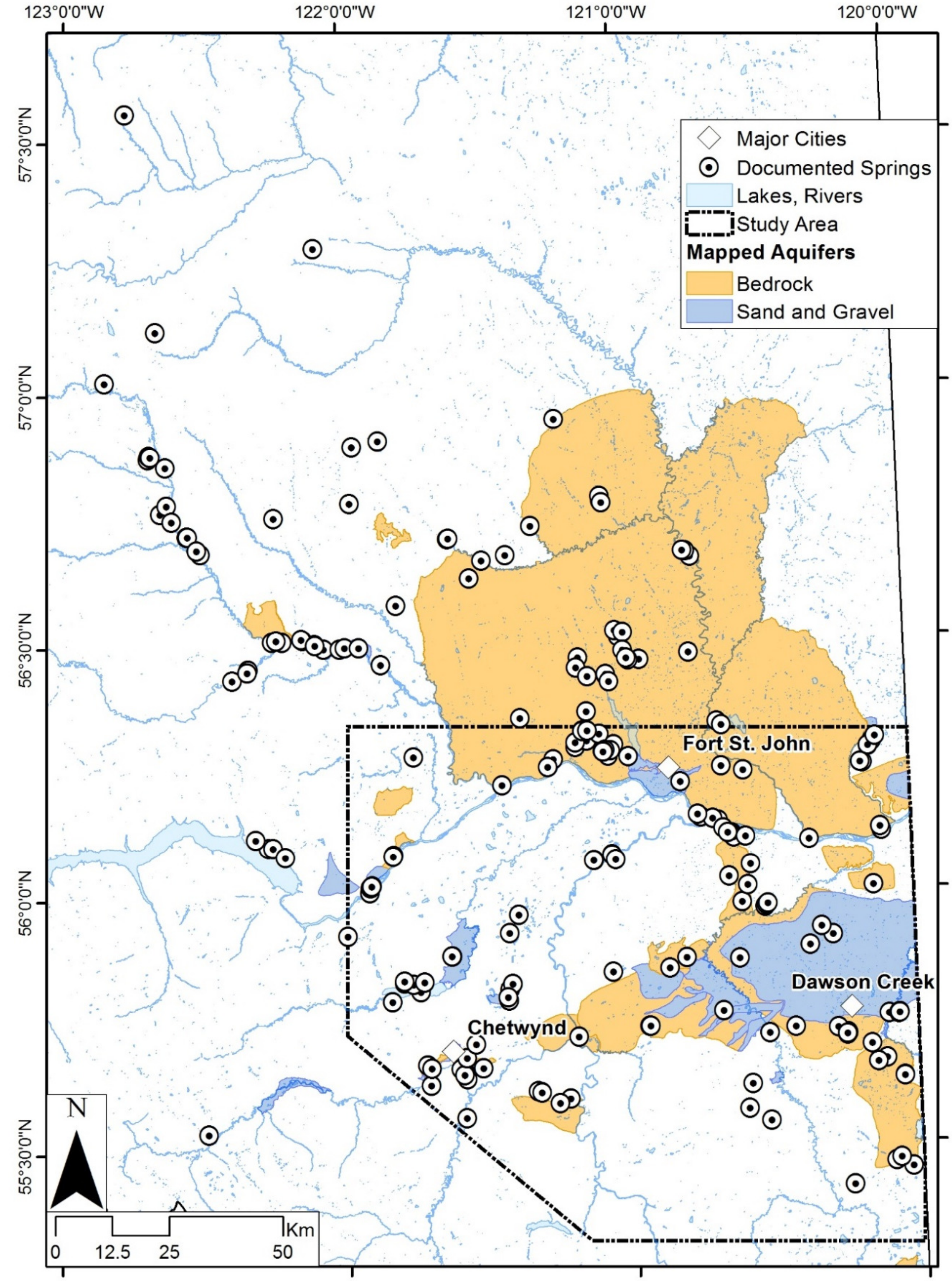

Figure 6. **Mapped bedrock and sand-gravel aquifers with documented spring locations in the PRRD.**

Source: BC Data Catalogue for BC Geographical Names, BC Freshwater Atlas, Groundwater Aquifers, and Licensed Springs.

2 METHODOLOGY

2.1 SPRING DATABASE DEVELOPMENT IN THE STUDY AREA

A database of known spring locations in the PRRD was developed for this project using the following information sources:

- A database of license records for spring water use (Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), 2011),
- Sampled spring sites in the NEBCAS (Baye et al., 2016; Wilford et al., 2012), and
- Springs or groundwater seeps identified during the field work program.

The MFLNRO Licensed Springs database contains accepted, refused, and expired application details from 167 springs within the study area. Sixteen (16) documented springs from the NEBCAS were identified within the study area, and during the field work component for this research eight (8) additional springs and seeps were documented.

A database was created to compile basic information for all 191 springs, such as license application number (if applicable), GPS coordinates in UTM, elevation data in metres, and 36 springs have information regarding their groundwater source type determined as part of this study from collected spring water chemistry. Detailed geochemical information could not be included in the database as the information is proprietary. This database can be imported into GIS software and joined with the Licensed Springs database, based on the license applicable number for appending springs' license information.

2.2 SPRING SAMPLING AND GEOCHEMICAL ANALYSIS

Springs were visited in September and November 2015 to verify spring locations, gather usage information from the spring licensees or users, collect spring water samples for isotopic and geochemical analysis, and where possible, measure discharge rates. A total of 30 springs were visited during the field program and 28 of those were sampled. Another eight (8) springs were previously sampled as part of the NEBCAS (Wilford et al., 2012) (Figure 7). Eleven of the 30 springs observed during the field program were natural flowing springs, whereas the remainder have been developed using cribs, culverts, underground pipe systems or dugouts.

Discharge measurements were only possible at five springs, where the discharge was concentrated at an outlet pipe, or at a developed spring with gravity fed flow and no pump. A simple time-and-bucket method, where the time required to fill a known volume large beaker or bucket was recorded and averaged from three measurements.

Permission was granted by spring licensees or users to sample their springs. At each spring, a YSI Pro Plus multi-parameter meter recorded instantaneous field parameters (temperature, pH, conductivity, dissolved oxygen (DO), oxidation-reduction potential (ORP)), and alkalinity was measured in triplicate on site with a Hach digital titration kit and 0.1 M HCl solution. Water samples were filtered with Watera 0.45 µm high capacity in-line filters and preserved on site for laboratory analysis.

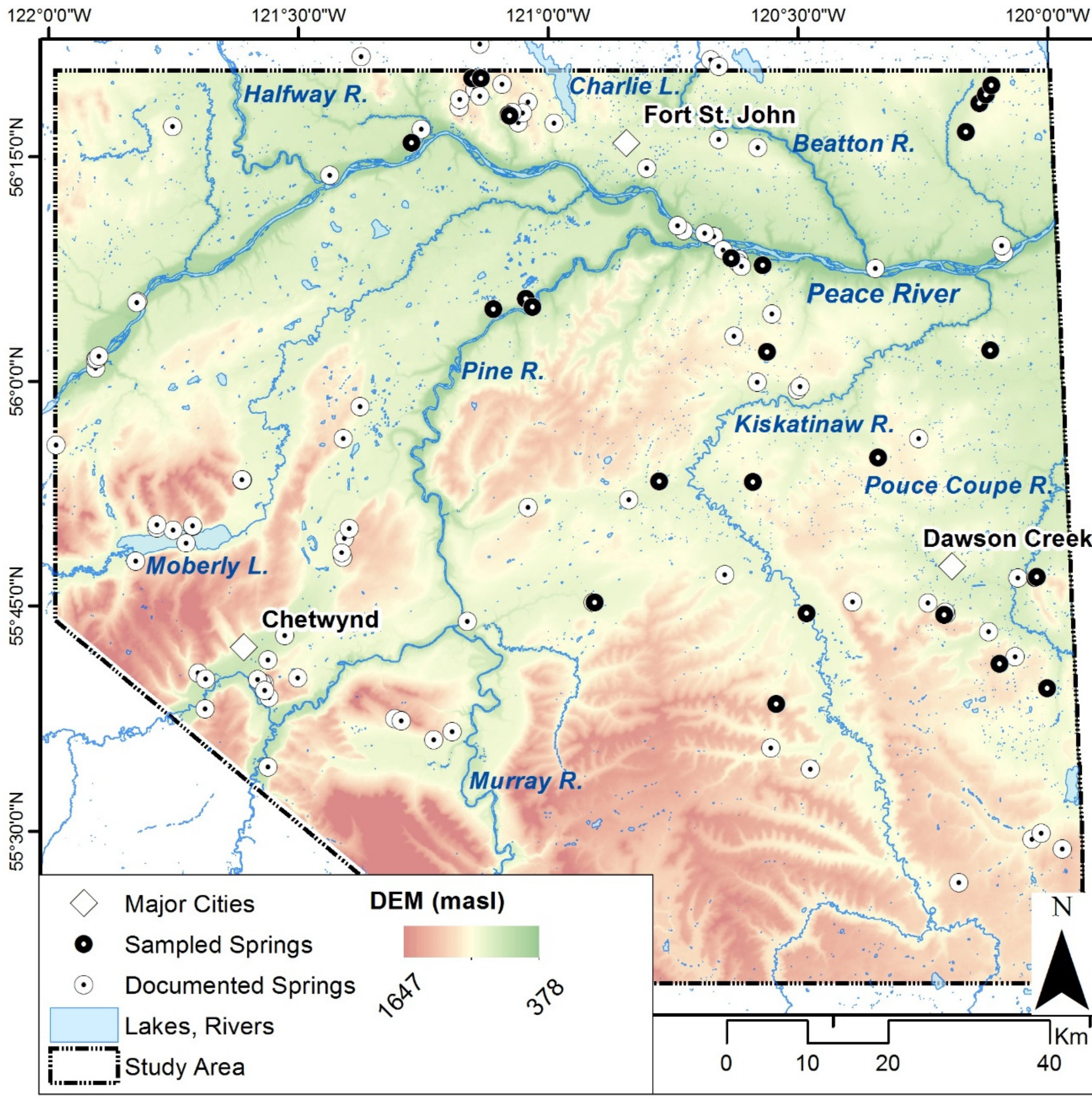

Figure 7. Locations of sampled springs.

The collected spring samples were kept refrigerated and shipped in coolers back to Simon Fraser University for analysis. All of the spring samples were analyzed for major, minor and trace elements (Al, As, B, Ba, Ca, Fe, K, Li, Mg, Mn, Mo, Na, Si, Sr, Zn) using a Jobin-Yvon Horiba Ultima II Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (1 σ error of ±3%). Major and minor anions (F^-, Cl^-, Br^-, NO_3^-, PO_4^{3-} and SO_4^{2-}) were analyzed by ion chromatography on a Dionex Ion Chromatography System (ICS) 3000 (1 σ error of ±3%). Ammonia content was determined using a Hach DR2800 spectrophotometer (1 σ error of ±5%). Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) were analyzed on a Los Gatos Research DLT-100 laser isotope analyzer at the University of British Columbia, and they are reported in permil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) (1 σ error of ±0.2‰ and ±1‰ VSMOW, respectively). Spring samples were analyzed by enrichment and low level proportional counting at the University of Miami Tritium Laboratory for Tritium (^3H) analysis (1 σ error of ±3%). Carbon-13 ($\delta^{13}C$) was determined at the University of Ottawa G.G. Hatch Stable Isotope laboratory by isotope ratio mass spectrometry on a Thermo Finnigan Delta XP and Gas Bench II, and it is reported in permill (‰) relative to the Vienna Pee Dee Belemnite (VPDB) (precision ±0.2‰ VPDB).

The groundwater source of springs was inferred from the measured field parameters and analyzed geochemical and isotopic data. Kirste (2016) (found in Baye et al., 2016) described groundwater in NEBC to be strongly controlled by lithology. Groundwater in the Quaternary aquifers has a chemical composition of $Ca\text{-}HCO_3$ and $Ca\text{-}Mg\text{-}HCO_3$. Groundwater in Bedrock aquifers has a chemical composition dominated by Na, HCO_3 and SO_4 relative to the Quaternary sourced groundwater. Stable isotopes ($\delta^{18}O$ and δ^2H) were found to not be useful in indicating aquifer type, except depleted groundwaters with $\delta^{18}O$ less than -24 ‰, are typically Bedrock groundwater. Finally, groundwater in Quaternary aquifers predominantly contained tritium in excess of 1 TU while groundwater from the bedrock aquifers had little or no tritium. These descriptions of Quaternary and Bedrock groundwater were used to group spring samples into most likely fed by a Quaternary or Bedrock aquifer. Five (5) springs showed mixed geochemical signatures, but they were assigned into the most dominant grouping. This was done to increase the number of springs in each grouping for statistical analysis, and verification of the Likelihood of Occurrence for Springs maps from the MCDA.

2.3 MULTI-CRITERIA DECISION ANALYSIS

The MCDA methodology can integrate multiple data sets in the GIS and yield an output map which can be used to support an objective or decision (Malczewski, 1999). In this case, two output maps were produced to identify the Likelihood of Occurrence for Bedrock and Quaternary-sourced Springs. The following list highlights the major steps taken to conduct a MCDA spatial analysis:

- Identify the dominant factors influencing Bedrock and Quaternary-sourced springs occurrence based on published studies and data availability;

- Develop preliminary models for Bedrock and Quaternary-sourced spring occurrence that attempt to explain spring occurrence, and re-evaluate and refine the model as more is learnt about the springs;
- Compile relevant geospatial data to represent spring-related factors;
- Conduct a statistical frequency analysis to understand the distribution of attribute data for the spring-related factors;
- Prepare the data for the MCDA by standardizing the spring-related factor attribute data and deriving weights for the spring-related factors included in the Likelihood of Occurrence for Bedrock Springs (LOBS) and Likelihood of Occurrence for Quaternary Springs (LOQS) equations;
- Generate two maps by integrating the spring-related factor data with the LOBS and LOQS equations in the GIS;
- Validate the Likelihood of Occurrence for Springs maps.

2.3.1 **Determining Spring Related Factors**

Potential spring occurrence has been studied with probabilistic statistical modelling, a method for evaluating relationships between different data (Ozdemir, 2011; Pourtaghi & Pourghasemi, 2014). Statistical methods such as weight of evidence, artificial neural networks, frequency ratios, and logistic regression are commonly applied to conduct the modelling (Corsini et al., 2009; Moghaddam et al., 2013; Pourtaghi & Pourghasemi, 2014). Of these methods, the frequency ratio is a simple statistic model that calculates the probability of occurrence of a certain attribute; for instance identifying relationships between spring locations and spring-related factors (Oh et al., 2011; Ozdemir, 2011). Those relationships can then be weighted by statistical means to develop a multi-criteria decision analysis method. Factors identified as important to influencing or controlling spring occurrence are evaluated by an equation which is a summation of all weighted factors, where the weights correspond to the frequency of an individual factor. The frequency ratio method has proven to be effective at predicting locations of documented springs (Ozdemir, 2011; Pourtaghi & Pourghasemi, 2014).

Two types of input data are used to define factors: constraints and criteria. Constraints are datasets comprised of Boolean variables, typically assigned values of 0 or 1 which can be used to delineate areas suitable/not suitable for consideration. This works well for discrete data, such as roads, which could be assigned a value of 0, whereas the remaining area is assigned a value of 1. Criteria are data sets with numerically continuous data (e.g. slope) or made up of multiple categories (e.g. surficial geology). This type of data requires standardization, where the user reclassifies the data with scores (0 to 100), in such a matter to support the MCDA objective. The standardization scores are chosen by the user, or the results of statistical analysis of the data are used to derive scores.

Based on the literature review, the data that are best suited to extracting criteria related to spring occurrence include: topographical (e.g. elevation, slope, aspect, curvature, topographic wetness index (TWI)); geological (e.g. surficial or bedrock geology, faults); hydrogeological (e.g. aquifer lithology or permeability, depth to groundwater, hydraulic conductivity); hydrological (e.g. streams, lakes, wetlands); climatic (e.g. recharge); and anthropogenic data (e.g. roads, land use). The combinations of datasets vary based on availability; Corsini et al. (2009) integrated geology and topography factors, whereas Ozdemir (2011) and Pourtagahi and Pourghasemi (2014) additionally included hydrogeological characteristics. Climate data, such as precipitation, was only included by Ozdemir (2011). These studies did not discuss hydrogeological models; however, the datasets included can easily conform to a hydrogeological model.

The spring-related factors used in this MCDA can be organized into three themes: terrain characteristics, hydrological features and hydrogeological data. The final spring-related factors chosen and represented by geospatial data in this MCDA were: slope; curvature; hydrological features; topographic wetness index; surficial geology; and drift thickness (Table 1). The data for these factors are assigned to an attribute table in the GIS and are referred to as attribute data. The data sources for the different factors are shown in Table 2.

Table 1. Spring-related factors for Likelihood of Occurrence for Bedrock and Quaternary Springs (LOBS, LOQS).

Themes	Bedrock	Quaternary
Terrain	Slope	Slope
	Curvature	Curvature
Hydrological	Proximity of Hydrological Features	Proximity of Hydrological Features
		Topographic Wetness Index (TWI)[1]
Hydrogeological	Surficial Geology	Surficial Geology
	Drift Thickness [2]	Drift Thickness[2]

[1] Topographic wetness index was not used as a factor in the LOBS analysis
[2] The drift thickness criteria has different standardization schemes, whereas identical standardization schemes are used for all other factors in both models.

Table 2. Geospatial data sources for the Multi-Criteria Decision Analysis.

Theme	Data File	Spring-related factor	Source	Data type and Resolution
Terrain	Shuttle Radar Topography Mission (SRTM) data	• Slope • Curvature • Topographic wetness index (TWI)	USGS Earth Explorer	• SRTM Raster. • 1-arc second ≈ 24.215 m
Hydrological	BC Freshwater Atlas	• Hydrological features (lakes, rivers, wetlands)	BC Data Catalogue (Ministry of Agriculture and Lands)	• Polygon shapefile
Hydrogeological	Digitized Surficial geology maps	• Surficial geology	Natural Resources Canada (Catto, 1991; Catto & Thirstle, 1993)	• Polygon shapefile • 1:50,000 scale maps
	Modelled Bedrock topography map	• Drift thickness	Ministry of Energy and Mines (Hickin, 2011)	• Gridded raster • 100 m

All of the pre-processing of data and spatial analysis was completed in ESRI ArcGIS v.10.3. Figure 8 shows the processing tools used to calculate the attribute data of the spring-related factors. The Digital Elevation Model (DEM) was downloaded from USGS Earth Explorer, and used to generate: slope; curvature; and topographic wetness index (TWI). Figure 8 shows a flow chart with the steps taken to process these spring-related factors. The Slope and Curvature tools were used to calculate slope and curvature. The Slope tool calculates the first derivative of the DEM to represent the “rate of change of elevation”, while Curvature calculates the second derivative of the DEM to represent the shape of the terrain as concave or convex (ESRI, n.d.; Li et al., 2005). The units of slope and curvature are ° degrees, and 1/100th metre, respectively (ESRI, n.d.). TWI is a secondary terrain factor that indicates the steady state soil wetness (Beven & Kirby, 1979; Schmidt & Persson, 2003). TWI was calculated utilizing Equation 1.

$$Topographic\ Wetness\ Index\ (TWI) = \ln\left(\frac{(a + 1 * cell\ size)}{\tan\beta}\right) \quad [1]$$

where *α* is the cumulative upslope area draining through a point, *cell size* was 24.215 m, and *β* represents the slope in radians units.

The 'proximity to hydrological features' factor was generated with the Euclidean Distance tool, which provides the distance from every cell to the closest hydrological feature (ESRI, n.d.). The hydrological features in the study area were merged from separate shapefiles for rivers, lakes and wetlands from the BC Water Atlas geodatabase.

Digitized surficial geology maps (1:50,000) were downloaded for the study area (Catto, 1991; Catto & Thistle, 1993), and no processing was required for this spring-related factor. Drift thickness was calculated from an interpreted bedrock topography map by Hickin (2011). The bedrock topography map has a resolution of 100 m. The Resample tool was used to change the cell size to match the DEM (~25 m), with a bilinear interpolation, which calculates the new cell value using the distance-weighted value of four nearest cells (ESRI, n.d.). Following this, the bedrock topography was subtracted from the DEM in the Map Algebra tool.

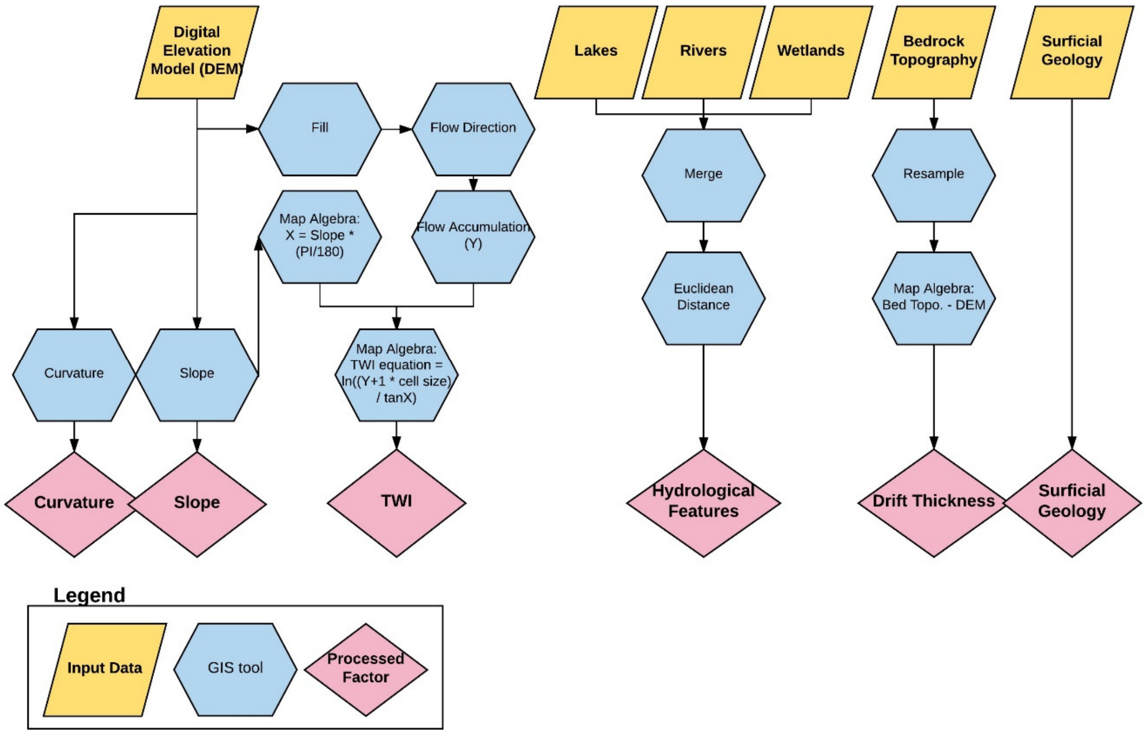

Figure 8. Flowchart showing the processing tools used in ArcGIS to generate the attribute data of the spring-related factors used in the MCDA.

2.3.2 Statistical Frequency Analysis and Standardization Scores

In the GIS attribute data were extracted using the Extract Multi Values Point tool from known spring locations for the following spring-related factors: slope; curvature; proximity to hydrological features; TWI; surficial geology; and drift thickness. These attribute data for the spring-related factors made up the data sets analyzed by descriptive statistics, histogram analysis and t-tests in Microsoft Excel or ‘R’ statistical software. The large dataset of all springs (n=191) in the PRRD was further broken down into the documented springs in the GIS study area (n=121) and, of those, the sampled springs with known groundwater sources (n=36).

The majority of the analyses were completed using all the springs (n=191) in the PRRD to strengthen the analysis. However, only the documented springs in the GIS study area were used for the Likelihood of Occurrence maps due to the limit of the bedrock topography coverage which provided data required to differentiate between Quaternary and Bedrock sourced springs. An exploratory data analysis was completed on all spring data to summarize spring-related factors. Each factor was examined with descriptive statistics (mean, standard deviation, variance, mode, and quantiles) to understand the distribution of the data. Histograms with varying discretization were produced to visually capture trends in the data.

The smaller sub-set of springs with known groundwater source (n=36) were used to investigate differences in trends amongst the Quaternary and Bedrock aquifer sourced springs, respectively. A t-test was used to determine if there is a statistically significant difference in the mean value of factors between Quaternary and Bedrock springs. A Pearson's Chi-square test was conducted on the categorical data (surficial geology) to test if the data are from different distributions.

To calibrate and standardize the data the following process was undertaken. At each spring location the attribute data for each of the spring-related factors was assigned a value between 0 and 100. For data that was continuous, like slope, curvature, proximity to hydrological features, TWI and drift thickness, the discretized ranges described above were assigned values based on the frequency of springs presenting in that data range (Table 3). Generally a value of 100 was assigned to the range with the most springs presenting, a value of 50 for lower frequency ranges and a score of 0 was assigned to ranges of data that did not correspond to spring locations. For example, through the extraction and analysis of the attribute data, it was found that springs occur on an average slope of 8.0°, and the data set in the study area ranges from 0° to 47.6°. Across the PRRD, the slope ranges from 0° to 74.3°. A score of 100 was assigned to the slope ranges of 1.25-30°, and zero to the remainder of the study area. For non-continuous data like the surficial geology factor, scores of 100 were assigned to the materials that the majority of springs occurred within and lower scores were assigned with decreasing frequency of spring occurrence. Table 3 shows the ranges of attribute data for spring-related factors and their associated standardization score.

In the GIS, the attribute data of each spring-related factor was then assigned the corresponding standardized score derived from the factor analysis with the Reclassify tool. The resultant maps and datasets were then used in the MCDA to construct the likelihood for occurrence maps.

Table 3. Standardization scores for all spring-related factors.

Factors Intervals or Categories	All Springs		Quaternary		Bedrock		Standardization Scores	
	Count	%	Count	%	Count	%		
Slope								
0-2.51	4	2	2	14	2	24	0	
2.51-30.0	184	96	19	86	15	76	100	
30.1°+	3	2	0	0	0	0	0	
Curvature								
<-1.5	2	1		0	0	0	0	
-1.51 to -0.5	27	14	2	10	3	18	50	
-0.51 to 0.5	131	69	18	86	14	82	100	
0.51 to 1.5	29	15	1	5	0	0	50	
>1.5	2	1		0	0	0	0	
Proximity to Hydrological Features								
0-900 m	150	79	14	67	14	82	100	
900-1600 m	32	17	5	24	3	18	50	
1600 m +	9	5	2	10	0	0	0	
Topographic Wetness Index								
0-0.3	159	83	18	86	9	53	100	
0.3-0.4	23	12	1	5	6	35	50	
0.4-1.0	9	5%	2	10%	2	12	0	
Surficial Geology							**Quat.**	**Bed.**
Aeolian deposits	3	2	2	10%			25	25
Aeolian veneer	0	0					0	50
Alluvial fan/plain/terrace	27	14	1	5	3	18	100	50
Bedrock	0	0					0	100
Colluvial deposits	17	9	6	29			75	75
Colluvial deposits veneer	8	4					0	100
Glaciofluvial blanket	0	0					100	0
Glaciofluvial fan/hummock./plain/ridge	9	5					75	50
Glaciofluvial veneer	0	0					0	100
Glaciolacustrine blanket	14	7	1	5	1	6	25	0
Glaciolacustrine plain	13	7	2	10	1	6	25	25
Glaciolacustrine veneer	6	3	1	5	1	6	0	50
Organic deposits	0	0					0	0
Till blanket	25	13	3	14	1	6	100	0
Till hummocky/plain/ridges	21	11	5	24	2	12	75	50
Till veneer	48	25			8	47	0	100
Bedrock Depth[1]								**Bed.**
0 to 3 m	47	39			12	71		100
3 to 10 m	13	11			3	18		50
10 m +	61	50			2	12		0

Factors Intervals or Categories	All Springs		Quaternary		Bedrock		Standardization Scores	
Drift Thickness[1]							Quat.	
0 m	32	26	3	14			0	
0 to 10 m	28	23	5	24			50	
10-30 m	36	30	6	29			100	
30 m +	25	21	7	33			0	

[1] Bedrock Depth and Drift Thickness are the same data, with different standardization schemes in the LOQS and LOBS.

2.3.3 Pairwise Comparison Method and the Likelihood of Occurrence for Bedrock or Quaternary Springs (LOBS, LOQS) Equation

The final step in the spatial analysis was construction of a weighted linear equation to identify the likelihood of occurrence for either Bedrock or Quaternary springs. These equations are referred to as the Likelihood of Occurrence for Bedrock Springs (LOBS) or Likelihood of Occurrence for Quaternary Springs (LOQS). The pairwise comparison method was used to determine relative importance of the spring-related factors in the LOBS and LOQS equations. In this method a weighting is given to each pairwise combination of spring-related factors (w_{ij}). Table 4 shows the fundamental scale of absolute numbers used in the matrices. The weighting is then normalized for each factor and the final equation is normalized for the number of factors (Saaty, 1987; Saaty, 1990).

Table 4. Saaty's fundamental scale of absolute numbers for the pairwise comparison method.

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Table from Saaty, 1990.

The LOQS and LOBS equations, are linear weighted equations which evaluate the standardized spring-related factors (Equation 1):

$$LOS = [(w_{x1} * f_{x1})(w_{x2} * f_{x2})(w_{x3} * f_{x3})(w_{x4} * f_{x4})] \quad [1]$$

where, w_{xi} is the calculated weight from the pairwise comparison, and f_{xi} are the standardized spring-related factors. The GIS produced two raster maps with a Likelihood score in each cell, ranging from 0 to 100 indicating the LOBS or LOQS. Each LOS map was multiplied by constraints to cancel out cells wherein springs could not occur. The constraints were additional geospatial layers that consist of roads, hydrological features like lakes, wetlands, rivers and streams and land-use included urban areas, mines and recreational areas. The output LOS maps were classified into five categories based on the Likelihood scores: 0-25 (Very Low); 25-50 (Low); 50-75 (Moderate); 75-90 (High); and 90-100 (Very High). The LOS maps were evaluated on a local scale for individual springs. The Likelihood score at each spring location from the LOS maps was compared, and the higher score in either LOBS or LOQS map is believed to indicate the type of groundwater source to feed a spring (Bedrock or Quaternary). The sub-set of springs with known groundwater source (n=36) were used to verify the maps, to see if the groundwater source matched the comparison of LOQS and LOBS maps.

2.4 SPRING SOURCE AREA DELINEATION

The spring source area delineation (SSAD) was completed in ESRI ArcMap 10.3. The source areas for the springs were initially defined using the Watershed Tool in ArcGIS. The Watershed Tool captures the area that is upslope and contributes to drainage to the location selected by the tool. The method is considered to be applicable for an approximation of the spring source area, because in the study area the water table in unconfined aquifers typically mimics the ground surface (Baye et al., 2016; Lowen, 2011). The SSAs delineated from this technique are approximate extents that are topographically derived and they estimate a local area which potentially contributes recharge to the spring due to direct infiltration of precipitation or snowmelt. These SSAs do not take into account large scale regional groundwater flow systems.

The following lists the steps undertaken to generate spring source areas, which are also shown in Figure 9. Table 5 shows the geospatial data used.

- The DEM and resampled bedrock topography were used to generate *Flow Direction* rasters. The output raster shows the flow direction from each cell to its steepest downslope neighbour;
- The *Flow Direction* rasters were used to generate *Flow Accumulation* rasters, where the output shows the accumulated flow to each cell;
- GPS spring coordinates were used to determine pour points to be input into the *Watershed* tool. The tool identifies a cell with the highest *Flow Accumulation* within a specified distance. A distance of 100 m and 300 m were used for Quaternary sourced springs and Bedrock sourced springs, respectively;
- The *Watershed* tool, which determines the contributing area above a set of cells in a raster, was utilized to determine spring source areas. This step was completed twice; once using the GPS coordinates of the spring area and second with a pour point. This step was conducted twice because in many cases the GPS spring location did not fall in a cell with a large flow accumulation and the result was a small SSA. Using the pour point typically generated larger SSA that encompassed the spring location and is believed to be representative.
    - Specifically for Bedrock sourced springs, the *Watershed* tool was run with both DEM and bedrock topography, producing up to four source areas.
    - For Quaternary sourced springs only the DEM was used.

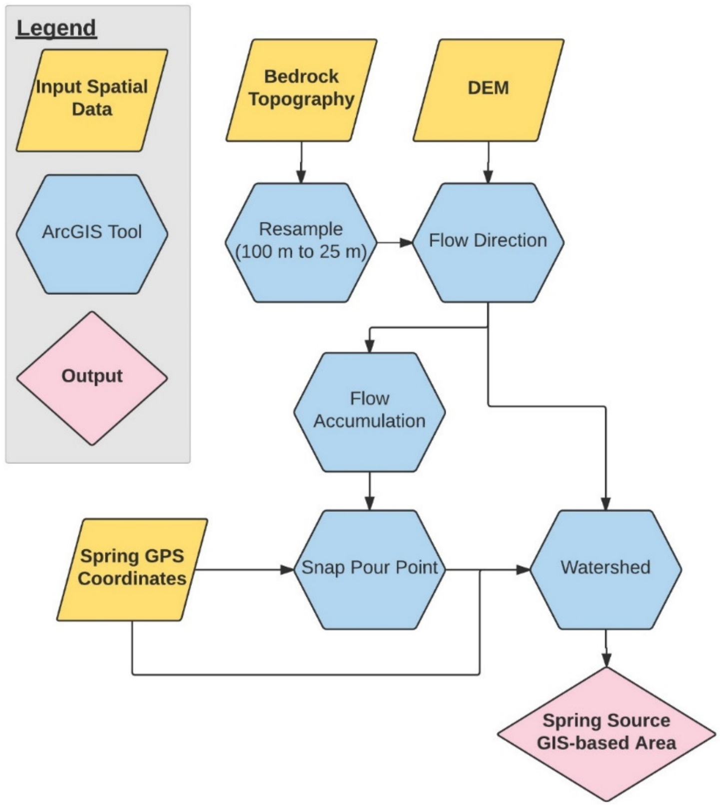

Figure 9. Flowchart showing processing tools used in ArcGIS to delineate GIS-based spring source areas.

Table 5. Geospatial data sources for spring source area delineation (SSAD).

Data File	Source	Resolution
Spring locations	Licensed springs (BC Data Catalogue) and field work for this study	±1 m for GPS coordinates
DEM	USGS Earth Explorer	Raster; 25 m resolution from SRTM 1-arc second
Modelled bedrock topography	Ministry of Energy and Mines (Hickin, 2011)	Raster; 100 m *resampled to match the DEM resolution

3 RESULTS

3.1 SPRING HYDROGEOCHEMISTRY

The field parameters and analytical results for 36 sampled springs are shown in the Appendix. The temperature of the spring waters ranged from 0.4 to 11.6℃ (average temperature was 6.4 ± 2.6℃), pH varied from 4.19 to 9.09 (average pH of 7.19 ± 0.7) and electrical conductivity (EC) of the spring waters ranged from 100 to 4449 μS/cm. Dissolved oxygen (DO) showed significant variation with values as low as 0.08 mg/L up to 11.53 mg/L (average DO was 4.0 ± 3.9 mg/L). Oxidation-reduction potential (ORP) ranged from -109 to 263 mV.

The water types ranged from Ca-HCO_3 and Ca-Mg-HCO_3 types to Ca-Mg-SO_4 and Na-HCO_3 to Na-HCO_3-SO_4 types. The Quaternary and Bedrock groundwater descriptions by Kirste (2016) were used to group springs. From the 36 springs with known groundwater composition, 22 were found to suggest a Quaternary source and 14 suggest a Bedrock source. Na-rich groundwater is typical of Bedrock-sourced groundwater, and tritium content greater than 1 TU is typical of Quaternary-sourced groundwater. Five springs contained both characteristics, likely representing mixed bedrock and Quaternary sourced water.

3.2 LIKELIHOOD OF OCCURRENCE FOR SPRINGS

The Multi-criteria decision analysis was used to produce two maps showing the Likelihood of Occurrence for Springs (LOS). A total of 9.5% and 5.8% of the study area scored in the highest likelihood for occurrence of Quaternary and Bedrock springs, respectively (Table 6). The highest scoring areas for Quaternary springs are along river valleys, scattered areas in the uplands between Hudson's Hope, Chetwynd and Dawson Creek, as well as the north-east and north-west corner of the study area north of the Peace River (Figure 10). On the other hand, the highest scoring areas for Bedrock springs are north of the Peace River, west of Fort St. John, and scattered throughout the study area south of the Peace River where there is relatively thin till deposits overlying the bedrock (Figure 11).

Of the 121 springs in the study area, the scores for all of the springs both in terms of LOQS and LOBS are shown in Table 6. Just under 50 % of the springs scored higher than 75 for Quaternary sourced versus only 36 % for bedrock sourced. However for the springs that scored higher for Quaternary sourced, 70.5 % had scores higher than 75 and 71.7 % of the springs that scored higher for a bedrock source had scores greater than 75. Of the springs that scored higher for LOQS the median score was 82.3 and for those that scored higher for LOBS, the median was 82.8. This indicates that the ranking system and the MCDA were effective in identifying areas that have springs and suggests that those areas ranking higher on the maps have higher potential for springs to occur.

Table 6. **Regional scores for the likelihood of occurrence for both Quaternary and Bedrock sourced springs. The columns for Higher Quaternary or Bedrock Score are for springs that scored higher for the one over the other only**

Likelihood Category	Score Range	Quaternary MCDA					Bedrock MCDA				
		Area (%)	Area (km^2)	All Springs	Higher Quaternary Score	Quaternary	Area (%)	Area (km^2)	All Springs	Higher Bedrock Score	Bedrock
None	0	7.6	98,721	0	0	0	7.6	98,721	0	0	0
Very Low	0-25	0.1	1,222	0	0	0	1.8	23,776	2	0	0
Low	25-50	5.7	73,732	7	3	1	32.6	421,945	27	2	2
Moderate	50-75	49.1	635,576	54	17	8	41.8	540,876	48	13	3
High	75-90	27.9	360,821	37	25	6	10.3	132,976	26	25	5
Very High	90-100	9.5	123,073	23	23	5	5.8	74,851	18	13	3

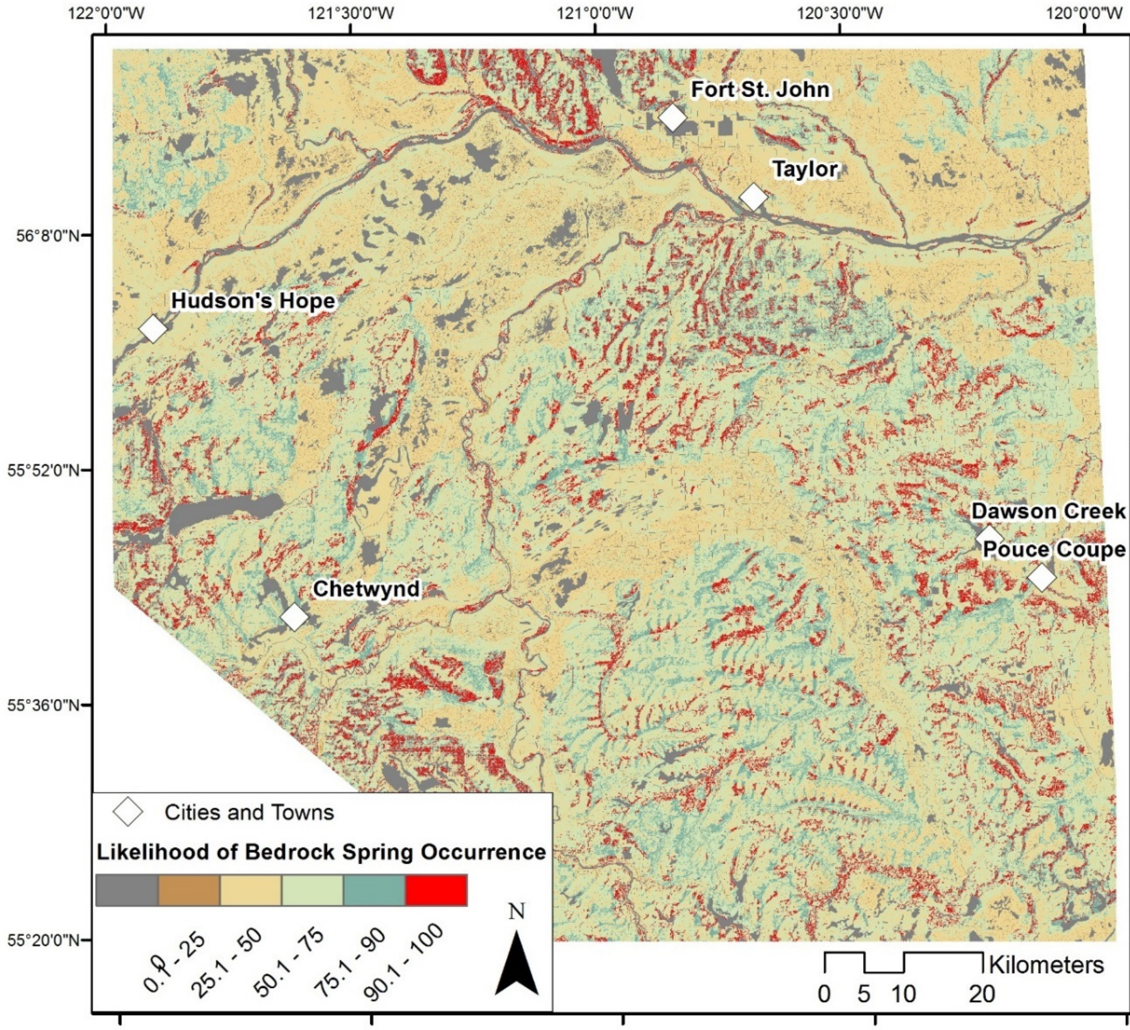

Figure 10. **Likelihood of Occurrence for Bedrock sourced springs (LOBS).**

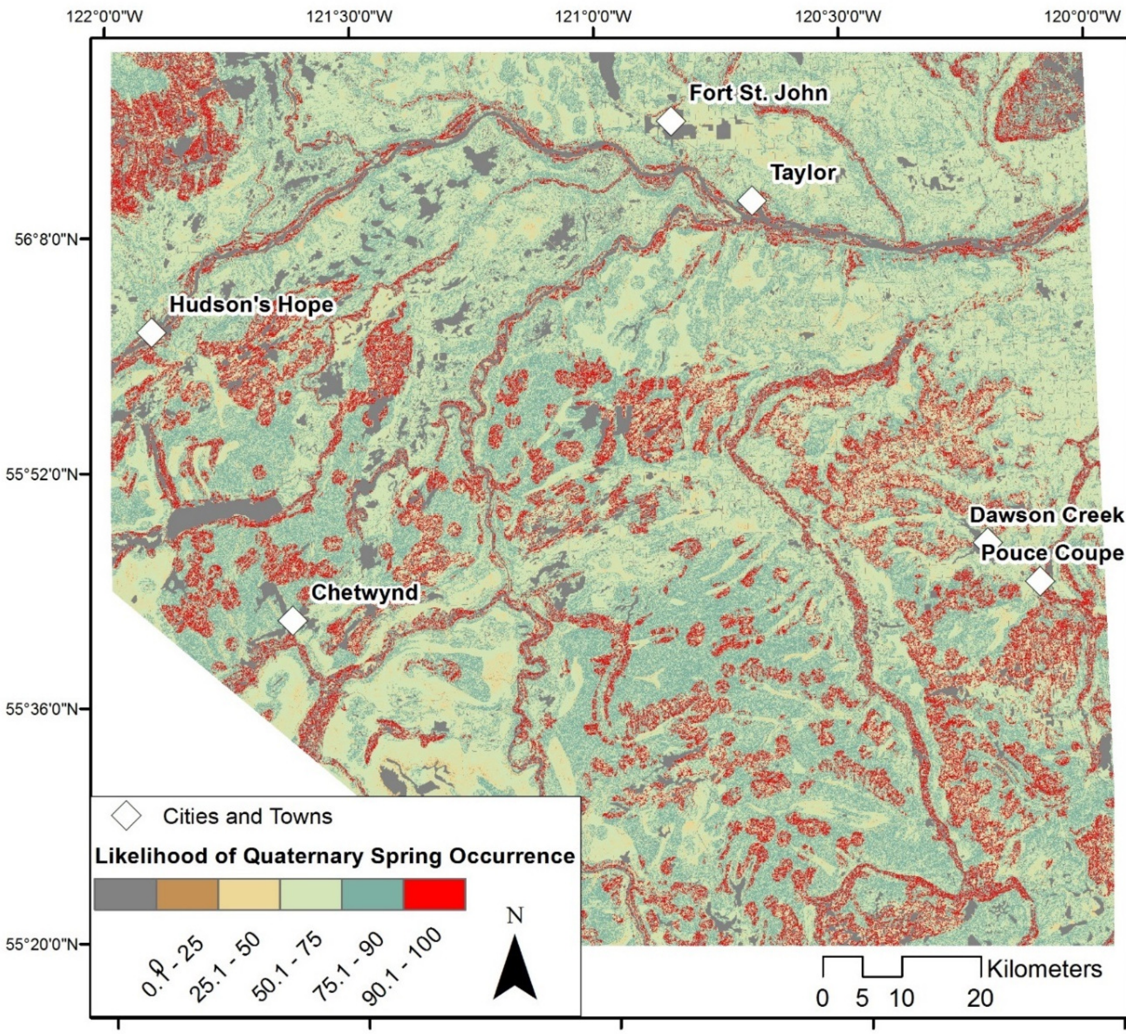

Figure 11. Likelihood of Occurrence for Quaternary sourced springs.

Likelihood of occurrence for springs scores (LOQS and LOBS) are normally distributed, if the zero value is ignored (Figure 12). The average score, excluding zero values are 70.2±14.6 and 56.5±19.3 in the LOQS and LOBS maps, respectively. There is more land area found in the Very High Likelihood category for Quaternary Springs, and the average map score is higher than Bedrock Springs (Figure 10). The LOBS and LOQS maps were also validated using just the 36 springs with known groundwater sources. The success rate for identifying Quaternary and Bedrock springs was 73% (16/22) and 71% (10/14), respectively. This success rate indicates that the Likelihood of Occurrence for Springs MCDA equations were capable of identifying the correct type of spring. For the correctly identified 16 Quaternary and 10 Bedrock springs, the average Likelihood score was 79.6 and 86.6, respectively. In the Appendix, Table A4 lists all of the Likelihood scores for every spring in the GIS study area.

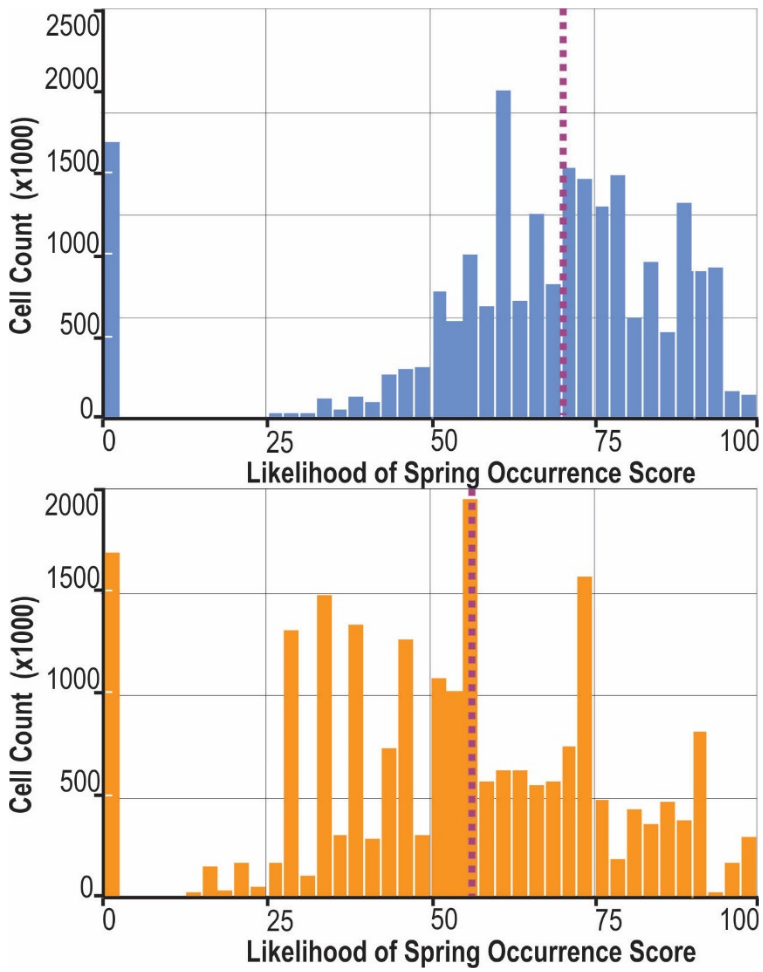

Figure 12. Distribution of scores for all springs in LOQS (top) and LOBS (bottom) across the maps, with the mean map score marked by the dashed line.

3.3 Spring Source Area Delineation

A GIS-based spring source area delineation technique was carried out for all of the sampled springs. The spring source areas that were derived with the Watershed tool are referred to as 'GIS-SSA'. The GIS-SSA are approximate extents derived mainly using the ground surface and bedrock surface topography and may be refined when additional geological or groundwater information is obtained. In addition to the topography based spring source area technique, the methodology of Kreye et al. (1996) which involves verifying these GIS-SSA with calculated SSAs based on a simple water balance was carried out for 5 springs but the results of this are not included in this report. The following sections provide examples of how the GIS-SSA method was applied and the results for 9 springs are detailed. The full set of GIS-SSA's can be found as shape files in the data store.

3.3.1 **Springs #3, #4 and #22**

Along the Pine River, there are three documented non-licensed springs providing water for domestic and livestock purposes. This SSA investigation focused on the main spring (Spring #3) which is developed, while the two additional springs (#4 and #22) on the property occur as natural springs. Spring #3 is found at a 566 m elevation on a south-easterly hillslope about midslope between a terrace and plateau, and Spring #4 is at 451 m elevation on the edge of a terrace below the main spring. Spring #22 is found towards the west of the main spring, at an elevation of 443 m, at the headwaters of a small creek in a small ravine. The surficial geology in the area consists of colluvium along the Pine River valley walls, and alluvial terraces. In the lower reaches just above the lower terrace near the River, there are areas with exposed glacial drift overlying shale indicating bedrock is present in the valley. There is limited groundwater data in this area, with no mapped aquifers or wells with water table levels.

Spring source area delineation

The GIS-SSA for the three springs are shown in Figure 13. Spring #3 had the smallest area, 0.04 km^2, while Spring #4 had the largest area (1.20 km^2). The NEWT derived River watersheds are also shown and the GIS-SSAs align partially, which would be expected as they are also derived based on topography. Springs #3 and #4 have chemical compositions typical of Quaternary sourced groundwater, while the chemical composition of Spring #22 indicates mixed groundwater. The GIS-SSA for Spring #22 overlaps with Spring #3's, which supports that Spring #22 may be mixed. The GIS-SSA that are identified are local SSAs, and it is possible that the Worth Marsh may recharge the groundwater system, but testing this hypothesis was beyond the scope of the project.

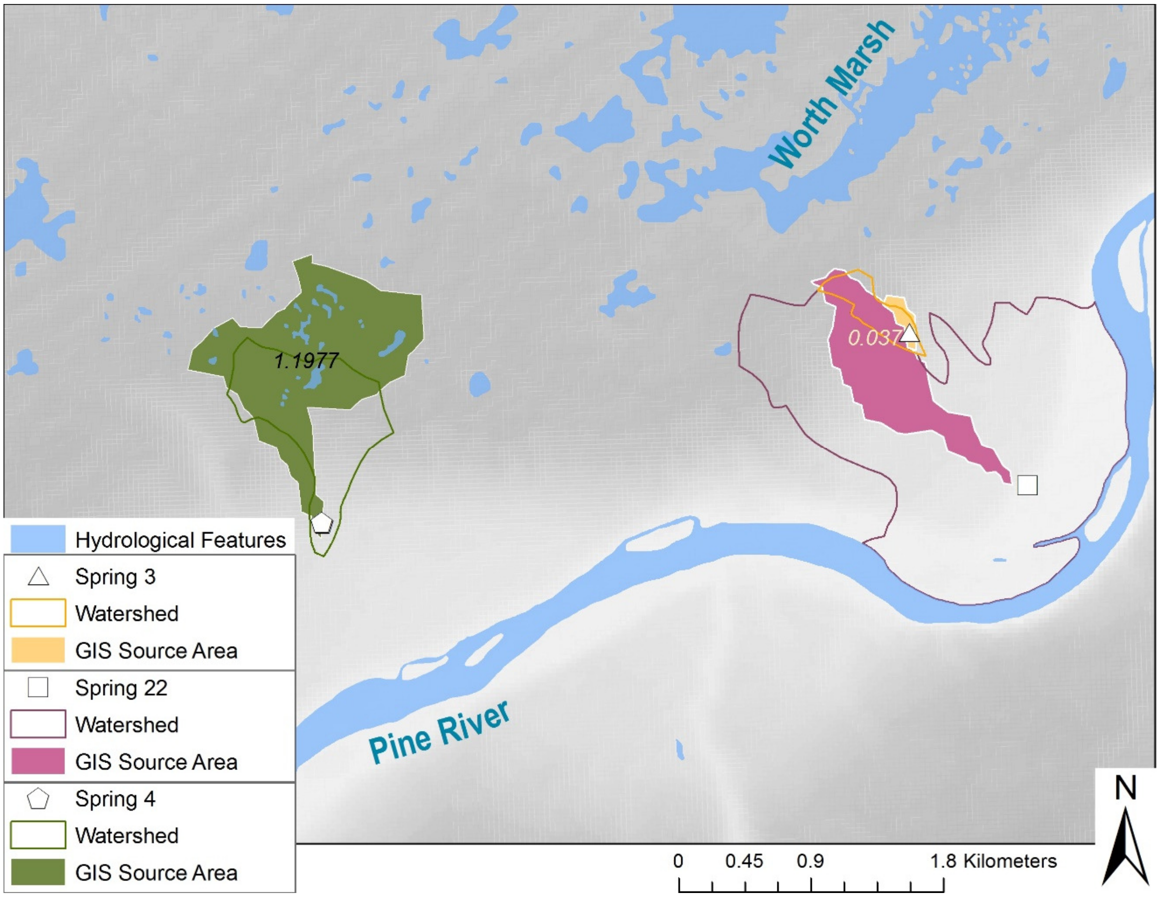

Figure 13. GIS-based spring source areas and Northeast Water Tool (NEWT) derived River watersheds for Springs #3, 4 and 22.
The number values are the calculated GIS-based source area's (km^2) corresponding to each spring.

3.3.2 **Spring #12 and #14**

Spring #12 was licensed in 1987 for waterworks purposes, and currently, the spring's licensed status is abandoned due to contamination (MFLNRO, 2011; J. Ron, 2015 (personal communication)). Spring #14 is an active licensed public water supply since 1978 (MFLNRO, 2011). Springs #12 and #14 are located at elevations of 706 m and 699 m, respectively, in an area of fairly low relief surrounded by wetlands. Surficial geology maps show the springs occur near the edge of till blanket sediments next to a glaciolacustrine blanket. Drift thickness at these spring locations was calculated to range from 16 – 22 m. The source area for Spring #14 was investigated previously by Lebedin (1990) and Cowen (2003) and they are shown in Figure 14. The spring source area was described to be "uplands adjacent to the spring consisting of (1-4 m^{-1}) thick glaciofluvial sands and gravels, overlying very thin, to patchy extremely stony till" (Lebedin, 1990).

Spring source area delineation

The GIS-SSAs for the two springs are shown in Figure 14 with the respective NEWT derived River watersheds. There are two watersheds for Spring #14 because the generated SSA clearly crossed both watersheds. The GIS-SSAs were calculated to be 0.02 km^2 and 0.24 km^2 for Springs #12 and #14, respectively. The GIS-SSA for Spring #14 is smaller when compared to the SSA from Lebedin (1990) and Cowen (2003). However, their method was more generic and did not rely on the detailed surface topography so is expected to differ from these estimates. The GIS-SSA of Spring #12 is much smaller and appears to be limited by the relatively low relief resulting in the GIS tool to be incapable of differentiating any topographical divide. This is a case where additional geological information can be used to modify the GIS-SSA and decrease the uncertainty. In addition the wetlands up-gradient from the springs can potentially be a source of recharge to the groundwater system and because the low relief impacts the GIS method, they are not taken into account.

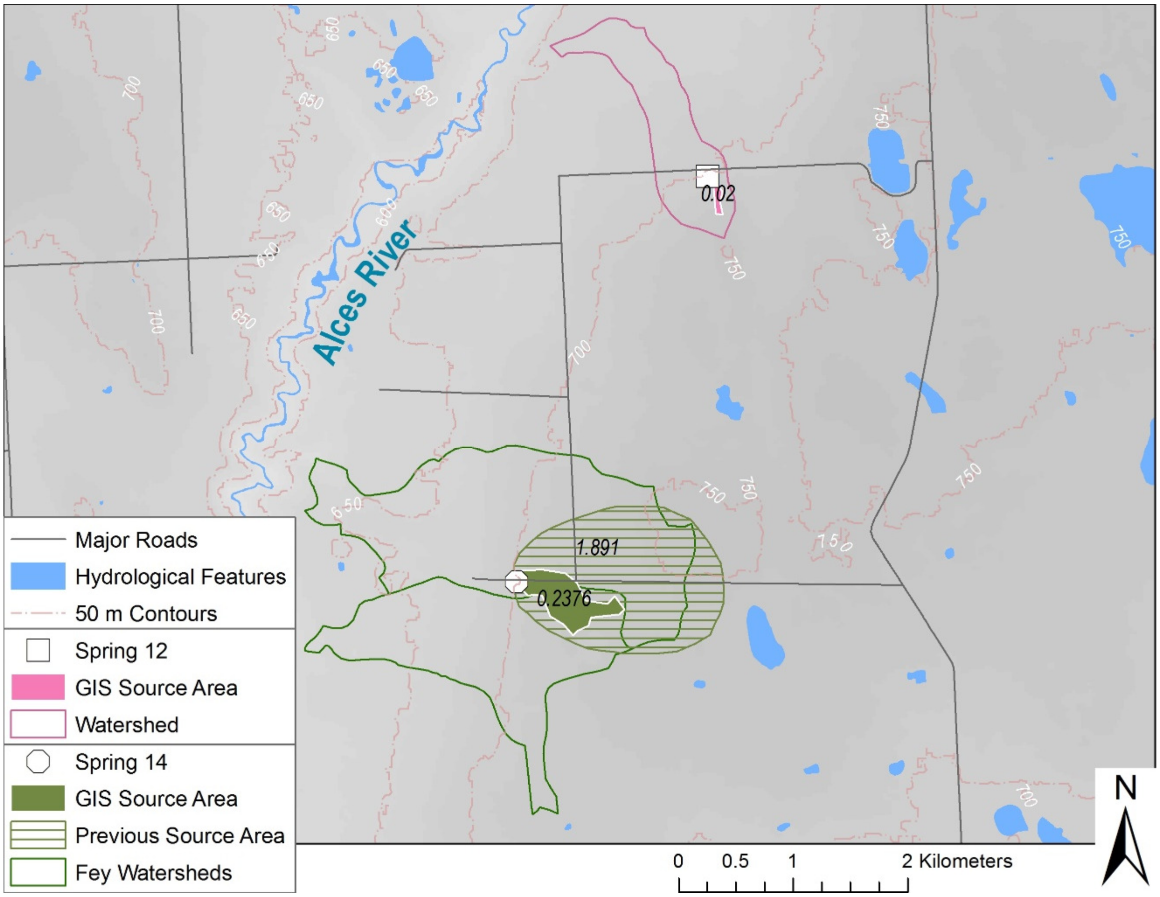

Figure 14. GIS-based spring source areas and NEWT derived River watersheds for Springs #12 and #14 including the previously determined source area for Spring #14.

3.3.3 **Spring #5**

Spring #5 has two licenses associated with this single spring, one has been active since 1985 for domestic purposes. The second license was issued for stockwatering in 1987 and was canceled in 1991 (MFLNRO, 2011). The spring is located at an elevation of 745 m, and the regional terrain gradually slopes down northeastward. The surficial geology surrounding the spring is mapped as till ridges, with alluvial sediments towards Pouce Coupe River. Groundwater well records from the area (within a 3.5 km radius) indicate clay sediments overlying sandy sediments over shale and sandstone (BC Ministry of Environment, 2016). This suggests there could be a confining layer over top of the Quaternary or Bedrock aquifers. Spring #5 is located within 500 m of the mapped bedrock geological contact between the Kaskapau and Cardium Formations of the Smokey Group, and the Lower Puskwaskau/Muskiki Formation. Springs have been reported to discharge from the Kaskapau Formation by Mathews (1950). The drift thickness in the vicinity of the spring is calculated to be 32 m, which decreases to ~5 m near the bedrock contact 500 m towards the west. The spring water geochemistry indicates Quaternary sourced groundwater that was recharged before the 1960's tritium bomb peak.

Spring source area delineation

The GIS-SSA for Spring #5 was calculated to be 1.0 km^2 (Figure 15). This GIS-SSA extends to the local topographic high northwest of the spring up to an elevation of ~825 m. The GIS-SSA compares well with the river watershed, and extends further upslope to the local topographic high. However, considering the drift thickness pinches out at ~ 500 m west of the spring, this could mark the extent of the aquifer feeding the spring unless there is a bedrock aquifer bringing water from further upslope. The relatively long residence time for this spring indicates this may be possible. The 500 m radius may be used to modify the GIS-SSA, as giving the localized SSA shown on Figure 15.

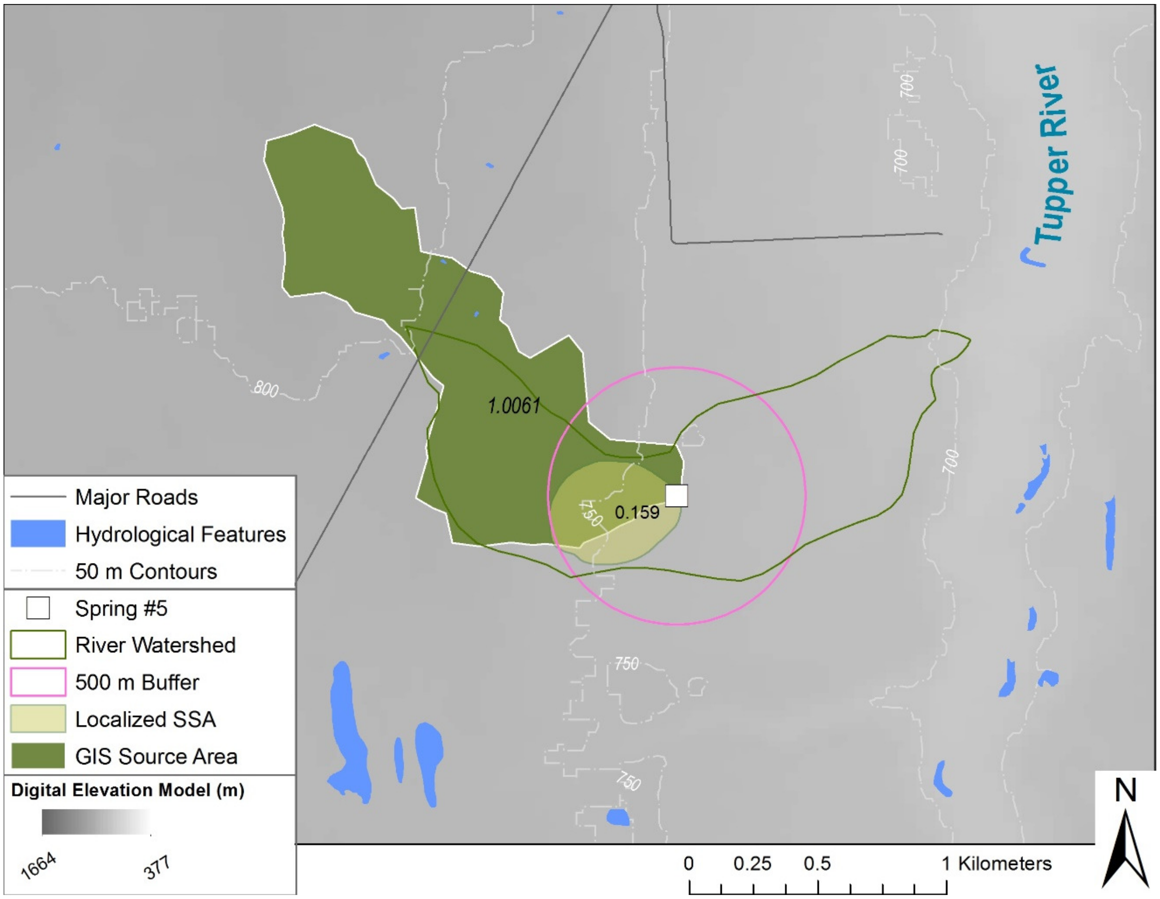

Figure 15. GIS-based spring source area, NEWT derived River watershed and localized SSA for Spring #5.

3.3.4 **Spring #23**

Spring #23 is an unlicensed spring located south-southeast of Taylor. The spring has been developed into a pump house, with an outflow pipe discharging into a water storage dugout. The landscape surrounding the spring is rolling, and the spring is found on a gentle slope, midslope at an elevation of 767 m. Surficial geology mapping shows the spring is in an area of till veneer that is thin and discontinuous. Spring #23 is mapped in the Dunvegan Formation, a coarse clastic sandstone, which is recognized as the regional bedrock aquifer (Lowen, 2011; Riddell, 2012). The drift thickness in the vicinity of the spring was calculated to be very thin, ~4 m. The spring has a chemical composition which strongly indicates a bedrock origin. The tritium content is below detection and the carbon-14 results indicate older groundwater (50 years+). The spring is on the north side of the Kiskatinaw River where Baye et al.'s (2016) groundwater potentiometric surface shows that the groundwater flow is south towards the river.

Spring source area delineation

Two small GIS-SSAs were generated using the digital elevation model and bedrock topography. The DEM GIS-SSA was 0.008 km^2, whereas the Bedrock-GIS-SSA was 0.021 km^2 (Figure 16). Additional SSAs were generated using the spring location and a 300 m pour point. The SSAs generated with the 300 m pour point are larger and extend further to the northwest, towards the topographic high.

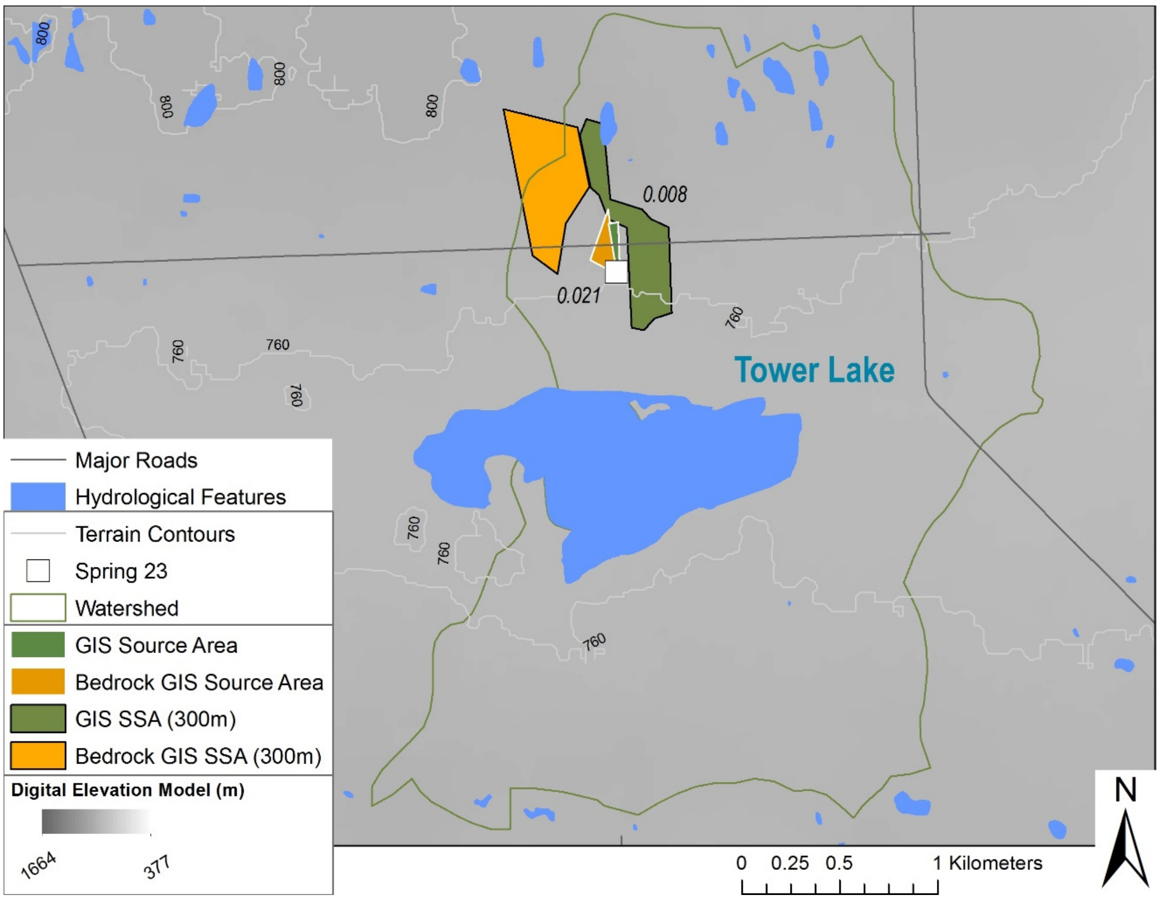

Figure 16. GIS-based spring source area and NEWT derived River watershed for Spring #23.

3.3.5 **Spring #29 and #30**

Spring #29 was licensed in 2001 for domestic use. Spring #29 is at an elevation of 760 m, located at near the top of a hill, on a northeast-facing slope. The natural location of the spring is unknown but the land owner describes it to be in this area. Spring #30 is found on the other side of this valley and closer to the bottom at 707 m, on a steeper south-southwest slope. In the middle of this valley, there is a wetland and river system flowing north-south. The surrounding area has thin discontinuous till veneers overlying the Dunvegan Formation. The drift thickness was calculated to be very thin to exposed bedrock in the valley with drift thickness increasing in local topographic highs.

There are three springs on the western valley wall 1-2 km south of Spring #29. These springs are found in a similar elevation range (710-769 m) as Springs #29 and #30. Also, there is a groundwater well in the valley between Springs #29 and #30, where depth to water was recorded to be ~20 m below ground surface with an estimated flow rate of 0.16 L/s (2.5 Gal/min) (BC Ministry of Environment, 2016). There are several additional groundwater wells upslope of Spring #29, where the groundwater level is approximately similar to the elevation of Spring #29 and the other springs on the same side of the valley.

Spring #29 has a Na-HCO_3 water type with low tritium, whereas Spring #30 shows signs of fresher water with moderate tritium. The compositions suggest a bedrock aquifer origin, although Spring #30 is possibly mixed or contains some younger recharge.

Spring source area delineation

The GIS-SSAs for Springs #29 and #30 are shown in Figure 17. Only the GIS-SSAs with 300 m pour points are shown because the GIS-SSAs with spring locations were only 1-2 cells in size which suggests some issue with the surface roughness of the topography in the DEM. This can lead to very small local highs that limit the GIS Watershed tool method unless larger pour points are used. The GIS-SSA for Spring #29 using the DEM and bedrock topography are approximately the same size, ranging 0.58 to 0.70 km^2. Neither captures the exact spring location, but both methods suggest the SSA for Spring #29 extends towards the topographic high in the southwest direction. The GIS-SSAs for Spring #30 are significantly larger, ranging 3.4 to 3.6 km^2. The GIS-SSA with the pour point begin in the valley where there is a wetland for Wilder Creek and extends upstream and upslope to the topographic highs. The SSA derived with the DEM extends up the western slope, whereas the SSA derived with the bedrock topography extends up the eastern hill. The presence of the spring on the eastern side of the valley and the SSA on the west suggests that the DEM SSA has poor resolution in the flat base of the valley. The eastern slope is likely the dominant source area for this spring as indicated by the bedrock aquifer type composition and the bedrock topography based SSA.

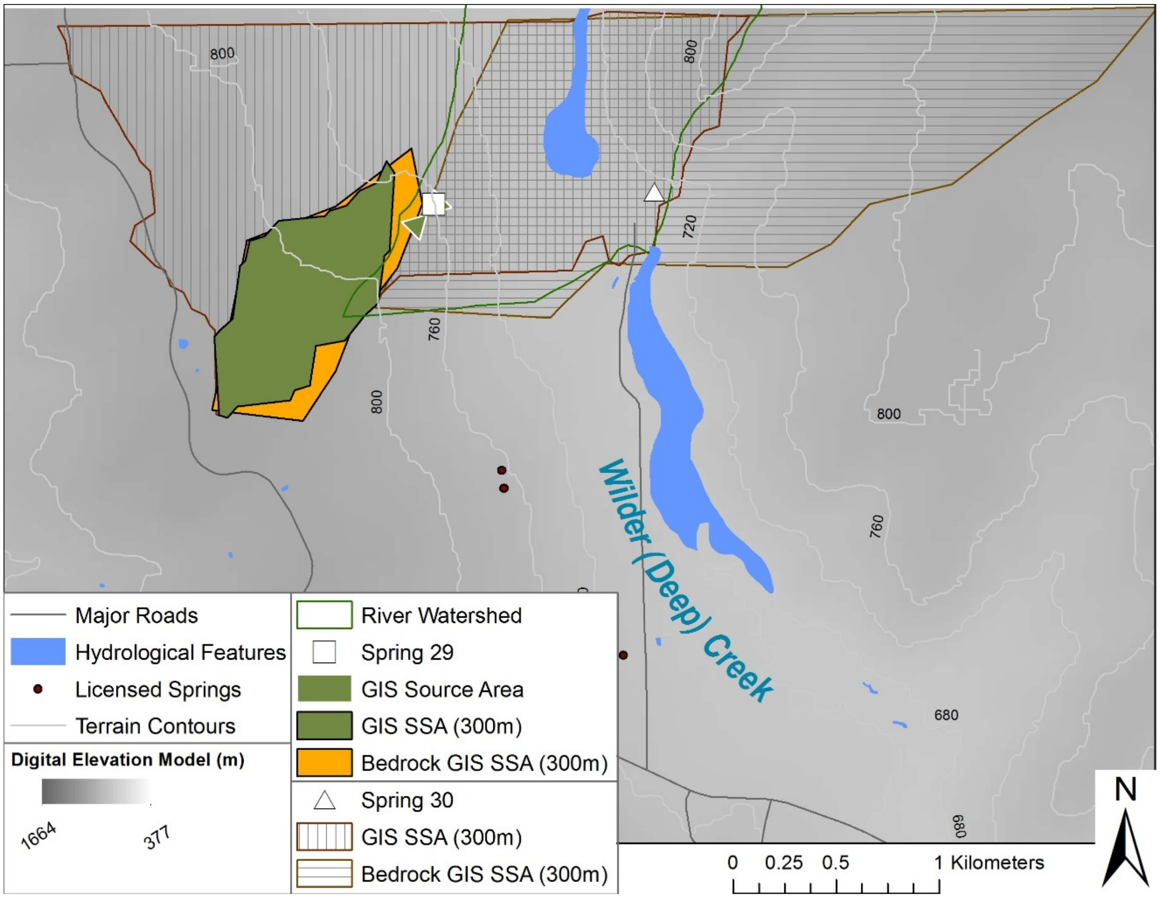

Figure 17. GIS-based spring source area for Springs #29 and #30.

4 DISCUSSION

4.1 EVALUATION OF THE MCDA RESULTS AND RECOMMENDATIONS

Important Factors in Spring Occurrence Mapping

Springs are an important water resource in NEBC and private and industry requirements for water as well as land has resulted in increasing demand for understanding the resource and its management. Being able to recognize where springs may occur is an important part of planning development in a way that is sensitive to needs of the different stakeholders. In this study, a GIS based technique utilizing available data sets was used to delineate areas that present a higher likelihood of occurrence for springs and to identify the potential source areas of the springs. The GIS technique allows for a large region to be characterized. In any areas identified to have an increased potential for springs further evaluation in greater detail and at a scale appropriate to the requirements of the investigation can be conducted. The MCDA method used to identify areas where springs are likely to occur resulted in 2 maps that show the likelihood of occurrence for Quaternary and Bedrock sourced springs in a region of the Peace River Regional District.

Overall the factors that were most important in determining where springs occur in the NEBC setting included: slope; curvature; proximity to hydrologic features; topographic wetness index; surficial geology, and; drift thickness. These data were extracted for a number of known spring locations and the MCDA was used to formulate weighted equations that scored the potential for a location to have a spring present. Most of the data was derived from standard datasets like the DEM, surficial geology map polygons and surface water polygons. The unique data set for the region is the bedrock topography map. The bedrock topography allowed the calculation of data on the thickness of overlying Quaternary sediments. These data were critical in enabling the differentiation of areas likely to present Quaternary sourced versus Bedrock sourced springs.

Based on the analysis of the results for known spring locations, the MCDA was satisfactory in identifying the potential for spring occurrence. In particular the median scores of known springs when separated into higher scoring for either Quaternary or Bedrock sourced were very high (82.3 and 82.8 respectively). These high median scores indicate that the method captures most of the known springs and would perform well for identifying areas with high potential for springs to occur, either bedrock or Quaternary sourced. A relatively large proportion of the study area had scores indicating a high potential for springs (37.1 % and 16.1 % of the land area for Quaternary and Bedrock sourced respectively). While the number for Quaternary is particularly high, the nature of the landscape, particularly the incised valleys of the rivers and streams plays a significant role in controlling the magnitude of that number. Additional data that could help differentiate the higher scoring areas is a map of the water table. Even if only applied in smaller areas where greater confidence in the distribution of the water table exists, the spring potential could be significantly refined.

The GIS-based MCDA method in this study was unique because it is the first application of MCDA for spring mapping. The MCDA approach in combination with GIS has been used in other hydrogeological studies such as predicting groundwater resource potential (Adiat et al., 2012; Fenta et al., 2015; Rahmati et al., 2015) and recharge zone mapping (Chenini, et al., 2010; Kumar et al., 2016). In these studies the analytical hierarchy process of the MCDA was identified as a potential source of uncertainty because of the requirement of 'expert' analysis of the relative weighting of the criteria. To reduce this uncertainty, a sensitivity analysis is advised. In this study, the weighting for the different factors was varied and the resultant scores for individual springs were compared to determine the best weighting scheme. The final weighting used was the combination that resulted in the highest median scores for the known springs.

Ozdemir (2011) mapped spring occurrence with a GIS-based statistical model, identifing geology and drainage density as the two most influential factors for spring occurrence. Another GIS-based statistical modelling study for spring occurrence, found that slope aspect, followed by land use and lithology were the most influential factors (Pourtaghi & Pourghasemi, 2014). A third study which also applied GIS-based statistical modelling did not identify the most influential factors, but the factors with the highest frequency ratios were short slope lengths, high topographic wetness index, proximity to roads and slope ranging from 20-30° degrees (Moghaddam, et al., 2013). In this study, the most important factors based on the MCDA weighting were curvature, drift thickness, surficial geology and slope. Due to the difference in methodologies and environments, the results of the different studies cannot be easily compared, but nevertheless it shows that the various environments have unique dominant factors and that, in general, a variety of factors can contribute to springs occurrence.

Uncertainty and Limitations in the MCDA

In the statistical analysis, a data set of 191 springs, of which 121 were within the area covered by the bedrock topography dataset including 36 that were sampled and analyzed for chemical and isotopic composition, was used to evaluate trends in spring factors. Thereafter, the subset was used to verify the MCA results and factor sensitivity results. The springs were lumped into a Bedrock or Quaternary sourced grouping based on their geochemical and isotopic signatures; however, in the PRRD there are two types of aquifers and mixing between the two aquifers is possible (Kirste, 2017 in Baye et al., 2017). Groundwater mixing was not determined in this study, but it is hypothesized that some of the identified springs are made up of mixed groundwaters and consequentially express mixed physical factors and lower scores.

The biggest limitation of the MCDA methodology is the flexibility of the data input and set-up which may bias the MCDA results (Knudby, 2015). Steps were taken throughout the methodology to ensure the lowest level of bias. Statistics were used to find trends in the data and derive standardization score intervals; this ensured the intervals were quantitative, where possible. There is also uncertainty in the calculated weights from the pairwise comparison. The weights chosen conformed to what was observed in the majority of spring locations.

The uncontrollable limitations in the MCDA methodology include the input data resolution and inherent uncertainty in the data. All of the input geospatial data were processed to equal resolution of the DEM (24.215 m). Features that present at a finer resolution could not be considered. In addition, the drift thickness was resampled down to the 24.215 m resolution from 100 m, introducing error into the data layer. The DEM is at a sufficient resolution for regional studies, as in this study. However, springs are metre-scale features and the details of spring features are not as precise. The inherent data uncertainty exists in these data sets as incorrectly identified geological materials, digitizing errors, and calculated factors such as TWI and drift thickness.

4.2 Evaluation of GIS-Based Spring Source Area Delineation

The SSA delineation technique is a desktop approach that provides approximations of SSAs. The use of the technique is reasonable in cases where topographically driven groundwater flow can be inferred. However, this application does not consider geological heterogeneities which can affect groundwater flow toward springs and final SSAs. The method utilizes the GIS tools that identify surface flow paths for water and applies these to define the source area for recharge that can discharge as a spring. This is a refinement of methods that relied on topographic groundwater divides (Kreye et al., 1996) or the arbitrary application of a zone of some radius surrounding the spring location.

The GIS-SSA technique provided SSAs that should be applied with a note of caution. Springs exist as a combination of topographic, geologic and climatic factors (Alfaro & Wallace, 1994), and in a few cases it was concluded that additional data needs to be integrated to further refine the SSA. Springs #12 and #5 are examples where topography alone cannot define the SSA, as the GIS-SSA was under- and over-estimated, respectively. Once geological data were considered and the SSA was refined and the confidence in the SSA extents increased.

Although both GIS-SSA for Quaternary and Bedrock springs require further refinement, there is higher confidence in the Quaternary SSAs than the Bedrock SSAs. The GIS-SSAs derived using Bedrock topography provide good insight into the possible source areas, however the 100 m resolution of the bedrock topography map is problematic and a source of uncertainty. As can be seen in the Spring #23 case study, the Bedrock GIS-SSA did not encompass the spring location, and this could be attributed to the data resolution. The conclusion is that the GIS-SSAs are currently approximate extents derived mainly on topography and should be refined when additional information is obtained. Aquifer mapping and groundwater potentiometric surfaces are examples of two valuable datasets that could improve the SSA extents, because they could confirm known extents of aquifers and groundwater flow direction.

5 CONCLUSIONS

There is no dominant factor that determines spring occurrence, but rather a combination of geological, topographical and hydrogeological characteristics can influence spring occurrence (Borneuf, 1984; Alfaro and Wallace, 1994). Based on a review of the literature and spring classification systems, terrain and hydrogeological characteristics are likely the two most dominant influences for spring occurrence.

In this study, a GIS-based multi-criteria decision analysis was completed to generate Likelihood of Occurrence for Bedrock Springs (LOBS) and Likelihood of Occurrence for Quaternary Springs (LOQS) in the Peace River Region District. First, spring water samples were collected and analyzed for major, minor and trace elements, stable isotopes ($\delta^{18}O$, $\delta^{2}H$), $\delta^{13}C_{DIC}$, $\delta^{14}C$ and tritium (^{3}H). The geochemistry and isotopic composition of springs was used to group springs into Bedrock or Quaternary sourced and develop a subset of springs with known groundwater sources (n=36), which was used to verify the LOBS and LOQS maps. For the MCDA, the spring-related factors used were: slope, curvature, proximity to hydrological features and topographic wetness index, surficial geology and drift thickness. The geospatial data for these spring-related factors was statistically analyzed to identify characteristic traits of springs, which was used in standardizing the data. A pairwise comparison was completed to derive spring-related factor weights, which were used to integrate the standardized factors using a weighted linear equation to produce LOBS and LOQS maps. A pairwise comparison was completed to derive spring-related factor weights, which were used to integrate the standardized factors using a weighted linear equation to produce LOBS and LOQS maps. These maps show that 8% and 5.2% of the area has a very high likelihood of occurrence for Quaternary and Bedrock springs, respectively. The subset of sampled springs verified the maps with a success rate with a 76% (16/21) and 67% (10/15), success rate for Quaternary and Bedrock sourced springs, respectively. Overall, the MCDA approach was found to be an effective way of integrating geospatial data for mapping spring occurrence. This method is encouraged to be modified with newly available data and to test spring occurrence in a variety of terrains in British Columbia to better understand controls on spring occurrence

A GIS-based spring source delineation that was a desktop-approach to provide basic approximation of SSAs was conducted. The GIS-SSA for five spring case studies were presented, and the final GIS-SSA ranged from 0.008 to 3.6 km^2. There are uncertainties regarding each of the SSA's due to assumptions in the methodology and poor resolution or quantity of hydrogeological data, thus a high degree of confidence in the SSAs could not be established.

6 REFERENCES

Adiat, K. a. N., Nawawi, M. N. M., & Abdullah, K. (2012). Assessing the accuracy of GIS-based elementary multi criteria decision analysis as a spatial prediction tool - A case of predicting potential zones of sustainable groundwater resources. *Journal of Hydrology*, 440, 75–89. https://doi.org/10.1016/j.jhydro.2012.03.028

Alfaro, C., & Wallace, M. (1994). Origin and classification of springs and historical review with current applications. *Environmental Geology*, 24(2), 112–124. https://doi.org/10.1007/BF00767884

Baye, A., Rathfelder, K., Wei, M., & Yin, J. (2016). *Hydrostratigraphic, Hydraulic and Hydrogeochemical Descriptions of Dawson Creek-Groundbirch Areas, Northeast BC* (Water Science Series No. 2016-01). Victoria, BC.

BC Ministry of Environment. (2016). WELLS Database. Victoria: BC, BC Ministry of Environment.

Bellefontaine, K., Alldrick, D., & Desjardins, P. J. (1995). *Mineral Potential Project, Digital Geological Compilation NEBC South half, (83D, E; 93F, G, H, I, J, K, N, O, P).* Victoria, BC: BC Ministry of Energy and Mines, Open File 1995-24.

Berardinucci, J., & Ronneseth, K. (2002). *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater.* Victoria BC: BC Ministry of Water, Land and Air Protection.

Beven, K. J., & Kirby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24(1), 43–69. https://doi.org/10.1080/02626667909491834

Bryan, K. (1919). Classification of Springs. *Journal of Geology*, 27(7), 522–561.

Catto, N. R. (1991). *Quaternary Geology and Landforms of the Eastern Peace River Region, British Columbia NTS 94A/1,2,7,8.* Victoria, BC: BC Ministry of Energy and Mines, Open File 1991-11.

Catto, N. R., & Thistle. (1993). *Quaternary Geology and Landforms of the Dawson Creek Region, British Columbia NTS 93P/9,10,15,16.* Victoria, BC: BC Ministry of Energy and Mines, Open File 1993-29.

Chenini, I., Mammou, A. B., & El May, M. (2010). Groundwater Recharge Zone Mapping Using GIS-Based Multi-criteria Analysis: A Case Study in Central Tunisia (Maknassy Basin). *Water Resources Management*, 24(5), 921–939.

Corsini, A., Cervi, F., & Ronchetti, F. (2009). Weight of evidence and artificial neural networks for potential groundwater spring mapping: an application to the Mt. Modino area (Northern Apennines, Italy). *Geomorphology*, 111(1–2), 79–87. https://doi.org/10.1016/j.geomorph.2008.03.015

Cowen, T. (2003, July 7). Recharge and Capture Area Delineation - Fey and Romedo Springs.

ESRI. (n.d.). ArcGIS Pro Help.

Fenta, A. A., Kifle, A., Gebreyohannes, T., & Hailu, G. (2015). Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. Hydrogeology Journal, 23(1), 195–206. https://doi.org/10.1007/s10040-014-1198-x

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater* (1st ed.). Englewood Cliffs, New Jersey: Prentice Hall, Inc.

Government of British Columbia. (2010). *Comprehensive Drinking Water Source-to-Tap Assessment Guideline. Module 1: Delineate and Characterize Drinking Water Sources*. Victoria, BC

Hartman, G. M. D., & Clague, J. J. (2008). Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia. *Canadian Journal of Earth Sciences*, 45(5), 549–564. https://doi.org/10.1139/E07-069

Hickin, A. S. (2011). *Preliminary bedrock topography and drift thickness of the Montney Play area*. Geoscience BC and Ministry of Energy and Mines, Open Report 2011-7.

Jones, J. F. (1966). *Geology and Groundwater Resources of the Peace River District, Northwestern Alberta* (No. 016). Research Council of Alberta.

Knudby, A. (2015, April 14). SFU Climate Energy Days Poster Presentation Discussion. [Personal Communication]

Kreye, R., Wei, M., & Reksten, D. (1996). *Defining the source area of water supply springs*. Victoria, BC: Ministry of Environment, Lands and Parks, Hydrology Branch.

Kumar, T., Gautam, A. K., & Jhariya, D. C. (2016). Multi-criteria decision analysis for planning and management of groundwater resources in Balod District, India. *Environmental Earth Sciences*, 75(8), 649. https://doi.org/10.1007/s12665-016-5462-3

Lebedin, J. (Prairie F. R. A. (1990, August 2). Fey and Romedo Spring.

Li, Z., Zhu, Q., & Gold, C. (2005). *Digital Terrain Modeling: Principles and Methodology*. CRC Press.

Lowen. (2011). *Aquifer Classification Mapping in the Peace River Region for the Montney Water Project* (No. 1026). Geoscience BC.

MacIntyre, D. G., Legun, A., Bellefontaine, K., & Massey, N. W. D. (1995). *B.C. Mineral Potential Project: Digital Geological Compilation, Northeast British Columbia 94A, B, C, F, G, H, I, J, K, N, O, P).* Ministry of Energy, Mines and Petroleum Resources, Open File 1995-6.

Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis*. John Wiley & Sons.

Mathews, W. H. (1950). *Preliminary report on ground water studies, Peace River, BC: notes to accompany groundwater studies and map*. Victoria, BC: BC Ministry of Energy and Mines

Meinzer, O. E. (1923). *Outline of Ground-Water Hydrology with Definitions* (Geological Survey Water-Supply Paper No. 494). Washington DC: USGS.

Ministry of Forests, Lands and Natural Resource Operations. (2011, March 9). *Licensed Springs*.

Moghaddam, D. D., Rezaei, M., Pourghasemi, H. R., Pourtaghie, Z. S., & Pradhan, B. (2013). Groundwater spring potential mapping using bivariate statistical model and GIS in the Taleghan Watershed, Iran. *Arabian Journal of Geosciences*, 8(2), 913–929. https://doi.org/10.1007/s12517-013-1161-5

Ozdemir, A. (2011). GIS-based groundwater spring potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison*. Journal of Hydrology*, 411(3–4), 290–308. https://doi.org/10.1016/j.jhydrol.2011.10.010

Pourtaghi, Z. S., & Pourghasemi, H. R. (2014). GIS-based groundwater spring potential assessment and mapping in the Birjand Township, southern Khorasan Province, Iran. *Hydrogeology Journal*, 22(3), 643–662. https://doi.org/10.1007/s10040-013-1089-6

Rahmati, O., Samani, A. N., Mahdavi, M., Pourghasemi, H. R., & Zeinivand, H. (2015). Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. Arabian *Journal of Geosciences*, 8(9), 7059–7071. https://doi.org/10.1007/s12517-014-1668-4

Riddell, J. (2012). *Potential for freshwater bedrock aquifers in Northeast British Columbia: Regional distribution and lithology of surface and shallow subsurface bedrock units* (Geoscience Report 2012-04). Victoria, BC: BC Ministry of Energy and Mines

Ron, J. (2015, September 4). Interview Regarding Springs in Peace River Regional District [Telephone Interview].

Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, 9(3), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L. (1990). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*: 2 (2nd ed.). RWS.

Schmidt, F., & Persson, A. (2003). Comparison of DEM Data Capture and Topographic Wetness Indices. *Precision Agriculture*, 4(2), 179–192. https://doi.org/10.1023/A:1024509322709

Stott, D. F. (1982). *Lower Cretaceous Fort St. John Group and upper Cretaceous Dunvegan Formation of the foothills and plains of Alberta, British Columbia, District of Mackenzie and Yukon Territory* (Bulletin No. 328). Geological Survey of Canada, Bulletin 328.

Wilford, D., Hickin, A., Chapman, A., Kelly, J., Janicki, E. P., Kerr, B., & Wei, M. (2012). *Collaborative interagency water projects in British Columbia: Introduction to the Northeast British Columbia Aquifer Project and Streamflow Modelling Decision Support Tool* (Geoscience Reports 2012). Victoria, BC: BC Ministry of Energy and Mines

7 APPENDIX

Table A1. Spring field measurements.

Spring Number	**Month-Year**	**Conductivity (µS/cm)**	**pH**	**Temp (°C)**	**DO (mg/L)**	**ORP (mV SHE)**	**Alkalinity as HCO_3 (mg/L)**
Q1	Sep-15 [a]	915	7.00	5.6	0.19	99	351
	Oct-12	910	6.52	5	1.42	-50	327
Q2	Sep-15 [a]	1788	7.05	7.5	0.59	175	302
	Nov-14	1706	7.10	3.8	6.09	224	276
Q3	Sep-15 [a]	538.	7.26	8.3	7.19	226	253
Q4	Sep-15 [a, d]	1208	7.12	4.6	0.48	143	715
	Jan-12 [d]	802	7.20	4.3	5.53	-32	660
	Jan-12 [d]	1231	7.71	1	12.50	77	648
Q5	Sep-15 [a]	843	7.52	11.6	5.88	235	494
	Nov-11	826	6.85	6.6	2.50	149	494
Q6	Oct-14	750	6.76	8.7	2.72	226	399
Q7	Nov-15 [a]	1333	6.97	5.7	0.37	133	356
	Nov-15 [a]	1333	6.97	5.7	0.37	133	371
Q8	Sep-15 [a]	1438	8.00	10.2	8.30	217	613
Q9	Nov-14	1579	7.19	1.8	5.19	236	531
	Sep-15 [a]	1844	7.44	8.4	5.05	187	570
Q10	Sep-15 [a,b]	618	7.73	6.1	n.d.	n.d.	451
	Sep-14 [b]	283	8.12	9.7	10.04	121	181
Q11	Sep-15 [a, c]	935	7.69	7.3	6.79	245	459
	Sep-12 [c]	919	6.50	10.1	1.64	29	443

Spring Number	**Month-Year**	**Conductivity (µS/cm)**	**pH**	**Temp (°C)**	**DO (mg/L)**	**ORP (mV SHE)**	**Alkalinity as HCO_3 (mg/L)**
Q12	Sep-15 [a]	1704	6.97	7.3	1.55	247	773
	Jan-12	1744	6.89	3.4	2.47	129	743
Q13	Sep-15 [a]	735	6.76	6.8	0.41	-109	260
Q14	Nov-15 [a]	1080	7.47	8	11.00	132	423
	Sep-14	1128	7.74	7.9	10.42	87	418
Q15	Oct-14	828	7.28	8.1	2.89	207	481
Q16	Sep-15 [a]	228	7.16	6	10.48	214	134
Q17	Sep-15 [a]	329	7.31	6.5	0.84	227	197
Q18	Nov-15 [a]	570	7.51	5.9	11.53	138	366
Q19	Nov-15 [a]	193	6.65	3	0.39	74	113
Q20	Sep-15 [a]	101	6.85	7.5	681.5	n.d.	50
B1	Aug-14	1616	7.15	7.3	1.66	90.6	690
B2	Feb-13	4449	7.25	1.9	1.45	-183	1155
B3	Sep-15 [a]	621	4.43	10.4	694.5	632*	n.d.
B4	Nov-14	758	7.91	1.8	3.92	209	522
	Sep-15	636	9.09	8	0.08	-163	458
B5	Sep-15 [a]	1526	7.63	8.9	8.55	231	445
	Nov-14	1629	7.31	0.4	6.62	231	417
B6	Sep-15 [a]	1335	7.34	6.7	1.3	182	535
B7	Sep-15 [a]	1569	4.19	6.7	3.82	279	n.d.
B8	Aug-14	2176	6.5	5.8	2.09	38	424
B9	Sep-15 [a]	2719	6.83	6.5	2.75	231	420

Spring Number	**Month-Year**	**Conductivity (µS/cm)**	**pH**	**Temp (°C)**	**DO (mg/L)**	**ORP (mV SHE)**	**Alkalinity as HCO_3 (mg/L)**
	Feb-12	2843	6.64	2.2	0.54	85	396
B10	Sep-15 [a]	1823	7.26	9.5	3.37	223	876
B11	Oct-14	1208	7.06	3.3	12.08	230	796
B12	Sep-15 [a]	2974	8.27	7.7	3.82	224	1114
	Feb-14	2927	7.97	3.9	1.56	-47	983
B13	Sep-15 [a]	1065	7.23	7.3	0.78	173	756
B14	Aug-14	4180	6.74	8	10.12	71	1440
B15	Sep-15 [a]	3.85	6.85	7.4	0.1	169	792
B16	Sep-15 [a]	1234	7.29	9.2	1.19	190	850
	Jul-14	1220	7.05	10	0.16	-66	770
	Jul-14	1254	7.12	8.1	0.36	-88	744

Missing measurements are indicated with ‘n.d.’.
[a] Springs sampled as part of this research project. The remaining springs were sampled as part of the NEBC Aquifer Study (Wilford et al., 2012).
[b] sampled as close as possible to the natural outlet (small ponded pool), whereas the earlier sample was from the pump house.
[c] sampled at an outflow pipe near the spring development, but earlier sample was collected approximately 1 mile down-pipe at a different outlet.
[d] 2 different locations which are believed to originate from the same groundwater source.
[*]Incorrect measurements by the multi-parameter probe.

TableA2. Major cations and anions for spring waters

Spring Number	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	F^-	Cl^-	SO_4^{2-}	NO_3^-	TDS
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Q1	12.6	4.0	190	19.6	0.2	0.93	19.6	246	n.d.	622
	12.5	4.1	146	16.6	0.18	0.92	0.5	224	1.6	540
Q2	69.3	3.8	280	89.6	0.84	0.40	2.2	874	n.d.	1692
	82.0	4.4	238	93.0	0.01	0.14	2.6	947	2.9	1744
Q3	15.6	2.6	74	26.5	d.l.	0.32	0.8	118	n.d.	334
Q4	33.9	3.6	133	85.8	0.35	0.33	0.2	181	n.d.	563
	29.5	3.8	127	89.5	0.35	0.26	0.3	194	0.44	538
	37.8	3.8	135	78.9	0.31	0.31	0.4	187	n.d.	535
Q5	9.8	4.6	133	35.7	0	0.51	0.4	108	n.d.	355
	8.8	5.2	133	38.1	0.01	0.59	0.5	113	3	363
Q6	25.1	2.7	99	30.3	0.04	0.30	47.0	65	0.6	320
Q7	51.2	4.7	146	46.9	0	0.19	183.0	139	1.9	720
	50.1	4.6	140	46.5	0	0.20	184.0	141	1.8	716
Q8	42.5	3.9	152	119.0	d.l.	0.28	8.3	513	n.d.	1112
Q9	47.5	4.1	215	152.0	0.02	0.10	1.5	783	1.3	1553
	46.1	4.2	238	153.0	0.1	0.23	1.5	797	n.d.	1569
Q10	3.6	1.4	101	27.4	0	0.16	1.4	12	n.d.	161
	3.4	1.4	32	21.7	0	0.09	0.9	12	n.d.	83
Q11	24.5	2.6	130	55.8	0	0.44	55.8	1	n.d.	365
	20.9	2.0	109	48.3	0.1	0.38	0.8	169	n.d.	423
Q12	116.0	6.6	206	75.5	d.l.	0.21	0.7	444	n.d.	1034
	94.2	6.2	212	76.4	0.01	0.75	0.7	425	1	986
Q13	21.4	2.8	94	34.9	0.15	0.89	0.3	200	n.d.	517
Q14	8.4	1.6	132	75.1	0	0.12	2.3	306	n.d.	1385
	9.3	1.9	163	86.0	0	0.13	2.0	364	1	817
Q15	49.1	3.2	77	54.1	0.01	0.03	0.5	101	0.03	349
Q16	3.3	4.0	34	8.9	d.l.	0.08	0.3	15	n.d.	87
Q17	4.7	5.2	55	12.1	0.13	0.09	1.2	46	n.d.	173
Q18	11.4	5.3	84	25.2	0.01	0.07	3.1	28	n.d.	254
Q19	3.2	1.2	24	6.2	0.01	0.26	0.2	3	n.d.	62
Q20	2.0	1.2	15	3.3	0	0.49	0.3	3	n.d.	47
B1	214.0	2.6	54.4	44.9	0.02	0.15	6.1	178	n.d.	595
B2	956.0	7.7	93.2	63.2	1.02	d.l.	1.5	1521	n.d.	4575
B3	132.0	2.6	65.3	23.0	0	0.45	10.5	616	n.d.	1117
B4	132.7	6.2	27.9	25.8	1.17	0.63	1.8	4	n.d.	215
	109.0	3.3	18.6	20.0	0.52	0.54	1.3	1	n.d.	160

Spring Number	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	F^-	Cl^-	SO_4^{2-}	NO_3^-	TDS
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
B5	200.0	4.5	121.0	46.4	-0.01	0.11	6.5	488	n.d.	1086
	294.0	4.9	107.0	46.5	0.02	0.16	7.8	659	0.5	1393
B6	112.0	3.5	95.0	44.7	0.09	0.10	0.7	107	n.d.	453
B7	55.6	4.1	226.0	56.3	0.03	0.44	6.5	994	n.d.	1841
B8	129.0	3.4	225.0	111.0	0	2.17	0.3	1019	n.d.	1889
B9	274.0	5.9	285.0	111.0	0.03	1.05	11.5	1429	n.d.	2812
	397.0	6.067	328.0	152.0	0.14	1.11	2.0	1900	0.2	3432
B10	368.0	2.1	9.8	3.3	-0.02	0.21	0.8	98	n.d.	559
B11	201.0	4.4	150.0	99.0	0.06	0.08	0.8	544	3.2	1296
B12	711.0	3.2	16.5	7.2	1.23	0.99	2.9	763	n.d.	1821
	706.0	2.7	17.9	7.5	1.05	1.23	4.5	764	n.d.	1766
B13	115.0	2.9	74.2	47.3	0.1	0.06	0.7	56	n.d.	334
B14	584.0	4.1	243.0	214.0	0	d.l.	7.2	1540	n.d.	3285
B15	442.0	7.7	341.0	172.0	0.52	d.l.	56.0	1800	0.2	3827
	228.0	3	39.8	33.0	0.01	0.13	3.1	62	n.d.	408
	210.0	2.8	39.8	32.7	0.05	0.24	3.5	59	n.d.	380
B16	202.0	3.3	48.6	29.8	0.11	0.36	3.2	62	n.d.	380

Missing measurements are marked with ‘n.d.’ and samples below the detection limit are marked with ‘d.l.’.

Table A3. Isotopic composition of spring waters.

Spring Number	$\delta^{18}O$ ‰ VSMOW	$\delta^{2}H$ ‰ VSMOW	Tritium TU	^{14}C pmC	$\delta^{13}C$ ‰ VPDB
Q1	-20.9	-161	8.93 ± 0.29	61.1	-15.5
	-20.1	-161	n.a.	n.a.	n.a.
Q2	-21.5	-170	0.04 ± 0.09	29.5	-15.0
	-21.7	-170	n.a.	n.a.	n.a.
Q3	-21.1	-162	7.03 ± 0.23	69.5	-13.8
Q4	-21.0	-162	0.00 ± 0.09	49.1	-12.1
	-20.3	-158	n.a.	n.a.	n.a.
	-20.8	-160	n.a.	n.a.	n.a.
Q5	-20.5	-161	4.46 ± 0.15	80.6	-12.4
	-20.4	-157	n.a.	n.a.	n.a.
Q6	-20.6	-161	6.97 ± 0.23	n.a.	n.a.
Q7	-20.3	-157	n.a.	n.a.	n.a.
	-20.8	-157	n.a.	n.a.	n.a.
Q8	-17.9	-144	6.01 ± 0.2	28.6	-4.0
Q9	-20.6	-167	n.a.	n.a.	n.a.
	-21.3	-169	1.45 ± 0.09	45.4	-12.1
Q10	-20.2	-162	6.9 ± 0.23	98.6	-11.3
	-17.1	-144	n.a.	n.a.	n.a.
Q11	-21.7	-166	0.00± 0.09	22.2	-10.0
	-21.6	-164	n.a.	n.a.	n.a.
Q12	-21.0	-162	4.61 ± 0.15	38.3	-11.2
	-20.5	-160	n.a.	n.a.	n.a.
Q13	-21.8	-169	0.33 ± 0.09	40.1	-11.0
Q14	-19.2	-160	n.a.	n.a.	n.a.
	-22.2	-162	n.a.	0.35	n.a.
Q15	-21.0	-163	n.a.	n.a.	n.a.
Q16	-21.9	-168	7.4 ± 0.24	71.8	-15.1
Q17	-21.6	-165	8.21 ± 0.27	74.5	-14.3
Q18	-22.3	-175	n.a.	n.a.	n.a.
Q19	-20.8	-159	n.a.	n.a.	n.a.
Q20	-20.9	-161	12.4 ± 0.4	97.1	-19.5
B1	-23.3	-180	1.77 ± 0.09	19.6	-9.3
B2	-18.7	-157	n.a.	n.a.	n.a.
B3	-20.8	-162	8.53 ± 0.28	77.2	-20.4
B4	-22.7	-171	n.a.	n.a.	n.a.
	n.a.	n.a.	n.a.	n.a.	n.a.
B5	-21.2	-169	6.16 ± 0.2	74.5	-10.0

Spring Number	δ¹⁸O ‰ VSMOW	δ²H ‰ VSMOW	Tritium TU	¹⁴C pmC	δ¹³C ‰ VPDB
	-21.1	-167	n.a.	n.a.	n.a.
B6	-22.5	-168	3.29 ± 0.11	27.0	-9.3
B7	-18.6	-149	7.85 ± 0.26	89.6	-18.5
B8	-18.2	-153	n.a.	n.a.	n.a.
B9	-20.5	-162	2.18 ± 0.09	43.5	-11.4
	-20.7	-159			
B10	-22.5	-173	0.52 ±0.09	23.8	-8.6
B11	-20.4	-163	n.a.	**n.a.**	n.a.
B12	-23.2	-181	0.00 ± 0.09	8.0	-3.7
	-23.4	-181	n.a.	n.a.	n.a.
B13	-21.7	-169	n.a.	n.a.	n.a.
B14	-23.2	-182	0.00 ± 0.09	5.8	-4.0
B15	-22.0	-170	0.26 ± 0.09	17.0	-7.1
B16	-21.4	-168	n.a.	66.4	-9.5
	-21.9	-166	5.16 ± 0.17	n.a.	n.a.
	-21.9	-166	n.a.	n.a.	n.a.

Samples not analyzed are marked with ‘n.a.’.

Table A4. The standardization scores for every spring-related factor and final Likelihood of Occurrence for Springs Score for each springs in the GIS study area.

Spring Number	Slope	Curvature	Proximity to Hydrological Features	TWI	Surficial Geology (Q)	Surficial Geology (B)	Drift Thickness (Q)	Drift Thickness (B)	Likelihood of Occurrence for Bedrock Springs	Likelihood of Occurrence for Quaternary Springs
1	100	50	100	100	100	50	0	0	43.0	76.0
2	100	100	100	100	75	50	100	0	56.3	94.8
3	100	50	100	100	75	75	0	0	47.6	70.9
4	100	100	100	100	75	75	0	0	60.9	88.6
5	0	100	50	100	75	50	0	0	37.5	65.1
6	100	100	100	100	75	50	50	100	90.7	91.7
7	100	50	100	100	75	75	100	0	47.6	77.1
8	100	50	100	100	0	50	50	100	77.4	59.0

Spring Number	Slope	Curvature	Proximity to Hydrological Features	TWI	Surficial Geology (Q)	Surficial Geology (B)	Drift Thickness (Q)	Drift Thickness (B)	Likelihood of Occurrence for Bedrock Springs	Likelihood of Occurrence for Quaternary Springs
9	0	100	100	0	25	25	0	0	34.4	51.0
10	0	50	100	100	75	50	50	100	60.1	55.9
11	100	100	50	100	100	0	50	50	62.8	91.4
12	100	100	50	100	100	0	100	0	45.6	94.5
13	0	100	0	50	25	0	50	100	61.1	48.1
14	100	100	50	0	100	0	100	0	45.6	85.1
15	100	100	100	100	75	50	100	0	56.3	94.8
16	100	50	100	100	100	50	100	0	43.0	82.2
17	100	50	100	100	75	75	0	100	82.0	70.9
18	100	100	50	100	25	25	0	100	84.6	73.2
19	100	50	0	100	100	50	0	100	74.3	65.3
20	100	100	100	100	75	75	0	0	60.9	88.6
21	100	50	100	50	0	100	50	50	69.4	54.3
22	100	50	100	100	100	50	0	100	77.4	76.0
23	100	100	100	100	0	100	50	100	99.9	76.6
24	100	50	100	100	0	100	50	50	69.4	59.0
25	100	100	100	100	0	100	0	100	99.9	73.5
26	100	50	100	50	0	100	0	100	86.6	51.2
27	100	100	100	100	75	50	0	100	90.7	88.6
28	100	50	50	100	75	50	50	50	58.6	68.7
29	100	50	100	100	0	100	0	100	86.6	55.9
30	100	50	100	100	0	100	0	100	86.6	55.9
31	0	100	50	100	0	50	0	0	37.5	50.1
32	100	100	50	100	100	0	0	100	80.0	88.3
35	0	100	100	100	25	25	0	0	34.4	60.4
37	100	100	100	100	0	100	50	50	82.7	76.6
38	100	50	100	100	100	50	100	0	43.0	82.2
39	100	100	0	100	75	50	100	0	53.2	84.1
40	100	100	100	100	100	50	100	0	56.3	99.8
41	100	100	50	50	0	50	0	100	89.2	63.5
42	100	0	50	50	0	100	100	0	37.3	34.4
43	100	50	50	100	25	25	50	100	71.2	58.6
44	100	100	100	100	0	100	50	50	82.7	76.6
45	100	100	100	100	100	50	50	50	73.5	96.7

Spring Number	Slope	Curvature	Proximity to Hydrological Features	TWI	Surficial Geology (Q)	Surficial Geology (B)	Drift Thickness (Q)	Drift Thickness (B)	Likelihood of Occurrence for Bedrock Springs	Likelihood of Occurrence for Quaternary Springs
46	100	100	100	100	0	50	100	0	56.3	79.7
47	100	50	100	100	75	75	100	0	47.6	77.1
48	100	100	100	100	0	100	100	0	65.5	79.7
49	100	100	100	100	0	100	0	100	99.9	73.5
50	100	100	100	100	75	50	100	0	56.3	94.8
51	100	100	0	100	100	50	0	100	87.6	82.9
52	100	50	100	100	75	75	50	50	64.8	74.0
53	100	100	100	100	0	100	100	0	65.5	79.7
54	100	50	100	50	50	0	0	100	68.2	61.2
55	100	50	50	50	25	25	50	100	71.2	53.9
56	100	100	0	50	0	100	0	100	96.8	58.1
57	100	50	100	100	0	100	0	100	86.6	55.9
58	100	50	100	100	75	50	0	100	77.4	70.9
59	100	50	50	100	0	100	100	0	50.6	56.7
60	100	100	0	100	0	100	0	100	96.8	62.8
61	100	50	100	100	75	75	0	0	47.6	70.9
62	100	100	100	100	0	100	0	100	99.9	73.5
63	100	100	100	0	75	75	0	100	95.3	79.2
64	0	100	100	100	100	50	0	0	39.0	75.5
65	100	100	50	100	75	50	0	100	89.2	83.2
66	100	50	100	100	0	100	0	100	86.6	55.9
67	100	100	50	100	75	50	50	50	72.0	86.3
68	100	100	100	50	100	50	100	0	56.3	95.1
69	100	100	50	100	100	50	100	0	54.8	94.5
70	100	100	100	100	75	50	50	50	73.5	91.7
71	100	50	100	100	100	50	0	0	43.0	76.0
72	100	50	100	100	75	50	100	0	43.0	77.1
73	0	100	100	0	100	50	0	0	39.0	66.1
74	0	0	100	100	75	75	0	0	16.9	35.2
75	100	50	50	50	0	100	50	50	67.8	48.9
76	100	100	100	100	75	50	50	100	90.7	91.7
77	100	100	100	100	75	75	100	0	60.9	94.8
78	0	100	100	100	0	50	0	0	39.0	55.4
79	100	50	100	100	75	75	0	0	47.6	70.9

Spring Number	Slope	Curvature	Proximity to Hydrological Features	TWI	Surficial Geology (Q)	Surficial Geology (B)	Drift Thickness (Q)	Drift Thickness (B)	Likelihood of Occurrence for Bedrock Springs	Likelihood of Occurrence for Quaternary Springs
80	0	100	50	100	75	50	100	0	37.5	71.3
81	100	50	100	100	50	0	0	100	68.2	65.9
82	100	50	100	100	0	100	50	50	69.4	59.0
83	100	100	100	100	100	50	100	0	56.3	99.8
84	100	50	100	100	0	100	100	0	52.2	62.1
85	100	100	100	100	75	50	50	100	90.7	91.7
86	100	50	100	100	75	50	0	100	77.4	70.9
87	100	100	0	50	0	100	50	100	96.8	61.2
88	100	100	100	100	100	50	0	0	56.3	93.6
89	100	0	50	100	75	75	0	0	32.7	47.9
90	100	100	100	100	75	75	0	0	60.9	88.6
91	0	0	100	100	75	75	100	0	16.9	41.4
92	100	100	100	100	50	0	0	100	81.5	83.6
93	100	100	100	100	0	100	0	100	99.9	73.5
94	100	100	100	100	25	25	50	100	86.1	81.6
95	100	100	100	100	75	75	0	0	60.9	88.6
96	100	100	100	100	0	100	50	50	82.7	76.6
97	100	100	50	100	75	50	0	100	89.2	83.2
98	100	100	50	100	25	25	0	100	84.6	73.2
99	100	50	100	100	100	50	0	100	77.4	76.0
100	100	100	100	50	100	50	0	0	56.3	88.9
101	0	100	100	0	0	100	0	0	48.2	46.0
102	100	100	100	50	100	50	50	50	73.5	92.0
103	100	100	100	100	100	50	0	0	56.3	93.6
104	100	100	100	50	25	25	50	50	68.9	76.9
105	100	100	100	100	100	50	0	100	90.7	93.6
106	100	100	100	100	0	100	0	100	99.9	73.5
107	100	100	100	50	100	50	100	0	56.3	95.1
108	100	100	100	100	0	100	100	0	65.5	79.7
109	100	50	100	100	0	50	50	50	60.2	59.0
110	100	50	100	100	25	25	0	0	38.4	60.9
111	0	100	100	100	0	100	50	50	65.4	58.5
112	100	50	100	50	75	75	50	100	82.0	69.3
113	100	100	100	100	100	50	50	100	90.7	96.7

Spring Number	Slope	Curvature	Proximity to Hydrological Features	TWI	Surficial Geology (Q)	Surficial Geology (B)	Drift Thickness (Q)	Drift Thickness (B)	Likelihood of Occurrence for Bedrock Springs	Likelihood of Occurrence for Quaternary Springs
114	100	100	50	100	75	50	0	100	89.2	83.2
115	100	100	100	100	75	50	100	0	56.3	94.8
116	100	100	50	100	0	100	50	50	81.2	71.3
117	100	100	100	100	75	50	50	50	73.5	91.7
118	100	50	100	100	25	25	50	50	55.6	64.0
119	100	50	50	100	25	25	0	100	71.2	55.5
120	0	100	100	100	100	50	0	0	39.0	75.5
121	0	100	100	0	75	50	100	0	39.0	67.3
122	100	100	100	100	0	100	0	100	99.9	73.5
123	100	100	100	100	0	100	0	100	99.9	73.5