Department of
Earth Sciences

Final Report:
Shallow Groundwater Intrinsic Vulnerability Mapping in Northeast British Columbia

Prepared for:

Pacific Institute for Climate Solutions
Knowledge. Insight. Action.

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EXECUTIVE SUMMARY

Simon Fraser University (SFU), with financial support from the BC Ministry of Forests, Lands and Natural Resource Operations (FLNRO) and the Pacific Institute for Climate Solutions (PICS), developed a Shallow Groundwater Intrinsic Vulnerability Map of Northeast British Columbia (BC). The assessment was conducted in response to mounting concerns surrounding water management and protection in Northeast BC in relation to shale gas development. The intent of the mapping is to characterise the intrinsic vulnerability of near surface geological materials to contamination originating at land surface. The resulting map is intended to support agencies in the development of policies and regulations that protect groundwater quality.

The shallow groundwater intrinsic vulnerability was characterised using the DRASTIC assessment method (Aller et al. 1987), which has been used in many other areas of the province (Wei, 1998; Liggett and Gilchrist, 2010; Liggett and Allen, 2011). DRASTIC is comprised of seven input parameters: Depth to water (D); Recharge (R); Aquifer media (A); Soil media (S); Topography (T); Impact of the vadose zone (I); and Hydraulic conductivity (C). The geospatial distribution of each input parameter was mapped with rankings from 1-10 (low to high) based on parameter-specific ranking tables. The final intrinsic vulnerability map was generated by summing the individual input parameter maps according to the DRASTIC weightings, where:

$$\text{Intrinsic Vulnerability} = 5D + 4R + 3A + 2S + 1T + 5I + 2C$$

The input parameter maps were developed using publically available datasets for Northeast BC. Data include surficial and bedrock geology maps, water well records, the digital elevation model, and soil survey data. Additional recharge modelling was conducted to assess potential recharge rates in the region. The assessment focused on the near surface geological materials comprising permeable (aquifers) and less permeable materials; the assessment did not consider confined aquifers. In instances where there were limited data, the DRASTIC approach was modified to represent estimated values. Detailed presentation of the ranking schemes and approach are provided for each parameter.

The final shallow groundwater intrinsic vulnerability map shows areas of relatively higher intrinsic vulnerability corresponding to areas where the geological materials have high permeability, where there is limited soil cover, and where recharge rates are high. Other higher vulnerability areas include river valleys where the vadose zone and geological materials have large proportions of sand and gravel. As the assessment is based on relative ranking, even areas that are ranked low represent some vulnerability to contamination, albeit less than other parts of the study area. When the DRASTIC results are categorised according to the BC Ministry of Environment scale of low, moderate and high vulnerability, the maps indicate predominantly low to moderate vulnerability.

Despite limitations in data, the assessment represents the existing data and allows for interpretation of relative intrinsic vulnerability in areas with poor data coverage. In the future, the assessment may be adjusted and updated as additional data become available. In the meantime, the resulting map presents a preliminary assessment of the relative shallow groundwater intrinsic vulnerability throughout Northeast BC and provides a useful tool to support groundwater management and protection, and the development of policy and regulations in the region.

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1. INTRODUCTION

There are mounting concerns surrounding water management and protection in Northeast British Columbia (BC) due to a rapidly developing shale gas sector that has not been matched by advances in characterisation of the potential impacts to water security (Council of Canadian Academies (CCA), 2014). Northeast BC is estimated to hold large reserves of unconventional natural gas and has experienced significant growth in shale gas development activities over the last several decades (Goss et al., 2015). Shale gas development activities represent major industrial operations which pose a threat to drinking water supplies and the aquatic ecosystem (CCA, 2014). Among other impacts, shale gas development has the potential to contaminate groundwater quality (Vengosh et al., 2014). The majority of contamination risk is related to spills and leaks resulting from the handling and transport of chemicals used in hydraulic fracturing or the wastewater that is produced (Rozell and Reaven, 2012). Surface spills have a high likelihood of occurrence due to the large volumes handled and number of trucks used to transport wastewater (Mokhatab et al., 2006; Soeder et al., 2014). Therefore, it is clear that the groundwater resources of Northeast BC require protection, specifically in relation to spills or releases of contaminants at ground surface.

In order to address this need, shallow groundwater intrinsic vulnerability mapping of the region was undertaken by Simon Fraser University (SFU) with financial support from FLNRO and the Pacific Institute for Climate Solutions (PICS). The intent of the mapping was to characterise the intrinsic vulnerability of near surface (< 30 m) geological materials to contamination originating at land surface. The resulting map is intended to support agencies in the development of appropriate policies and regulations to protect groundwater quality in the region and for determining future monitoring priorities. The mapping will also support other initiatives being carried out in the region, including cumulative effects assessments and joint (i.e., provincial-provincial and provincial-territorial) management of groundwater in the Mackenzie River and Liard River basins. The shallow groundwater intrinsic vulnerability map and this report will be made publically available on iMapBC (the provincial GIS and data warehouse).

The intrinsic vulnerability is assessed using the DRASTIC method which specifically focuses on shallow groundwater contamination from land sources. This approach is appropriate given the context of potential contamination risk in Northeast BC from surface spills / releases of contaminants. In addition, the DRASTIC assessment approach allows for interpretation to estimate aquifer characteristics in areas with poor data coverage and provides an estimate of relative intrinsic vulnerability throughout the region.

2. STUDY AREA

Northeast BC covers two districts: the Peace River Regional District and the Northern Rockies Regional Municipality. There are several towns, communities and First Nations' territories throughout the region. The predominant urban centers include Fort Nelson, Fort St. John and Dawson Creek. The study area for this assessment was defined in consultation with FLNRO (Figure 1). The western and southern boundary is based on the topographic high of the mountainous region, and the northern and eastern boundaries are based on the provincial borders. The study area comprises part of the Cordilleran and Interior Plains hydrogeological regions, including the mountains to the west as well as the low-lying flat areas where the majority of the population resides and shale gas development occurs (Sharpe et al., 2014).

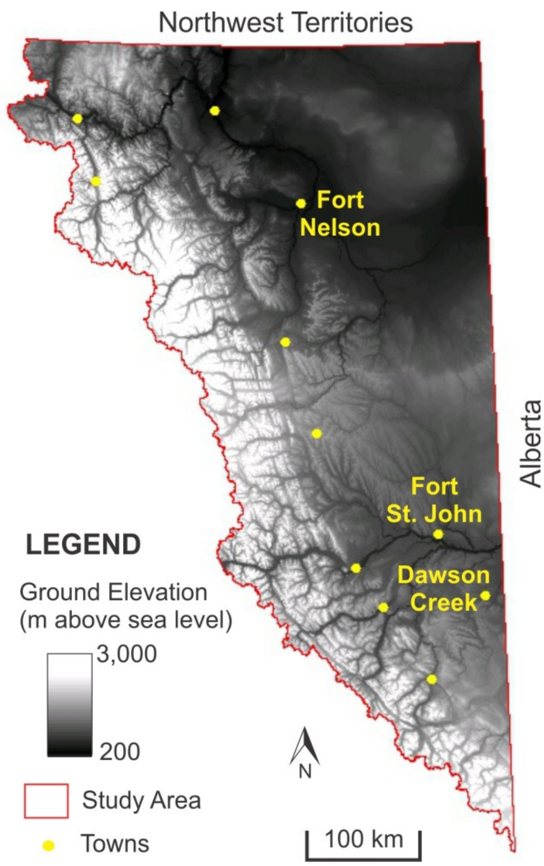

Figure 1 Northeast BC Study Area

Northeast BC experiences cold winters and warm summers. Temperatures are relatively uniform throughout the region, with average daily temperatures ranging between -20°C to +17°C throughout the year (Environment Canada Climate Normals 1981-2010). Annual average precipitation ranges from 400 to 2000 mm/year, with higher precipitation in the mountainous western portions of the study area than the relatively flatter eastern portions (Wang et al., 2012).

3. METHODS

Intrinsic vulnerability relates to the physical characteristics (thickness and permeability) of the geological materials that make them more or less susceptible to groundwater contamination (Vrba and Zoporozec, 1994). Generally, intrinsic vulnerability is referred to as intrinsic aquifer vulnerability or as aquifer susceptibility. In this study, shallow geological materials < 30 m deep are considered with no specific emphasis on aquifers. Hereafter, the term intrinsic vulnerability is used.

While there are several methods for assessing intrinsic vulnerability, this study uses the DRASTIC method (Aller et al., 1987), which is universally recognized and has been applied to numerous hydrogeological settings in other areas of BC (e.g. Fraser Valley: Wei, 1998; Vancouver Island: Liggett and Gilchrist, 2010; Okanagan Valley: Liggett and Allen, 2011) and elsewhere throughout the world (e.g. Rosen, 1994). The DRASTIC approach is based on the premise that contaminants originate from ground surface sources and migrate vertically through the vadose zone to the aquifer at the same rate as infiltrating recharge. While the term "aquifer" is used, the approach considers all unconfined geological materials in the near surface which comprise both permeable (aquifers) and less permeable materials; the assessment does not consider confined aquifers. In this study, geological materials within approximately 30 metres (m) of ground surface are considered.

The DRASTIC method is based on the rating of seven input parameters that influence the vertical migration of potential contaminants into the aquifer (these parameters also form the acronym "DRASTIC"): **D**epth to water; **R**echarge; **A**quifer media; **S**oil media; **T**opography; **I**mpact of the vadose zone; and hydraulic **C**onductivity. Each input parameter is mapped from geospatial datasets and assigned a ranking from 1-10 (low to high) according to the DRASTIC ranking tables (Aller et al., 1987). The final vulnerability is calculated by summing the spatial distribution maps for each parameter according to specific weightings assigned in the DRASTIC approach (Table 1).

For some parameters, it is necessary to modify the ranking table in order to capture the local variability and data range (Liggett and Allen, 2011). For example, if all hydraulic conductivity values for a study area fall within a similar category according to the original DRASTIC ranking tables, the range for the ranking tables can be adjusted to represent the variability between different parts of the study area. This approach does not affect the accuracy of the assessment, as each parameter is characterised on a relative scale (1-10); however, it does impact the total DRASTIC score (see Section 4.0).

Table 1 DRASTIC Parameter Summary

	Parameter	Impact on Intrinsic Vulnerability	Weight
D	Depth to water	Increasing depth to water increases the migration pathway for surface contamination to reach the aquifer, thus reducing vulnerability.	5
R	Recharge	Higher rates of recharge promote vertical migration through the vadose zone, thus increasing vulnerability	4
A	Aquifer media	Aquifer materials with physical properties that make the aquifer more likely to be permeable result in increased vulnerability	3
S	Soil media	Soils with higher drainage capacity increase the potential for contaminants to enter the vadose zone, this increasing vulnerability	2
T	Topography	Areas with steeper topographic slope result in more runoff generated, thus reducing vulnerability	1
I	Impact of vadose zone	Vadose zone materials with lower permeability may impede infiltration of contaminants, thus reducing vulnerability	5
C	Hydraulic Conductivity	Higher hydraulic conductivity values may allow contaminants to move quickly through the aquifer and spread, thus increasing vulnerability	3

Note: Intrinsic vulnerability = 5D + 4R + 3A+ 2S+1T+5I + 3C

In this study, the parameters were characterised based on publically available datasets for Northeast BC, such as the digital elevation model, geological maps, and soil survey maps. The data sources used in this study are shown in Table 2.

Many areas in Northeast BC have limited data, which posed the most significant challenge in implementing the DRASTIC assessment. There is a concentration of higher quality and higher resolution data surrounding the Fort St. John area where many studies and detailed mapping have been undertaken. In other areas of the region, such as to the north and east of Fort Nelson, there are generally fewer data available which may also be of a lower resolution. Therefore, due to data limitations, the DRASTIC assessment presented here is more generalised than other applications of DRASTIC in the province. The approach used in this assessment was to evaluate shallow groundwater vulnerability throughout Northeast BC to provide a general, large-scale assessment that identifies areas of higher intrinsic vulnerability relative to areas of lower intrinsic vulnerability. In the absence of complete data coverage, the objective was to provide preliminary information for protecting groundwater in the region to assist water managers, policy makers and government agencies, particularly within the context of a rapidly developing shale gas sector. Descriptions of the data sources and the assignment of each DRASTIC parameter are discussed in the following sections; specific details and rationale are provided where the methodology deviates from the original DRASTIC approach (Aller et al., 1987).

Table 2 Data Sources

Data Set	Source	Description / Coverage	DRASTIC Input Parameters
Digital Elevation Model	USGS SRTM	Digital elevation of the ground surface (25 m) / Full coverage of study area	D, T, Visual
Water Wells	Standardised BC WELLS database	SFU standardised driller's logs including well lithology and depth to water.	D, A, I, C
Soils Survey	Ministry of Environment	Soil mapping for BC 1:50k / Full coverage of study area	S
Surficial Geology	a) Natural Resources Canada	Geological Survey of Canada Surficial Materials of Canada 1:5,000K	A, I, C
	b) Geoscience BC/GSC	Geological Survey of Canada Surficial Geology Maps for NTS 94A and 93P (Fort St John/Dawson Creek vicinity) 1:250K	A, I, C
Bedrock Geology	Ministry of Energy and Mines	Compilation of digital geology maps 1:250K / Full coverage of study area	A, I, C
Bedrock Topography	Ministry of Energy and Mines	Partial coverage in the vicinity of Fort St. John providing interpreted bedrock topography (Hickin, 2011)	A
Aquifer Outlines	Ministry of Environment	Mapped and classified aquifers with vulnerability rankings	A, I, C
Mean Annual Precipitation	Climate BC	Spatial distribution of mean annual precipitation based on downscaled PRISM climate normals (1981-2010)	R
Hydrogeological Reports	Various	Results of various pumping tests, well yield estimates	C
Basemap Features	Data BC	Communities	Visual

3.1 DEPTH TO WATER

The depth to water parameter describes the travel distance for potential contaminants before reaching the aquifer. When the aquifer is shallow and water levels are near ground surface, there is a higher intrinsic vulnerability of the aquifer. Water level data were compiled from 1,665 water well records[1] from the BC WELLS database for the study area of Northeast BC (Figure 2). These data are recorded as depth to water and measurements are generally made shortly after the well has been drilled. Therefore, not only do these measurements reflect water levels at different times of the year and over many decades, but the true water level may be shallower or deeper simply because the water level has not readjusted to equilibrium conditions following drilling. Moreover, these measurements may be referenced to the top of

[1] As the submission of well logs to the Province is currently voluntary in BC, it has been estimated that perhaps only 50% of all wells are reported in the WELLS database.

casing, drill stand, or ground level. As such, the data are highly variable and not particularly reliable, although they represent the best spatial coverage available. Depth to water measurements range from 1 to 134 m below ground surface (mbgs), with the majority of the wells (74%) having depth to water less than 30 mbgs (see Appendix 1).

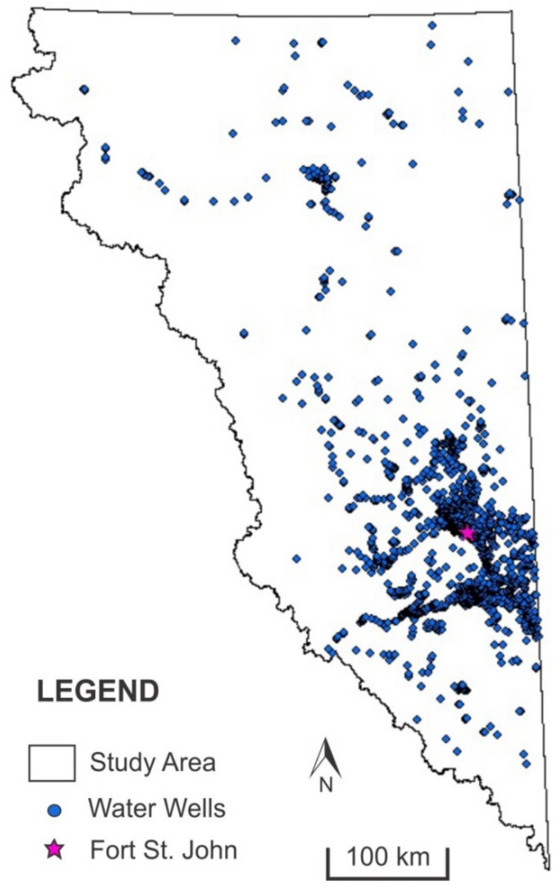

Figure 2 Distribution of Water Well Records in the WELLS Database across the Study Area

A depth to water map requires that point measurements be interpolated to provide a continuous surface. This can be accomplished using an interpolation algorithm in a geographic information system (GIS). However, in Northeast BC, water level measurements are limited to the areas where water wells are located, so there are large areas with few or no water wells. This lack of data presented a challenge for interpolation. Even in areas with a relatively high concentration of water wells (such as around Fort St. John in Figure 2), the water level data could not be interpolated to yield meaningful results. Wells with very shallow depths to water were located alongside wells with much deeper water levels. Spatial patterns were not evident even when the wells were sampled for interpolation according to total well depth (i.e. distinguishing deep from shallow wells) or by aquifer lithology. Instead more general patterns were observed, whereby high elevation mountainous areas tended to have shallow water levels, whereas the flatter unconsolidated aquifer areas tended to have deeper water levels.

The original DRASTIC approach is based on mapping the depth to water throughout the study area and ranking according to depth; higher rankings are assigned where water levels are near the surface and lower rankings are assigned to water depths greater than 30 mbgs (Aller et al., 1987). In the absence of spatial patterns from which the points could be interpolated and contoured, an alternative approach had to be developed to map depth to water.

Two approaches were tested for approximating depth to water. The first followed Denny et al. (2007), whereby an empirical relationship between ground surface elevation and groundwater elevation was estimated. However, this approach resulted in unrealistically shallow water levels in the low elevation areas and deeper water levels in the high elevation areas, which were inconsistent with the observed water level data in many instances (see Appendix 1). The second approach, also based on ground surface elevation, involved calculating the average depth to water measured in water wells classed according to a range of ground surface elevation (Table 3). The average water depth was then applied to all areas with the same ground elevation, resulting in an estimate of water levels across the region.

Table 3 Well Data Water Level Averages

Ground Elevation (m above sea level)	Range of Depth to Water (mbgs)	# of Data Points	Average Depth to Water (mbgs)
200 – 300	8 - 9	3	**9**
300 – 400	2 - 108	14	**27**
400 – 500	0 - 64	87	**17**
500 – 600	1 - 59	52	**20**
600 – 700	1 - 122	387	**21**
700 – 800	1 - 116	793	**22**
800 – 900	1 - 132	243	**26**
900 – 1000	1 - 134	58	**27**
1000 – 1100	9 - 60	9	**31**
1100 – 1200	5 - 33	9	**14**
1200 – 1300	6 - 44	4	**19**
1300 – 1400	17	1	**16**
1400 – 1500	3 - 22	5	**13**

Although, this method neglects the extreme values (high and low water levels that occur in each ground elevation category), it represents an estimate of a potential water level at any given point in the region based on the water level data. The results of this approach were compared with monitored water level data from 150 wells in the Fort St. John area. The mean water level of the monitored wells was 23 mbgs and the estimated map results using the approximation method indicated a range of water levels between

21-26 mbgs, indicating that the approach provides a reasonable estimate based on the small area where data were available.

DRASTIC rankings were assigned with an even distribution of high values for shallow estimated water levels and low values for deep estimated water levels within the top 30 mbgs (Table 4). The resulting depth to water parameter map is shown in Figure 3.

Table 4 Depth to Water Parameter Ranking Table

Average Depth to Water (mbgs)	Ranking
27 – 30+	1
24 – 27	2
21 – 24	3
18 – 21	4
15 – 18	5
12 – 15	6
9 – 12	7
6 – 9	8
3 – 6	9
0 – 3	10

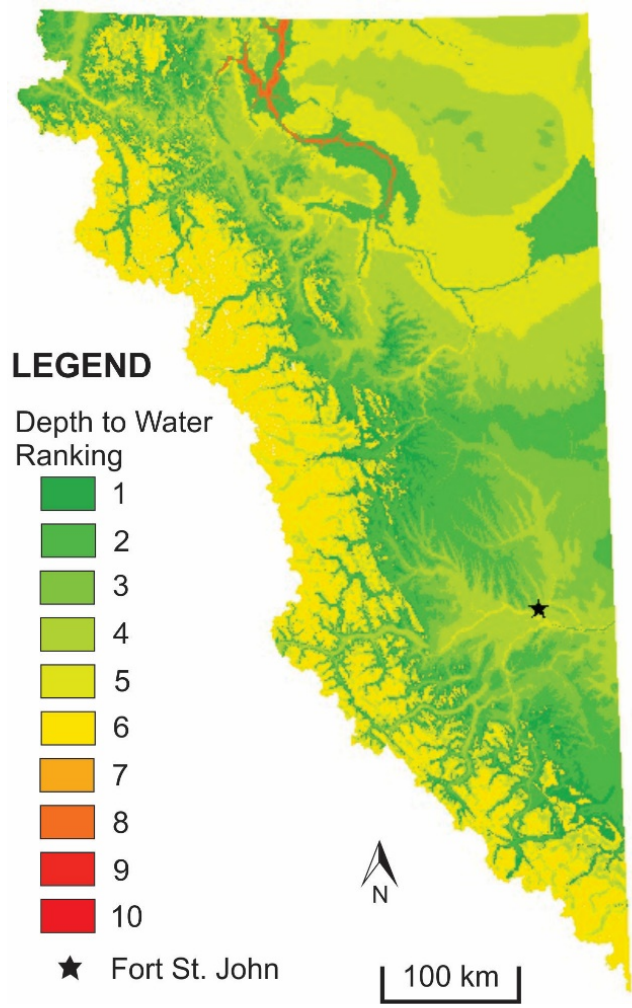

Figure 3 Depth to Water Parameter Map. The shallow water levels in the north relate to exposed bedrock areas within a river valley.

3.2 RECHARGE

The rate of recharge affects the vertical migration of potential contaminants through the vadose zone and into the aquifer. High rates of recharge are likely to transport contaminants more quickly and result in a higher intrinsic vulnerability. However, recharge is a highly uncertain parameter as there are often no specific field measured values of recharge for use in DRASTIC assessments.

Recharge is spatially variable and dependent on climatic factors (such as rate of precipitation and evapotranspiration) as well as geological parameters (such as vadose zone permeability and thickness). DRASTIC assessments commonly rely on an estimated percentage of mean annual precipitation to approximate recharge values (Wei, 1998; Liggett and Gilchrist, 2010). There are a number of methods to estimate the percentage of precipitation that forms recharge; however, many of these neglect the variability of subsurface materials. A modified approach was used in this study to estimate spatially distributed recharge using recharge models (as in Scibek and Allen, 2006). Recharge was estimated based on precipitation rates, the spatial distribution of which is known (PRISM data). Ranges of possible vadose zone hydraulic conductivity values and thicknesses were evaluated for different precipitation rates to determine the average recharge that may be expected to occur under different conditions. However, as spatially distributed hydraulic conductivity values are not available (see Section 3.7 for more details), recharge was mapped only according to precipitation variability using the average results for ranges of vadose zone property values.

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

A total of 360 recharge models were run using unique combinations of precipitation rates (9 categories), hydraulic conductivity values (8 categories), and vadose zone thicknesses (5 categories) to reflect the diversity in factors affecting recharge across the region (Table 5). Mean annual precipitation data were collected from ClimateBC as downscaled PRISM data for the period from 1981-2010 (Wang et al., 2012). Representative precipitation categories ranging from 400 to 2000 mm/year (intervals of 200 mm/year) were identified in PRISM data (Table 5). These categories represent the full range of mean annual precipitation within the study area. Mean monthly precipitation rates (for input to the stochastic weather generator) were then derived by distributing the mean annual precipitation throughout the year according to the distribution pattern observed in the climate normals for Dawson Creek (see Appendix 2; the climate normals and distribution patterns were similar for Dawson Creek and Fort Nelson climate stations). This approach presumes that precipitation has the same monthly distribution across the region, regardless of total annual precipitation amount.

Hydraulic conductivity categories for the subsurface were collected from available pumping test data representing the predominant aquifer lithologies identified in Northeast BC, such as till and fractured bedrock (see Section 3.7). Vadose zone thickness categories were determined to represent a range in commonly observed water levels in order to test the sensitivity of this parameter on the resulting recharge estimates. Vadose zone thickness is related to water depth as it represents the thickness of the unsaturated (i.e. vadose) zone. Therefore, a vadose zone thickness of 10 m represents depths to water of 10 m or less.

The influence of a soil layer was not included in the models due the uncertainty of soil thicknesses and properties throughout the study area (see Section 3.4). As a result, recharge estimates may be overestimated as soil layers tend to reduce the total recharge.

Table 5 Recharge Model Inputs: A Total of 360 Combinations.

Precipitation (mm/year)	Hydraulic Conductivity (m/day)	Vadose Zone Thickness (m)
400	0.01	10
600	0.1	15
800	0.5	20
1000	1.0	25
1200	4.0	30
1400	8.0	-
1600	20	-
1800	30	-
2000	-	-

The recharge models generate mean annual recharge values for each annual precipitation category for the different combinations of hydraulic conductivities and vadose zone thicknesses (8 x 5 = 40 combinations for each precipitation category). The average, minimum and maximum values of the mean annual recharge were determined for each precipitation category (Table 6). For each precipitation rate, the recharge estimates vary greatly due to the influence of different hydraulic conductivity values (see Appendix 3); the varying vadose zone thickness did not have a large impact on the results. In addition, the average values for mean annual recharge represent an increasing proportion of precipitation as total precipitation rates rise (see Appendix 3).

Table 6 Modelled Recharge Rates

Precipitation (mm/year)	Average Value Mean Annual Recharge (mm/year)	Minimum Value Mean Annual Recharge (mm/year)	Maximum Value Mean Annual Recharge (mm/year)
400	88	28	128
600	182	81	312
800	266	165	329
1000	377	266	441
1200	496	378	564
1400	620	494	691
1600	747	614	817
1800	876	737	948
2000	1006	859	1082

Although the average values for mean annual recharge do not represent the full range of possible recharge values resulting from varied hydraulic conductivities, they provide an estimate of recharge anticipated that is useful for relative ranking within the study area. HELP has previously been shown to overestimate recharge values in semi-arid areas (by ~20% of precipitation) due to an underestimation of evapotranspiration (Liggett and Allen, 2010); however, the modelling approach provides a range of spatially variable recharge for the study area.

Estimated recharge rates were mapped across the study area based on the spatial distribution of precipitation (PRISM data) by assigning the average value for mean annual recharge rate for each annual precipitation range. Recharge rates were ranked in equal intervals of 100 mm/year (Table 7). The resulting recharge parameter map is shown in Figure 4, representing the relative variations in recharge throughout the study area based on precipitation patterns. Areas with low ranking reflect low precipitation values, which are anticipated for much of the study region (e.g. annual precipitation is 482 mm at Dawson Creek and 513 mm at Fort St. John).

Table 7 Recharge Parameter Ranking Table

Average Annual Recharge (mm/year)	Ranking
0 – 99	1
100 – 199	2
200 – 299	3
300 – 399	4
400 – 499	5
500 – 599	6
600 – 699	7
700 – 799	8
800 – 899	9
900 – 999+	10

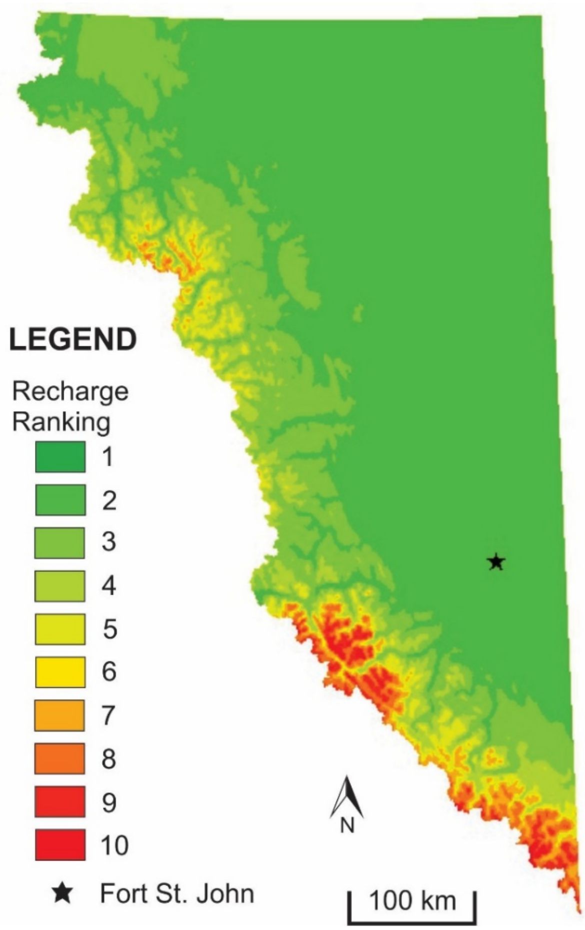

Figure 4 Recharge Parameter Map

3.3 AQUIFER MEDIA

The properties of the aquifer media affect the persistence and movement of potential contaminants, whereby more permeable aquifers (i.e. more pore space or more fracturing) lead to a decreased potential for natural attenuation of contaminants due to faster transport, thus increasing the intrinsic vulnerability (Aller et al., 1987). There are 59 mapped aquifers within the study area; however, several of these are confined, and the level of hydrogeological characterization for most of the aquifers is limited. In addition, the majority of the mapped aquifers are located near Fort St. John (Figure 5). Therefore, classification of the aquifer media was based on the surficial and bedrock geology maps that cover the Northeast BC region. This approach assumes that potential “aquifers” are present in all subsurface materials, albeit with varying characteristics and permeability.

The national low-resolution (1:5,000,000 scale) surficial geology map extends throughout the study area (Figure 5), with a higher resolution (1:250,000) map available surrounding Fort St. John (outline box in Figure 5). These maps were combined in GIS to represent the surficial geology throughout the region. It is assumed that where surficial materials are identified, they are of sufficient thickness to comprise the shallow near surface (~30 m) geological materials. This was confirmed by comparing the bedrock topography (where it is known within a small area around Fort St John) to ground surface elevation, which indicates surficial materials are up to 200 m thick. However, this neglects the potential of confined surficial sediments, where clay present at the surface may be overlying a more productive aquifer at depth. Without additional data regarding layering of the surficial sediments, this approach was considered a reasonable approximation. One exception is where the surficial geology maps identify materials less than 2 m thick, which is termed a “veneer”. It was assumed that where sediment veneer is present, the aquifer media is bedrock. All areas in the surficial geology maps identified as bedrock (either bedrock exposed at surface or sediment veneers) were imposed with the bedrock geology maps which provide detailed descriptions of the specific bedrock geology encountered.

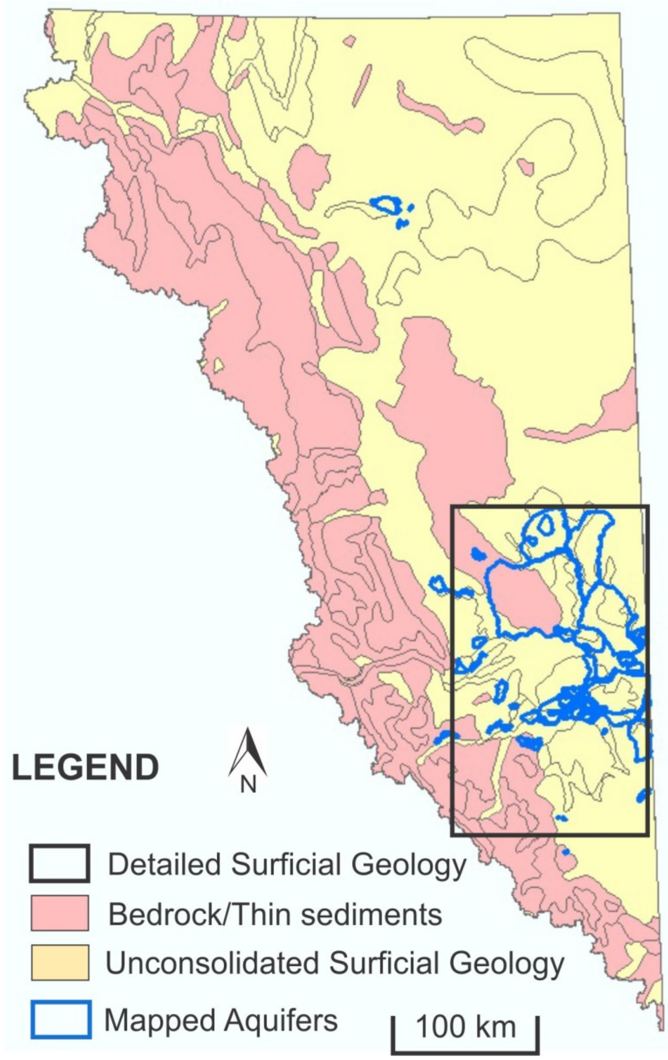

Figure 5 Generalised Surficial Geology and Mapped Aquifers in Northeast BC. [The black rectangle shows the area around Fort St. John with higher resolution surficial geology data].

Each aquifer material or rock type was ranked based on its hydrogeological properties according to the original DRASTIC ranking table (Table 8). An additional aquifer media class was identified in the study region that includes organic deposits of peat and muskeg. These deposits occur primarily in the northeast portion of the study area. The permeability of peat deposits generally decreases significantly with depth (Holden and Burt, 2003) so that the overall permeability of a peat aquifer is low. In addition, eolian sediments were ranked slightly lower than sand and glaciofluvial deposits due to their higher percentage of fine-grained materials. The resulting aquifer media parameter map is shown in Figure 6. As more detailed geologic maps become available (particularly in the northeastern portion of the study area), the aquifer media map could be refined.

Table 8 Aquifer Media Parameter Ranking Table

Aquifer Media	Ranking
Massive Shale	1
Metamorphic / Igneous	2
Organics	3
Silt, Clays, Glaciolacustrine	4
Glacial Till	5
Interbedded Sandstone and Shale	6
Massive Sandstone / Limestone	7
Eolian Sediments	8
Sand and Gravel, Glaciofluvial	9

Note: a ranking of 10 was not assigned as these materials (high permeability karstic limestone and basalt) were not identified in the study area.

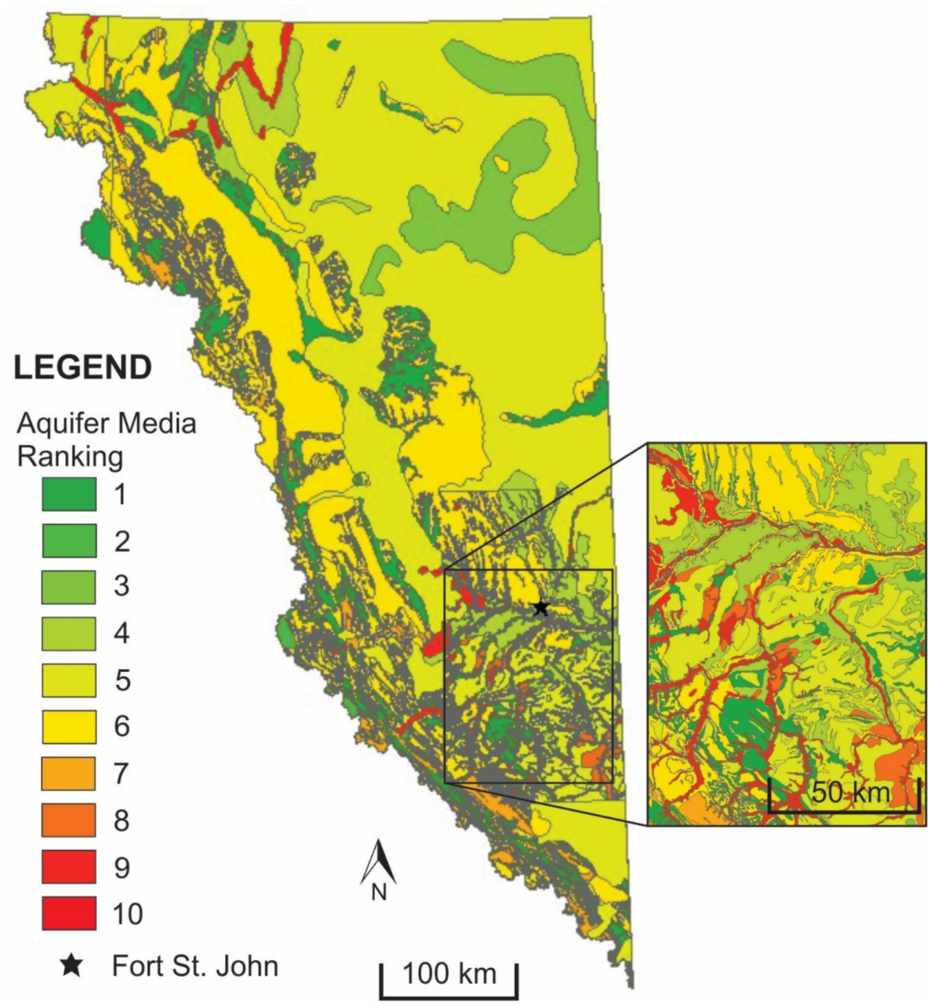

Figure 6 Aquifer Media Parameter Map

3.4 SOIL MEDIA

The properties of the soil media affect whether a potential contaminant is likely to infiltrate into the subsurface, rather than forming overland runoff. Infiltration potential is higher for soil materials that drain well; therefore, intrinsic vulnerability is higher. The soil media parameter was characterised based on the compiled soil survey map for Northeast BC (BCMOE Soil Mapping for BC 1:50,000). This map includes soil attributes such as the soil classification, texture, description, and parent material. However, the soil classifications do not match the DRASTIC original rankings which identify loams, muck, and non-shrinking clay. Therefore, a modified approach was used to assess the soil media in the study area based on the soil drainage characteristics.

Within the soil survey database, soil types are related to a soil drainage classification (Table 9). Each soil was assigned a ranking based on the drainage classification that corresponds to typical behaviour of the soil types found in the original DRASTIC assessment. All soil classifications are presented alongside the assigned drainage classification in Appendix 4.

Table 9 Soil Media Parameter Ranking Table

Soil Drainage Classification	Ranking
very poorly drained	3
poorly drained	4
imperfectly drained	5
moderately well drained	6
well drained	8
rapidly drained	9
very rapidly drained	10

Note: Rankings for 1 and 2 were not assigned as these correspond to soil types that were not identified in the soil survey (muck and confining clay).

The soil media parameter map is shown in Figure 7. The northern parts of the study area have no soil survey data, so the assessment is of lower confidence (hatched area in Figure 7). The soil types in these areas were interpreted based on adjacent areas with soils data, and the surficial geology. In areas where no soil texture or drainage class was specified (due to gaps in the database), the soils were classified based on the soil parent material according to an estimate of the likely corresponding drainage characteristics. Four parent material types are present in areas where soil texture classifications are absent. These include Peat (well drained); Till (imperfectly drained); Bedrock (soil absent); and Fluvial (rapidly drained). Areas with no soil (where bedrock is exposed at surface) were ranked as having soil that is very rapidly draining, in accordance with absent soil cover in the original DRASTIC rankings (Aller et al., 1987).

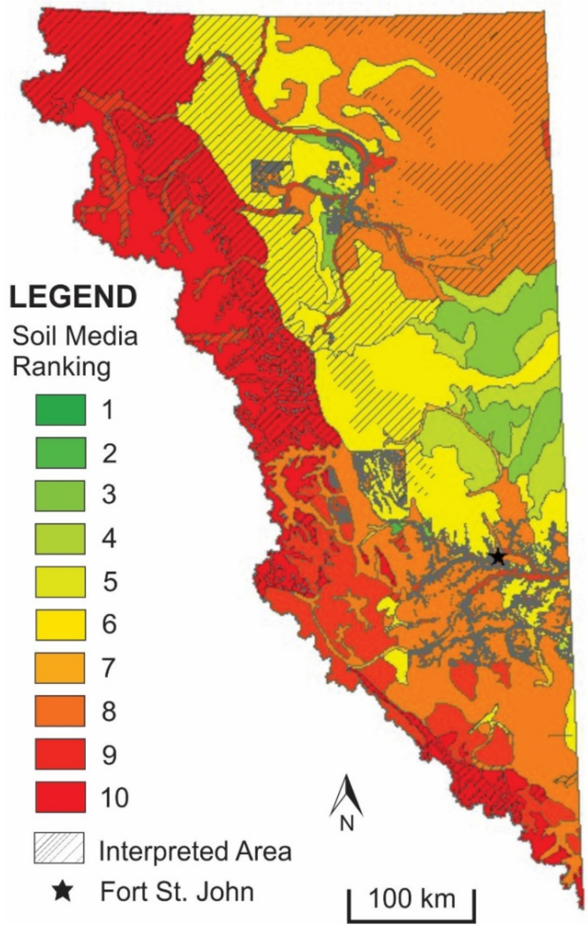

Figure 7 Soil Media Parameter Map

3.5 TOPOGRAPHY

The topography of the land surface affects whether the contaminant will move as overland runoff or whether it will infiltrate into the subsurface. Where there is steep topography, more runoff is expected. The topography parameter was characterised based on the slope of the land surface. Slope was calculated in GIS using the 25-m digital elevation model, and classified according to the original DRASTIC rankings (Table 10). The resulting topography parameter map is shown in Figure 8.

Table 10 **Topography Parameter Ranking Table**

Topography Slope (%)	Ranking
18+	1
13 – 18	3
7 – 12	5
3 – 6	9
0 – 2	10

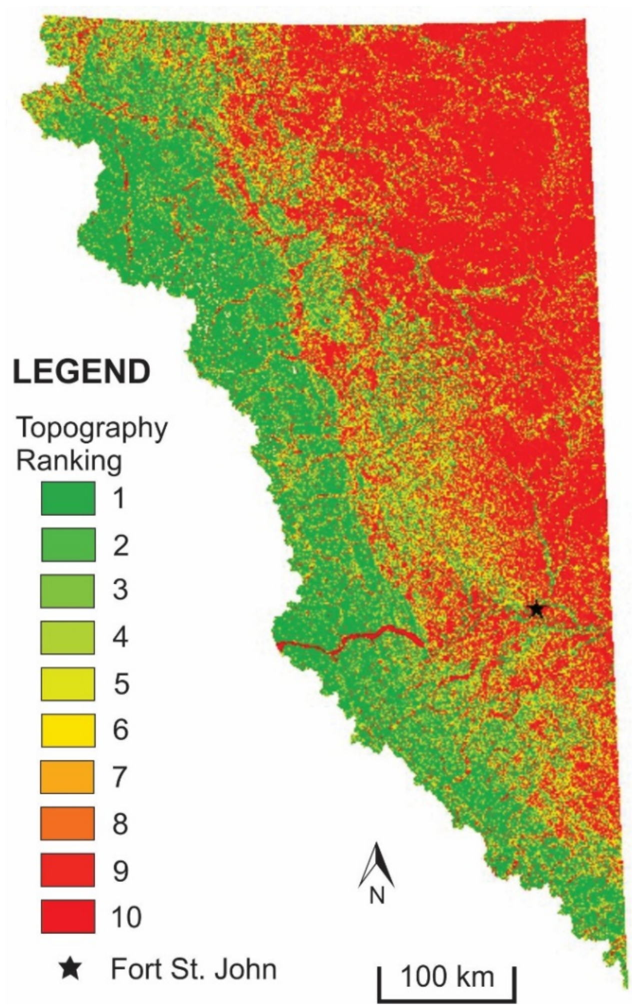

Figure 8 **Topography Parameter Map**

3.6 Impact of Vadose Zone

The properties of the vadose zone affect the migration of potential contaminants into the aquifer. The more permeable the vadose zone, the more likely the contaminant is able to reach the aquifer, thus increasing intrinsic vulnerability. The vadose zone materials were characterised based on the surficial geology maps described in Section 3.3. Areas with thin surficial sediments (i.e. veneers) were included in the impact of vadose zone assessment as they represent part of the vadose zone (i.e. these thin sediments were not ignored as they were for Aquifer Media). The impact of the vadose zone was classified according to the vadose zone material type, as in the original DRASTIC rankings (Table 11).

Table 11 Impact of Vadose Zone Parameter Ranking Table

Vadose Zone Material	Ranking
Glaciolacustrine, Organics	4
Till	5
Bedrock	6
Eolian	7
Glaciofluvial	8
Fluvial	9

Note: Rankings 1, 2, 3, and 10 were not assigned as these correspond to materials not identified in the study area (i.e. homogenous clays, and highly permeable bedrock materials).

Bedrock was assigned a moderately high impact of vadose zone rating (Table 11) based on the assumption that the bedrock near the surface is likely highly weathered and will allow for rapid infiltration. However, no distinction was made for type of bedrock. Organic peat and muskeg occurrences were assigned with the same ranking as glaciolacustrine materials, based on the rationale that although peat may have high permeability near the surface, the permeability tends to decrease rapidly within 1 m of the land surface (Holden and Burt, 2003). Therefore, these materials are likely to limit infiltration and are not anticipated to promote contaminant migration. The resulting impact of the vadose zone parameter map is shown in Figure 9.

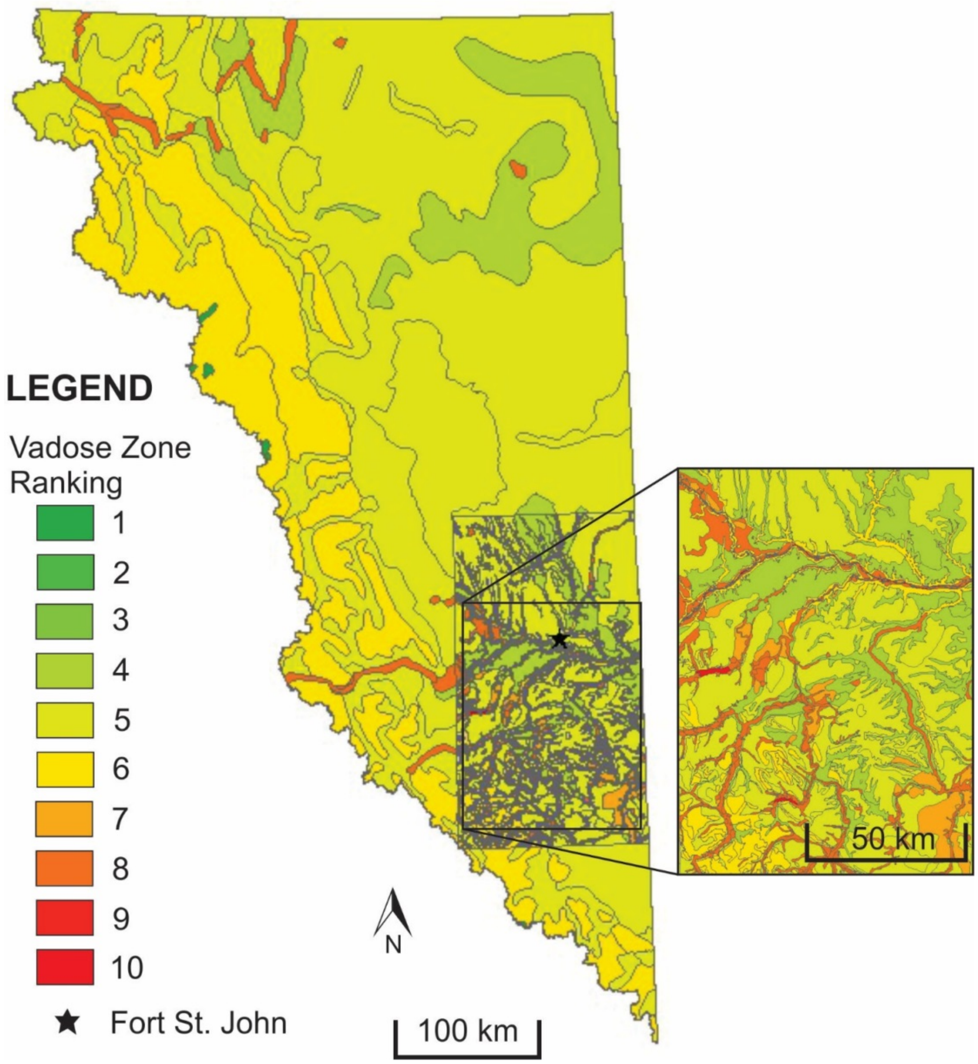

Figure 9 Impact of Vadose Zone Parameter Map

3.7 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity of the aquifer affects the rate at which potential contaminants spread once they have reached the water table, such that higher hydraulic conductivity results in higher intrinsic vulnerability. The hydraulic conductivity parameter is similar to the aquifer media and vadose zone media parameters as they also describe the relative permeability of the subsurface geological materials. Ideally, field-measured hydraulic conductivity values would be available for a study area. However, there are limited hydraulic conductivity data for Northeast BC; only five pumping tests were available at the time of this study for providing estimates of hydraulic conductivity in a few material types (Table 12).

Table 12 Pumping Test Results from Northeast BC

Test Well ID	Main Aquifer Lithology	Hydraulic Conductivity Range (m/day)
416	Shale and Sandstone	8 – 30
417	Shale and Sandstone	0.7 – 0.8
419	Shale and Sandstone	0.5 – 0.6
420	Weathered Shale	3 – 4
421	Till	0.01 – 0.1

Note: Test Well ID relates to the provincial observation well. Data from Baye (2013).

The large range in hydraulic conductivity values for similar aquifer lithologies (e.g. shale and sandstone) represents the heterogeneity and fracture-specific nature of hydraulic conductivity estimates. This poses a challenge for mapping the spatial distribution of hydraulic conductivity across the study area. Therefore, a modified approach was used to assign hydraulic conductivity rankings based on estimated values for the aquifer media (see Section 3.3). Each aquifer media type was assigned a typical hydraulic conductivity value based on literature ranges (Freeze and Cherry, 1977; Domenico and Schwartz, 1990). These ranges are lower than the limited pumping test data, indicating that the assessment may be under-estimating the conductivity in bedrock zones. However, the anticipated relative conductivity of the unconsolidated geology is preserved. A DRASTIC ranking was assigned to each aquifer material to represent the relative difference (in orders of magnitude) between estimated hydraulic conductivities (Table 13). The ranking used in this study represents a much larger range in data than the original DRASTIC tables, which only represent hydraulic conductivity values between approximately $1x10^{-2}$ to $1x10^{-+2}$ m/day (Aller et al., 1987). The modification to the rankings is appropriate to capture the variability in hydraulic conductivities anticipated for the study area. The resulting hydraulic conductivity parameter map is shown in Figure 10. Overall, the aquifer material is ranked with relatively low conductivity due to the predominance of till materials and bedrock.

Table 13 Hydraulic Conductivity Parameter Ranking Table

Aquifer Material	Estimated Hydraulic Conductivity (m/day)	Ranking
Massive Shale, Igneous, Metamorphic	$1x10^{-7}$	1
Organics, Silt, Clay, Glaciolacustrine	$1x10^{-6}$	2
Till, Bedded Sandstone/Shale	$1x10^{-4}$	4
Massive Sandstone, Shale	$1x10^{-3}$	5
Eolian Sediments	$1x10^{+1}$	9

Sand and Gravel, Glaciofluvial	$1x10^{+2}$	10

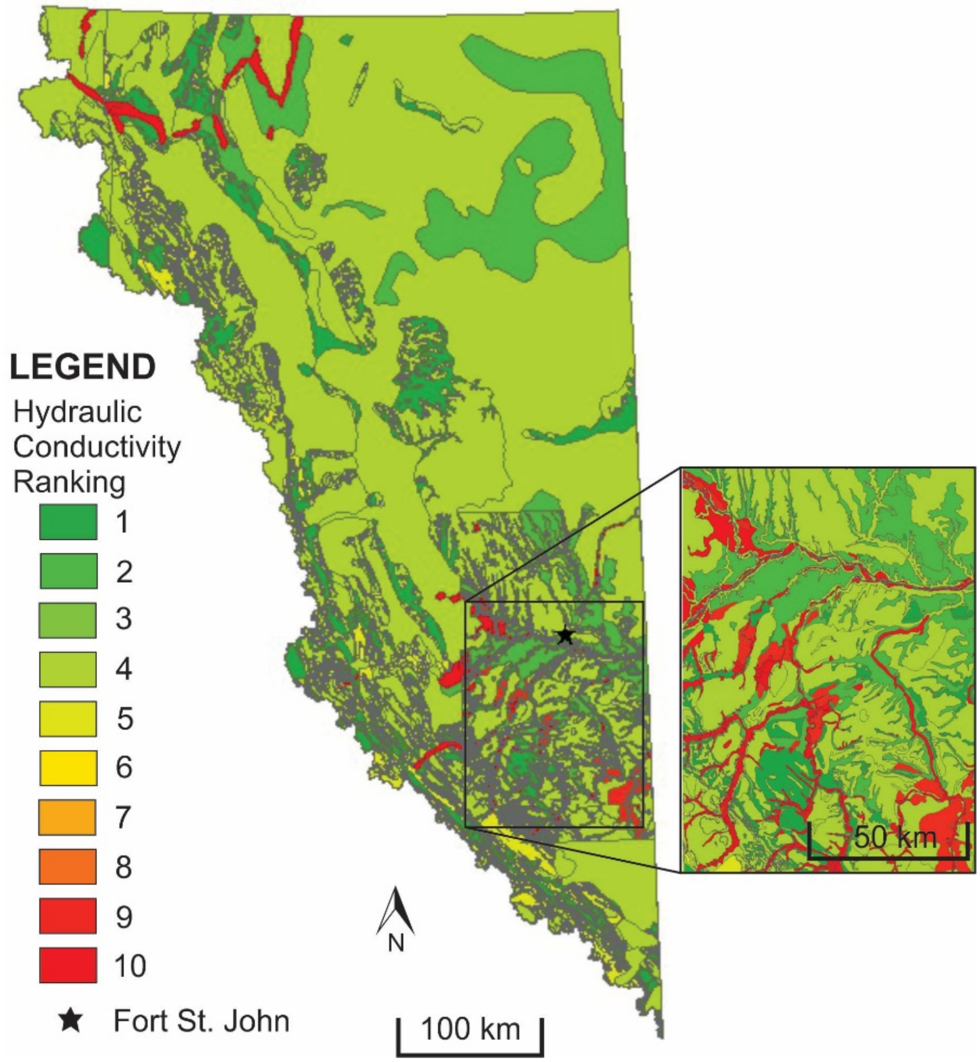

Figure 10 **Hydraulic Conductivity Parameter Map. Grey colouring reflects closely-spaced outlines of the different geologic units.**

4. RESULTS AND DISCUSSION

The maps for each parameter were weighted and added in GIS (see Table 1) to result in an intrinsic vulnerability map of the shallow subsurface for the study area (Figure 11). Areas of higher vulnerability are shown in red with areas of lower vulnerability in green. Areas of higher vulnerability are predominantly present along the mountainous western edge of the region where there is high elevation bedrock. Higher vulnerability is the result of generally shallow water tables combined with high recharge rates, high permeability weathered bedrock, and limited soil cover. Other higher vulnerability areas include river valleys where the vadose zone and aquifer media have large proportions of sand and gravel. It should be noted that the results represent the relative assessment of intrinsic vulnerability, so that areas ranked low are still vulnerable to surface contamination, although they are relatively less vulnerable than other parts of the study area. The DRASTIC score within the study area ranges from 55 to 191.

The MOE uses an additional classification approach for DRASTIC results based on the total DRASTIC score to distinguish areas of low (0-100), moderate (100-160) and high (160+) intrinsic vulnerability. When the results of this study are presented within this categorisation, the study area represents predominantly low or moderate intrinsic vulnerability (Figure 12). Areas of high vulnerability are present at a small scale, particularly where the aquifer media is characterised by high permeability.

The DRASTIC assessment results appear significantly different when comparing the results on a relative scale (Figure 11) to the results within the MOE categorisation (Figure 12). This is because the broad MOE categories reduce some of the resolution to the data. This broad approach is intended for comparison of the results with other areas across BC as they are based on the same classification of the final DRASTIC scores (low, moderate and high). However, due to the modifications in the rankings that many DRASTIC assessments (including this study) employ in order to capture local variability (Wei, 1998; Liggett and Gilchrist, 2010; Liggett and Allen, 2011) the total DRASTIC scores from assessments in different parts of BC may not be entirely comparable. For instance, hydraulic conductivity values may be ranked differently within different DRASTIC assessments. In addition, the broad MOE approach neglects some of the relative high and low areas of intrinsic vulnerability within the study area. At a local scale, these areas may be meaningful for informing water managers and decision-makers, and so were represented in this study. Overall, presentation of the DRASTIC results should be tailored to the intent of the application (i.e. local-scale decisions or province-wide comparisons).

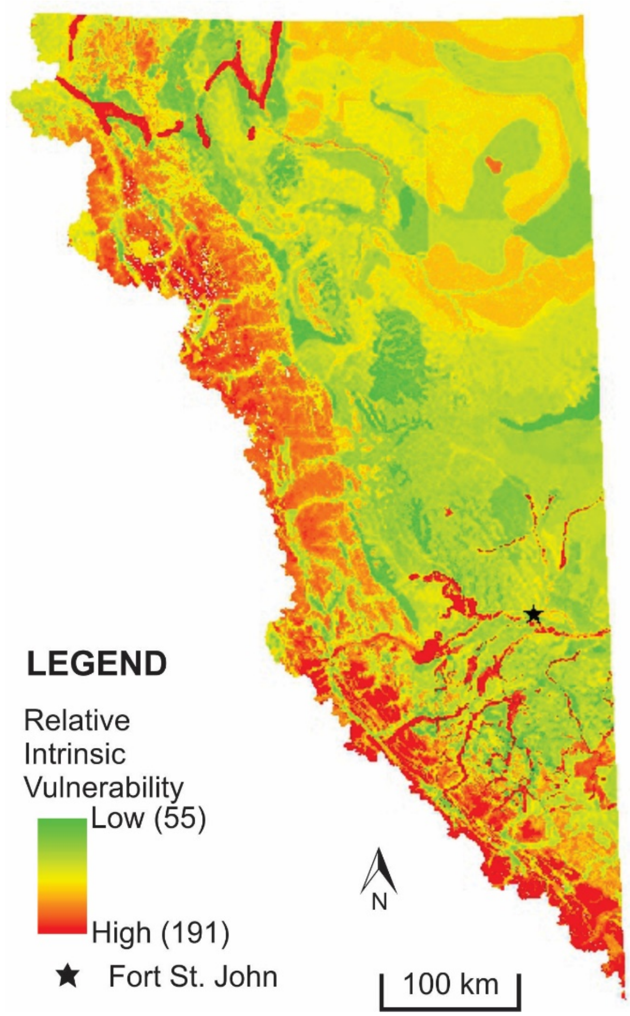

Figure 11 Relative DRASTIC Intrinsic Vulnerability. Areas ranked with low relative intrinsic permeability may be vulnerable to contamination as these areas only rank relatively lower compared to other areas.

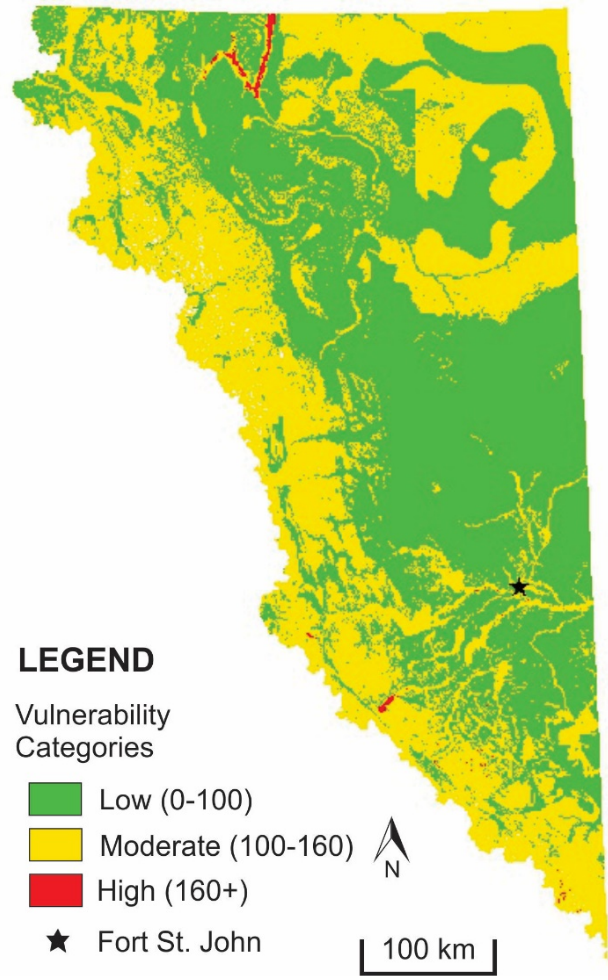

Figure 12 Ministry of Environment Categorisation of DRASTIC Intrinsic Vulnerability. Areas ranked with low relative intrinsic permeability may be vulnerable to contamination as these areas only rank relatively lower compared to other areas.

One limitation of the intrinsic vulnerability assessment is inherent to the DRASTIC method, which only accounts for potential groundwater contamination occurring from a source at ground surface. This means that potential contamination sources from below ground (e.g. gas migration along well casings; buried tanks or pipelines) are not represented. However, the predominant contaminant sources in the study area are related to land surface activities and are likely to result from surface spills (Rozell and Reaven, 2012). In addition, the majority of water wells within the study area are installed within the top 30 mbgs (see Section 3.1). Therefore, it is appropriate to focus on the shallow geological materials, and DRASTIC is considered a suitable approach. Another limitation of the assessment is due to the generalised approach adopted for this particular region with sparse data. The approach relies on estimated and representative values (e.g. hydraulic conductivity); however, it introduces potential error in the assumptions made. As a result, some local-scale features and areas of concern may not be captured. However, as additional data are made available, the assessment can be updated to reflect higher data resolution and to confirm or revise the approach as necessary.

In the meantime, the results of this assessment provide a preliminary assessment of the relative intrinsic vulnerability of near surface geological materials throughout Northeast BC based on the data available, so that areas of relatively higher vulnerability can be identified. This can assist water managers in identifying potential monitoring locations and investigation priorities, siting of wastewater facilities and spill response planning, as well as community land use planning. The results of the assessment may also support risk assessment when combined with specific hazards and known stresses to characterise the associated risk with these activities. In fact, this additional work is in progress at SFU. Finally, caution should be applied when using these maps to acknowledge the inherent limitations and uncertainty related to the data sources. This is particularly relevant for small-scale applications where local data should be included to augment the assessment and evaluate the vulnerability maps.

5. CONCLUSIONS

The intrinsic vulnerability assessment for Northeast BC was carried out to evaluate the intrinsic vulnerability of near surface geological materials (shallow groundwater) to contamination originating at land surface. Although there are limitations to the assessment, particularly sparse data for such a large region of the province, the intrinsic vulnerability map represents the existing data and allows for preliminary interpretation of potential aquifers where they are not yet characterised. It is anticipated that the assessment may be adjusted and updated as additional data characterising the aquifers become available. The results of this assessment may provide useful information to support water management and protection, and the development of policy and regulations in this region of rapid shale gas development.

Acknowledgements

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This report was reviewed by Laurie Welch (BC Oil and Gas Commission), Mike Wei and Klaus Rathfelder (BC Ministry of Environment).

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7. APPENDIX

APPENDIX 1

Figure A1.1: Scatter plot of inferred groundwater elevation (WELLS database and digital elevation model) vs. ground elevation in study area.

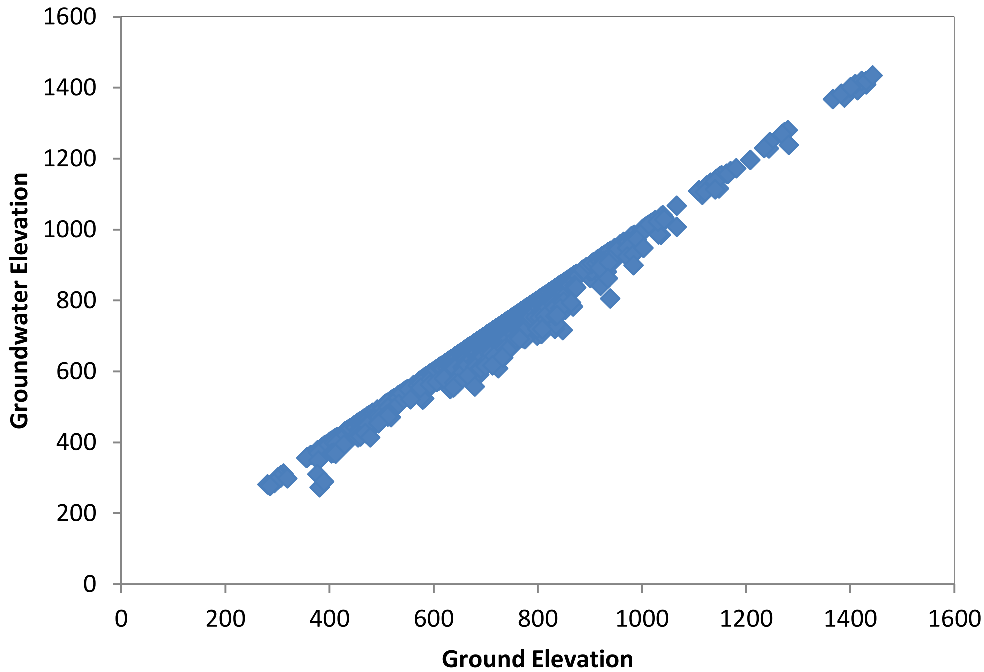
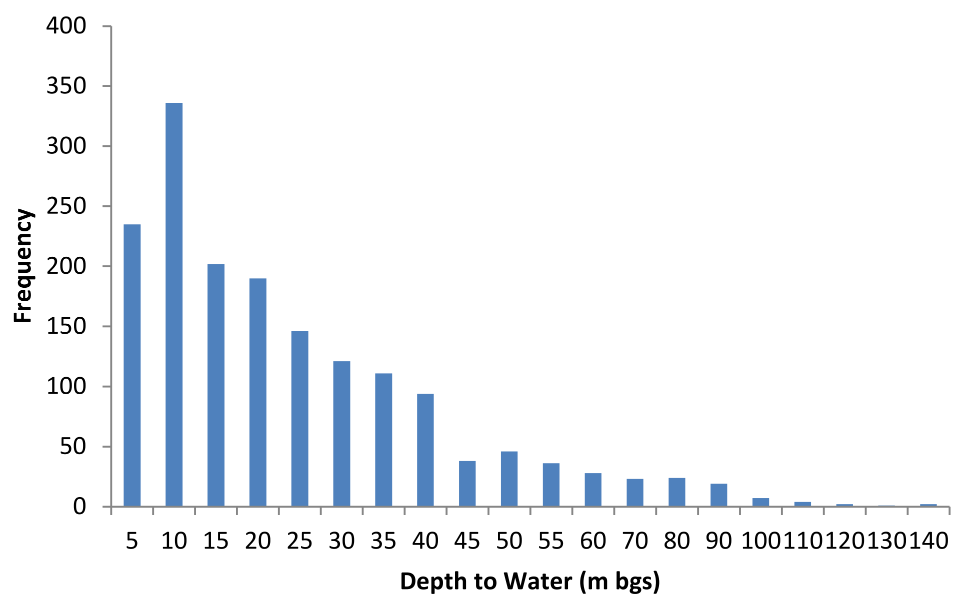


Figure A1.2: Histogram of depth to water measurements in study area (WELLS database).



APPENDIX 2

Figure A2.1: Climate Normals for Dawson Creek (DC) and Fort Nelson (FN) (1981-2010)

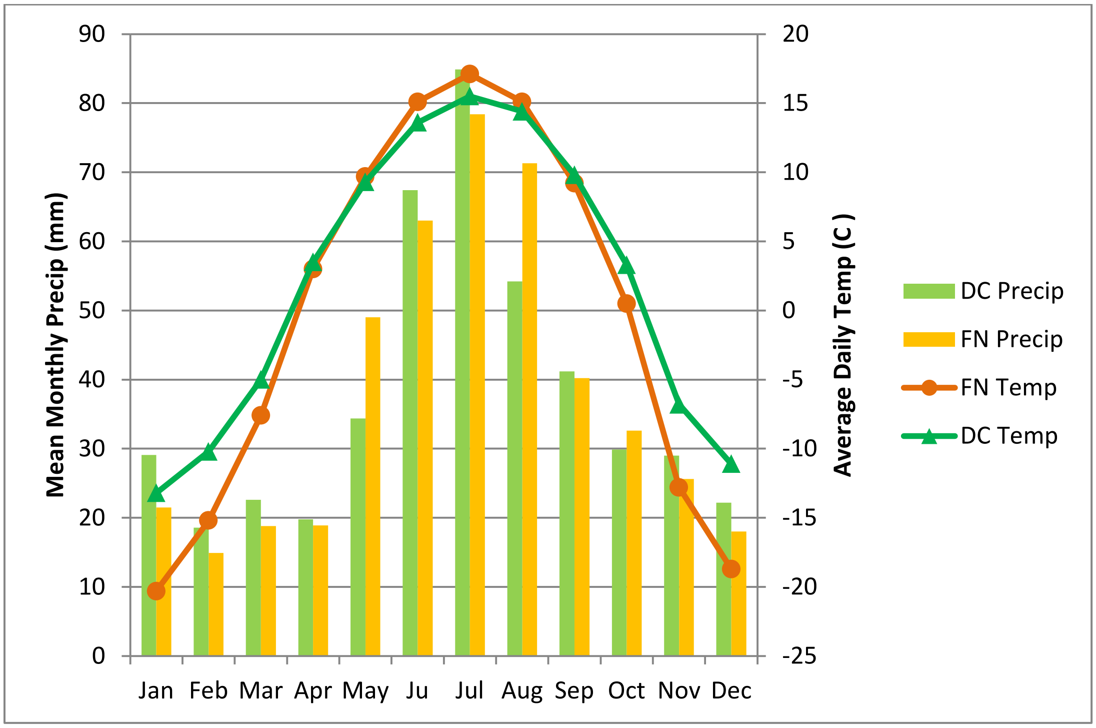
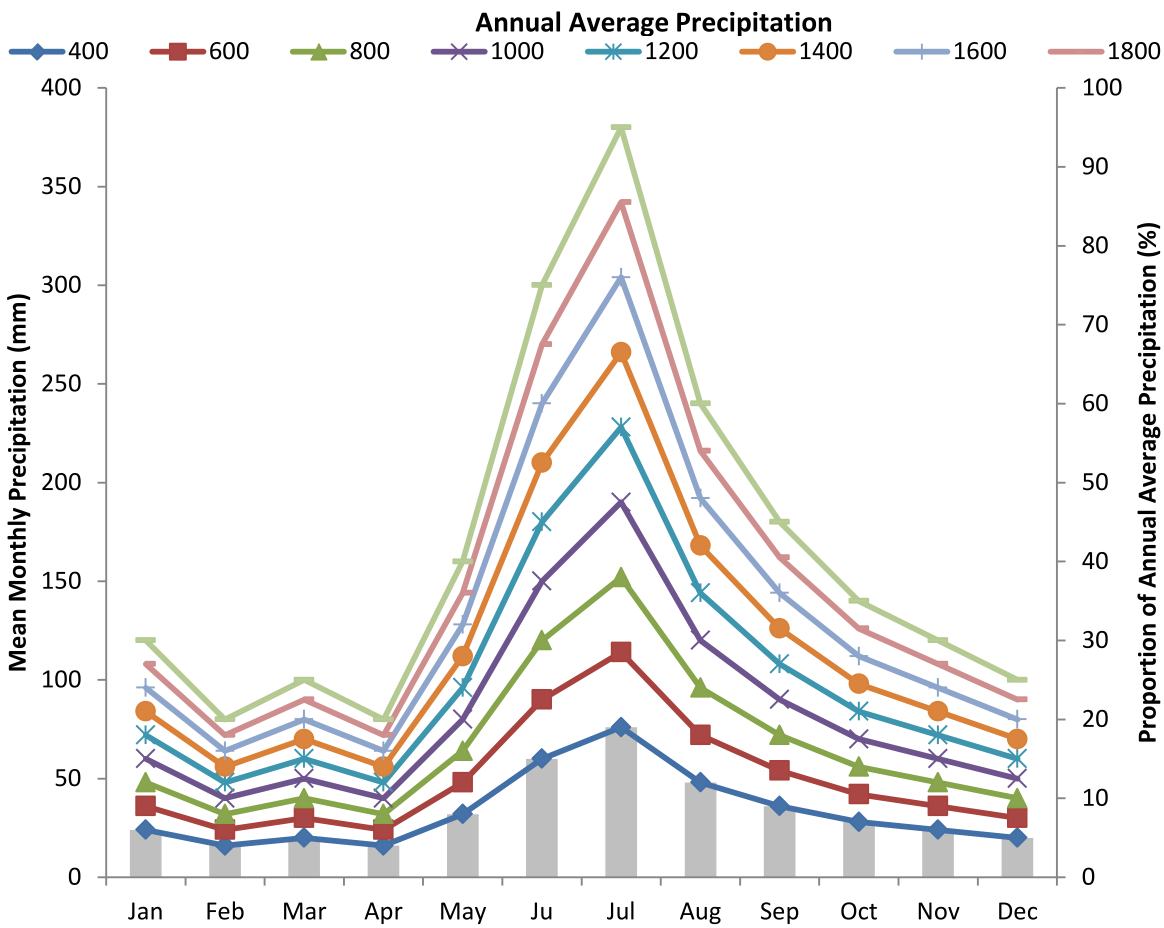


Figure A2.2: Mean Monthly Precipitation. These values were calculated based on the proportion of annual average precipitation that occurred in each month from the Dawson Creek climate normals (shown on the secondary axis). The estimated total annual average precipitation rates (from 400 to 2000 mm/year) were then distributed as mean monthly precipitation rates based on the same proportions.



APPENDIX 3

Figure A3.1: Recharge model results. Average annual recharge values are shown for different precipitation and hydraulic conductivity categories; results are shown for 10 m vadose zone category. Results for other vadose zone categories are very similar.

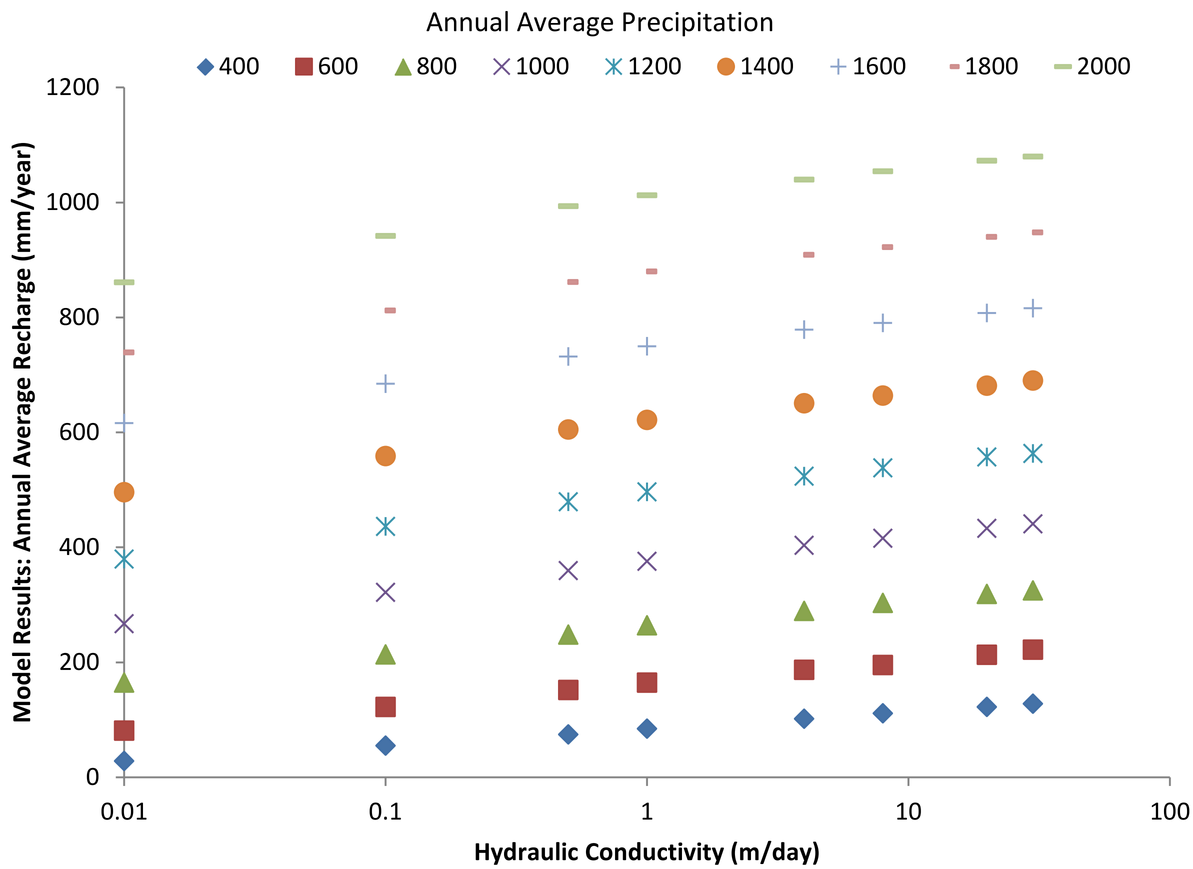
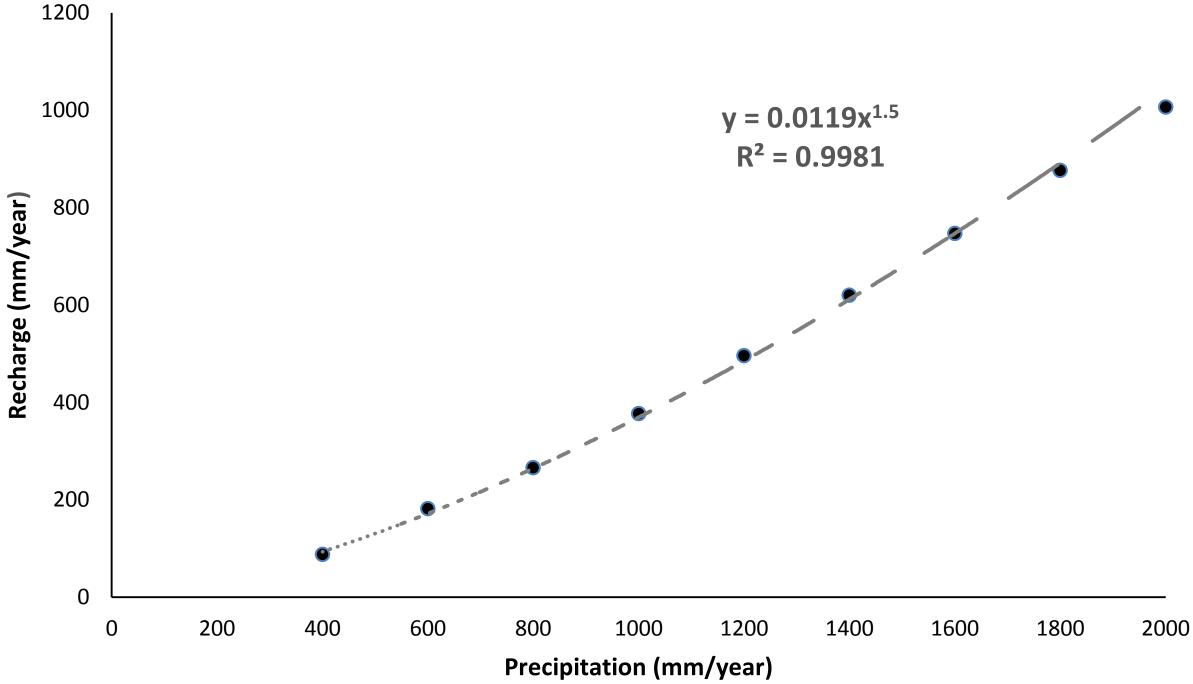


Figure A3.2: Average values for mean annual recharge as a power function equation of the relationship between recharge and precipitation.



APPENDIX 4

Table A4.1: Soil classifications with corresponding drainage classification (BCMOE Soil Mapping for BC 1:50,000)**.**

Soil Classification	Drainage Classification
BL.SO	Well Drained
BR.GL	Well Drained
CU.R	Moderately Drained
D.GL	Moderately Drained
DG.DYB	Rapidly Drained
DG.EB	Well Drained
DG.SO	Well Drained
E.BL	Well Drained
E.DYB	Rapidly Drained
E.EB	Well Drained
G.SO	Well Drained
GIO.GL	Imperfectly Drained
GL.GL	Imperfectly Drained
GL.R	Imperfectly Drained
GLSZ.GL	Poorly Drained
LI.DG.DY	Well Drained
LIO.GL	Well Drained
M	Poorly Drained
ME.OC	Very Poorly Drained
O.DYB	Rapidly Drained
O.EB	Rapidly Drained
O.G	Poorly Drained
O.GL	Imperfectly Drained
O.HG	Poorly Drained
O.LG	Poorly Drained
O.R.	Rapidly Drained
PZ.GL	Well Drained
R	Well Drained
R.B	Moderately Drained
R.BI	Rapidly Drained
R.BLC	Rapidly Drained
R.G	Poorly Drained
R.HG	Poorly Drained
SO.DG	Well Drained
SZ.DGC	Moderately Drained
SZ.GL	Well Drained
T.M	Very Poorly Drained
TFI.M	Very Poorly Drained
THU.F	Well Drained
TME.F	Very Poorly Drained
TY.M	Very Poorly Drained