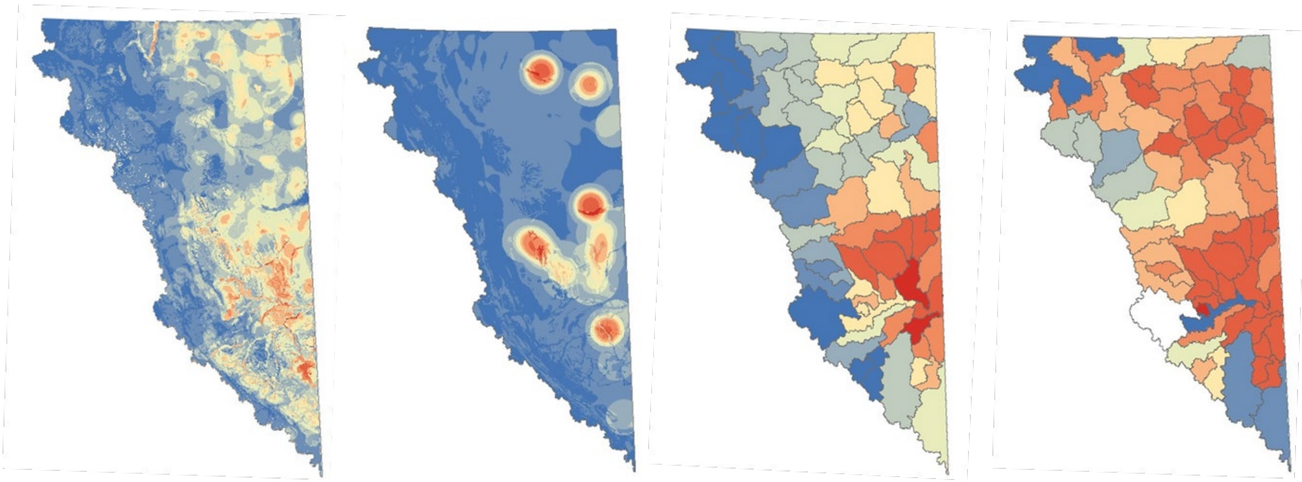
SFU
Department of
Earth Sciences



Groundwater and Surface Water Quality and Quantity Vulnerability Mapping in Northeast British Columbia

Technical Report

Shannon Holding, Zachary McKoen and Diana M. Allen
Simon Fraser University
June 2018

Suggested Citation: Holding, S., McKoen, Z. and Allen, D.M. (2015): Groundwater and Surface Water Quality and Quantity Vulnerability Mapping in Northeast British Columbia: Technical Report. Simon Fraser University, June 2018, 17 pp.

Executive Summary

Hazard-specific vulnerability mapping was conducted across Northeast British Columbia (NEBC) to identify areas most vulnerable to water quality and quantity deterioration due to oil and gas activities. Vulnerability represents the combination of a specific hazard threat and the susceptibility of the water system to that threat. Hazard threats (i.e. potential contamination sources and water abstraction) were mapped spatially across the region. The shallow aquifer susceptibility to contamination was assessed using the DRASTIC approach, while the aquifer susceptibility to abstraction was assessed according to aquifer productivity. Surface water susceptibility to contamination was assessed on a watershed basis to describe the propensity for overland flow (i.e. contaminant transport), while surface water susceptibility to water abstractions was assessed using watershed runoff estimates. The spatial distribution of hazard threats and susceptibility were combined to form hazard-specific vulnerability maps for groundwater quality, groundwater quantity, surface water quality and surface water quantity. The vulnerability maps identify priority areas for further research, monitoring and policy development.

Table of Contents

1. Introduction

Hydraulic fracturing and oil and gas production generate wastewater. The amount and chemical composition of wastewater depends on the type of fracturing activities, original source of water (fresh, saline, or recycled), subsurface geology, and the phase of well development (i.e. fracturing or production). Although wastewater varies in its composition, it is generally a solution with high concentrations of salts, metals, metalloids, naturally occurring radioactive materials (NORMs) as well as numerous proprietary chemical constituents. Recognized hazards associated with shale gas activities include spills and leakages resulting from handling, transport or disposal of the chemicals used in hydraulic fracturing or of the wastewater that is produced. The potential contamination from wastewater poses a threat to drinking water supplies and healthy aquatic ecosystems (Council of Canadian Academies, 2014).

This study builds on a previous study by Holding and Allen (2015) in which the intrinsic susceptibility of shallow groundwater was mapped throughout the Peace Region of Northeast British Columbia (NEBC). Here, the hazard-specific vulnerability mapping conducted in the Peace Region aims to characterize areas most vulnerable to water quality and quantity deterioration due to oil and gas activities. Vulnerability represents the combination of a specific hazard threat and the susceptibility of the water system to that threat (Equation 1).

$$\textbf{Vulnerability = Susceptibility x Hazard Threat} \qquad \text{Eq. 1}$$

Mapping of vulnerability, therefore, requires spatial datasets that can be integrated in such a fashion to assess susceptibility and the range of hazard threats. For this study, spatial physical data for characterizing the aquifer system and watersheds were acquired from Data BC (https://data.gov.bc.ca/). Spatial hazard data were gathered from the BCOGC public zone GIS data (http://data-bcogc.opendata.arcgis.com/) in July 2015.

The following sections provide an overview of the approaches used first to assess the susceptibility of groundwater and surface water to specific hazard threats that may impact the quality and quantity of water. The mapping was carried out in ArcGIS (v. 10). Details on the spatial dataset sources, the approaches used and the various intermediate and final GIS files are provided in in the Appendix.

2. Susceptibility and Hazard Threat Mapping

Susceptibility, in the context of water security, refers to the physical characteristics of the aquifer system or watershed that make it more or less susceptible to threats related to contamination or high demand (here termed hazard threats). By aquifer system, we mean the full range of geological materials that form aquifers (permeable units) and confining units (less permeable units).

In this study, different approaches were used to map 1) the susceptibility of groundwater and surface water to 2) hazard threats that may result in deterioration of water quality or water quantity. The following sections describe the approaches used. Table 1 gives an overview of the approaches used.

Table 1: Overview of approaches used to map the susceptibility of groundwater and surface water to various hazard threats associated with oil and gas activities.

Indicator Categories		Quality	Quantity
Groundwater	Hazards	1. Oil and gas wells (density) related to chemical handling at surface and spills/leaks (all inactive/abandoned /active wells included). 2. Transportation (density) (pipelines and all oil and gas developed roads). 3. Oil and Gas Infrastructure (density) (water hubs, facilities). Each hazard is ranked 1-10. Total hazards weighted: H = (4 x wells) + (3 x roads) + (2 x pipelines) + (1 x facilities)	(Demand): Source well groundwater abstractions (density characterized based on magnitude of abstraction). Includes all source wells (inactive and active) with active wells having a higher magnitude but inactive wells still having some baseline magnitude representing the potential.
	Susceptibility	DRASTIC shallow aquifer susceptibility, where: where: D is Depth to water table; R is recharge; A is aquifer media; S is soil media; T is topography; I is impact of vadose zone; and C is conductivity.	(Supply): Inverse of aquifer productivity (based on aquifer media from DRASTIC, where high density of domestic wells decreases potential productivity).
	Vulnerability	Hazards x Susceptibility	Supply x Demand
Surface Water	Hazards	Same Total Hazards as GW	(Demand): Surface water licenses (long and short-term) from NEWT (per watershed).
	Susceptibility	Overland flow susceptibility (T, S, I)	(Supply): Runoff from Northeast Water Tool (NEWT) per watershed. Points of surface water diversion subtracted for existing demand.
	Vulnerability	Hazards x Susceptibility (per watershed)	Supply – Demand (reclassified 1-10)

2.1. Groundwater Quality

Groundwater quality susceptibility was based on the DRASTIC method (Aller et al. 1987), where D is Depth to water table; R is recharge; A is aquifer media; S is soil media; T is topography; I is impact of vadose zone; and C is conductivity. DRASTIC is internationally known and has been applied to numerous hydrogeological settings. DRASTIC assumes that contamination occurs from ground surface sources; therefore, the method focuses on shallow geological materials and the groundwater contained in these materials within approximately 30 metres (m) of ground surface. The method does not assess the susceptibility of deeper groundwater that may be impacted from contamination originating at greater depth, but provides some indication of the relative susceptibility of shallow groundwater to sources at or just below the ground surface. Holding and Allen (2015) describe the DRASTIC mapping carried out in the Peace Region in detail. While DRASTIC was used for assessing aquifer susceptibility in this study, other methods could be employed.

The resulting groundwater susceptibility map is shown in Figure 1A (from Holding and Allen, 2015). Areas of higher susceptibility are shown in red with areas of lower susceptibility in blue. Areas of high susceptibility occur predominantly along the mountainous western edge of the region where there is high elevation bedrock. High susceptibility is the result of shallow water tables combined with high recharge rates, relatively high permeability, and limited soil cover. Other high susceptibility areas include river valleys where the vadose zone and aquifer materials have large proportions of sand and gravel.

Hazard threat to groundwater quality was assessed by mapping the potential for contamination of groundwater due to spills and leaks of industrial wastewater. Areas of high potential are associated with oil and gas wells, the location of transportation routes and pipelines, and the location of oil and gas related infrastructure. First, the spatial density of oil and gas wells was mapped. At the time of mapping, there were 30,711 recorded oil and gas wells of all operation types (active, disposal, abandoned, etc.) (Appendix). All well operation types were given the same hazard weight. Next, the spatial density of roads, pipelines (both permanent and currently in development), and oil and gas related facilities was mapped. At the time of mapping, there were 21 different facility types; all were assigned the same hazard weight.

The spatial density of all features was determined using a search radius of 15,000 km^2 and a 500 m output cell size. The total groundwater hazards layer (Figure 1B) was generated using a weighted sum (i.e. multiplying the individual density maps for facilities, wells, roads and pipelines by weights of 4, 3, 2 and 1, respectively). These weights were applied to reflect the relative likelihood of each being a potential source of contamination. This produced a combined hazard threat density map that was reclassified to a 1-10 scale (Figure 1B).

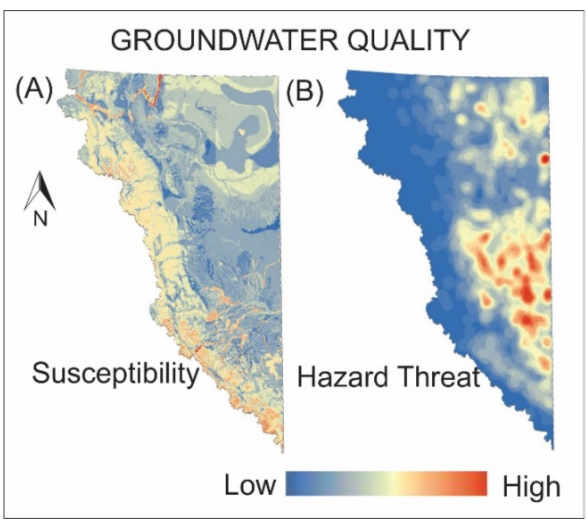


Figure 1. Groundwater Quality (A) Susceptibility: DRASTIC shallow aquifer susceptibility assessment. (B) Hazard Threat: associated with activities related to shale gas development (facilities, wells, roads, and pipelines). Hazard threat is represented as weighted cumulative density.

2.2. Surface Water Quality

Surface water quality susceptibility was assessed based on the potential for overland flow (i.e. the likelihood of surface water, which could potentially be contaminated, remaining on the surface and flowing into lakes, rivers and streams). This was done by combining select component maps from DRASTIC; specifically, soil media, vadose zone impact and topography (slope). For soil media, a reverse ranking to that used in DRASTIC was employed to allow for the least permeable soils to correspond to greater overland flow potential. The soil, vadose zone, and topography maps were assigned weights of 2, 5 and 1, respectively, and then added and reclassified to a 1-10 scale (Figure 2A).

Hazard threat to surface water quality was the same as for groundwater (described above) because it is based on the likelihood of contaminants being spilled on the surface or shallow sub-surface (Figure 2B).

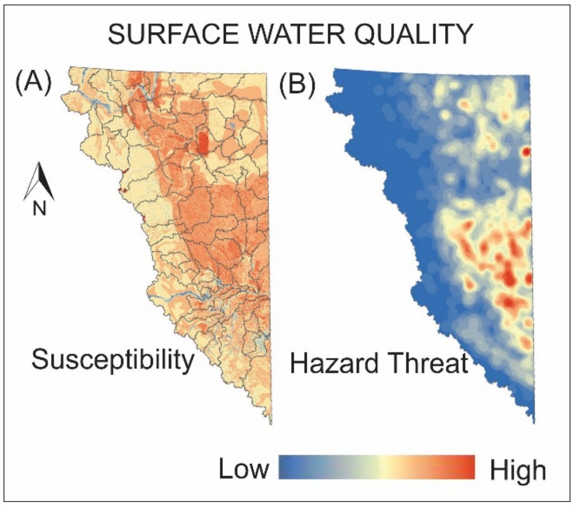


Figure 2. Surface water quality. (A) Susceptibility: Potential for overland flow, representing increased likelihood of migration of surface spills into surface water bodies. (B) Hazard Threat: associated with activities related to shale gas development (facilities, wells, roads, and pipelines). Hazard threat is represented as weighted cumulative density (same hazards used for groundwater).

2.3. Groundwater Quantity

Groundwater quantity susceptibility was assessed by estimating the aquifer supply available for shale gas development needs and was based on geological materials and existing domestic water use. First, a groundwater productivity map was generated using the aquifer media rating from DRASTIC. Areas of high groundwater productivity have highly permeable aquifer materials. The density of domestic wells was then subtracted from the groundwater productivity map to represent reduced groundwater quantity available in these areas. Thus, high groundwater productivity corresponds to low susceptibility to groundwater abstraction impacts (Figure 3A).

Hazard threat to groundwater quantity was assessed by mapping the density of oil and gas groundwater source wells. Density was assessed based on the abstraction rates for each well reported as by the BCOGC (Figure 3B).

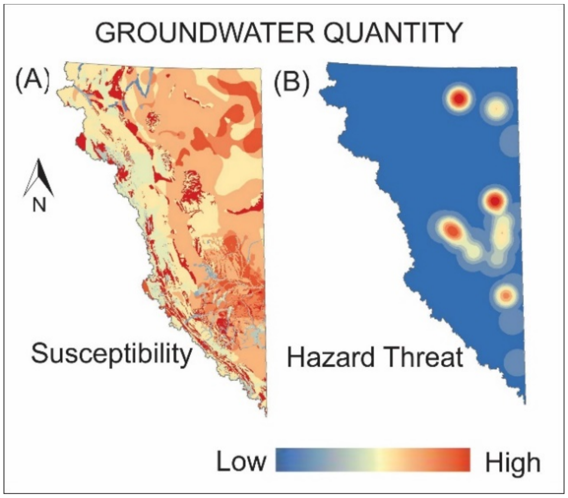


Figure 3. Groundwater Quantity (A) Susceptibility: Estimated aquifer supply available for shale gas development needs. (B) Hazard Threat: Water withdrawal for shale gas development. Represented as density map based on abstraction rates of source water wells used by the oil and gas industry.

2.4. Surface Water Quantity

Surface water quantity susceptibility was based on data extracted from the North East Water Tool (NEWT) for each watershed within Peace Region. The surface water supply per-watershed was assessed as the average annual runoff (m^3/year) minus the points of surface water diversion for uses other than oil and gas (i.e. domestic, agricultural, municipal) (Figure 4A).

Hazard threat to surface water quantity was the total approved surface water withdrawal volumes per watershed. These include short term water use approvals and long term water licenses (both oil and gas related) (Figure 4B).

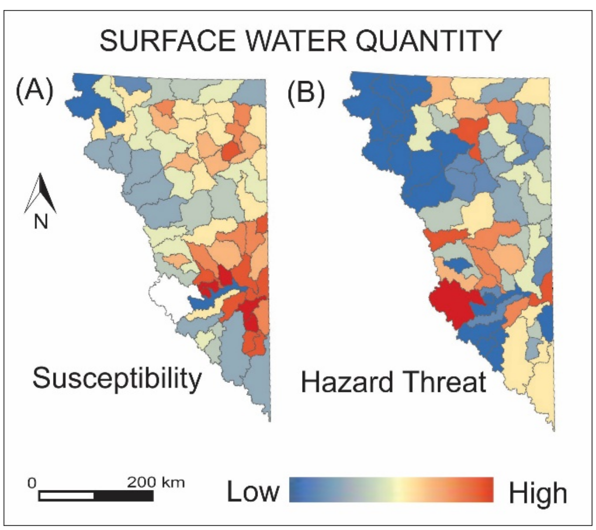


Figure 4. Surface water quantity. (A) Susceptibility: Estimated volume of surface water discharge available for shale gas development needs. (B) Hazard threat: Total approved surface water withdrawal volumes per watershed.

3. Vulnerability Mapping

Total vulnerability for each of component, groundwater quality, surface water quality, groundwater quantity, and surface water quantity, was calculated by multiplying the susceptibility map by the total hazard map. The final maps were reclassified to a 1-10 scale (Figure 5).

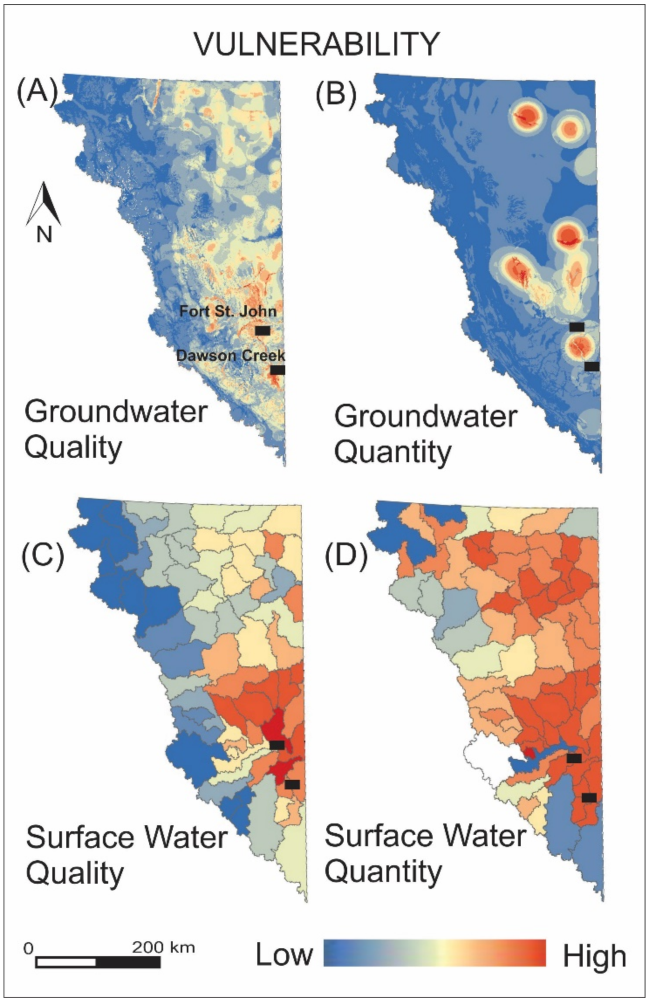


Figure 5. Vulnerability. (A) Groundwater Quality, (B) Groundwater Quantity, (C) Surface water quality, and (D) Surface water quantity.

The groundwater quality vulnerability map (Figure 5A) and the surface water quality vulnerability map (Figure 5C) identify broad areas surrounding Fort St. John and Dawson Creek where water quality vulnerability is high. These areas occur where high hazard threat (contamination potential) coincides with high aquifer susceptibility or high overland flow potential. The Montney shale gas play is situated in this area, and the associated infrastructure presents a risk to both surface water and groundwater quality due to potential spills and leaks of wastewater.

Areas of high vulnerability for water quantity occur where demand is estimated to represent a significant proportion of estimated supply. The groundwater quantity vulnerability map (Figure 5B) only shows isolated areas of high vulnerability related to industry groundwater source wells, but currently groundwater use by industry is low. If the demand for groundwater grows, this map will look considerably different. The surface water quantity vulnerability map (Figure 5D) shows many watersheds throughout the Peace Region with high vulnerability. These are concentrated in the low-lying, semi-arid regions that experience seasonal summer low flows.

4. Conclusions

The maps created in this study have the potential to identify areas where the groundwater and surface water quality and quantity may be vulnerable to activities associated with oil and gas development. In particular, the maps may support water management by:

- Informing policy and regulation decisions;
- Highlighting priority areas for further research, data collection and monitoring;
- Identifying areas in which to focus limited enforcement resources;

This vulnerability mapping approach, using the hazard threat and susceptibility indicators, can be applied to other shale gas areas to assess vulnerability. The approach can also be tailored to different settings as necessary (i.e. excluding surface water or groundwater if not affected).

Finally, the various maps were generated using datasets downloaded in July 2015, so they are already out of date. The objective of this study was not to prepare a set of maps that could be used indefinitely, but rather to test an approach for mapping water security vulnerability. It is hoped that the maps will be adopted by the BC Oil and Gas Commission, and continuously updated to assist in their decision making surrounding oil and gas development throughout the Peace Region in Northeast BC.

Acknowledgments

This research was supported by the Pacific Institute for Climate Solutions, Victoria, British Columbia, Canada and the Research Institute for Humanity and Nature, Kyoto, Japan.

References

Aller, L., T. Bennett, J. Lehr, R. Petty, and G. Hackett. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential us-ing Hydrogeologic Settings. EPA-600/2-87-035, National Water Well Associ-ation, Dublin, Ohio / EPA Ada. Oklahoma.

Council of Canadian Academies. 2014. Environmental Impacts of Shale Gas Extraction in Canada. The expert panel on harnessing science and technology to understand the environmental impacts of shale gas extraction, Council of Canadian Academies, Ottawa, ON, Canada. 266 p.

Holding, S. and Allen, D.M. 2015. Final Report: Shallow Groundwater Intrinsic Vulnerability Mapping in Northeast British Columbia. Report prepared for the Pacific Institute for Climate Solutions (PICS) and the BC Ministry of Forests, Lands and Natural Resource Operations (FLNRO), November 2015, 41 pp.

Appendix

This appendix provides details on the spatial datasets and approaches used to generate the four main rasters: groundwater quality vulnerability, groundwater quantity vulnerability, surface water quality vulnerability and surface water quantity vulnerability. The original datasets as well as the intermediate rasters are available through Simon Fraser University (D. Allen). It is noted that data were collected in July 2015.

GW Quality

Total oil and gas wells: 30711
Disposal: 197 – 111 active, 45 abandoned
Injection: 556 – 373 active, 67 abandoned
Undefined: 15142 – 1379 completed, 5678 abandoned
Oil and Gas Facilities: 14934 total
Test Facilities: 10911 (no longer in service)
Remaining: 4006

GW Quantity

Source wells: 123 – 34 active, 46 abandoned
Domestic wells: 2938

Basemaps

Initial data were gathered from the BC Oil and Gas Commission public zone GIS data or from a previous study by Holding and Allen (2015). The basemap outline layer (NEBC_area) serves as the study area projection for all following layers. All layers are spatially related by the NAD_1983_BC_Environment_Albers coordinate system and data points or polygons that fall outside the NEBC area have been clipped against the NEBC_area layer.

The water management basins, or watersheds layer (OGC_WtMngBsn), were also overlain on the NEBC_area layer and used as a visual reference for the location of subsequent features. The layer was also used to join data that needs to be represented on a per-watershed basis.

Table A1. Datasets used for basemaps

Source	Raw Data	Final File Name	Description
SFU GIS	NEBC_FullArea	NEBC_area	Outline of the full NEBC area, which contains the locations for all subsequent layers. This is also used to clip out data that falls outside the study area.
OGC GIS	OGC_WaterManagmentBasins	OGC_WtMngBsn	Shows the outline of all 69 watersheds within NEBC. This is used to join any data layer that is displayed on a per-watershed basis.

Groundwater Quality

The main goal of the Groundwater Quality Vulnerability mapping is to identify and rank the hazards that pose a risk of contamination to water in the saturated zone (i.e. groundwater). The areas of highest risk are associated with the distribution of oil and gas wells, location of transportation routes and pipelines and the location of oil and gas related facilities and infrastructure. Table A1 gives a brief description of each GW quality GIS layer and where it was sourced from.

The first step was to make a layer showing the locations of all oil and gas wells (GW_wells). There are currently 30711 recorded well locations, which include all well operation types (ops_type) and current status (mode_codes). A layer showing the spatial density of all the groundwater wells was also created (gw_well_den) ***Based on the operation types, layers for injection, disposal and undefined wells were created because each of these could be assigned a different hazard ranking. These layers can also be displayed by their different statuses, such as active, abandoned, cancelled etc. which may further influence their hazard rank.

The next step was to make a layer for the location of oil and gas related facilities (OGC_OG_fac) as well as a raster showing the spatial density of the facilities (ogc_fac_dens). All density layers were created using a 15000km^2 search radius and a 500m output cell size. There are 21 different facility types (fac_class) but they are all used for similar processes and, for the purpose of these indicator maps, will all be given the same hazard ranking***. However, layers were created containing only the injection and disposal facilities in order to compare their locations with the locations of injection and disposal wells. These layers (disp_fac_withwell & inj_fac_withwell) show the location of each facility and are color coded based on the presence or absence of a well within a 50m radius of the related facility.

Next, layers for the location of roads and pipelines throughout NEBC were created. The OGC GIS data contains files for permanent roads (OGC_perm_road) and roads currently in development for use by the oil and gas industry (OGC_PetDevRoad) but these pose the same risk regarding accidents and potential chemical spills so they have been joined into one layer (OGC_roads). The same was done for the locations of pipelines (OGC_pipeline). These layers have also been displayed as density maps for easier visualization of the areas of highest hazard potential (ogcroaddens, ogcplinedens).

Finally, rasters for total hazards to groundwater and total groundwater vulnerability were created. The total groundwater hazards (gwhazardsfull) layer was made by multiplying the density rasters for facilities, wells, roads and pipelines together with weights of 4, 3, 2 and 1, respectively (i.e. H = 4wells + 3roads + 2pipes + 1facilities). Note: these weights are subjective as insufficient data are available on historical spills and leaks form these various sources. This produced a combined density map that was reclassified to a 1-10 scale (gwhazrc).

Total groundwater vulnerability (gwvulfull) is the product (multiplication) of the total hazards and the susceptibility of shallow groundwater to potential contamination. A raster file of the susceptibility of shallow groundwater was created by S. Holding and D. Allen using the DRASTIC approach (gw_suscept). This is displayed with 1-10 values and is based on the likelihood of water flowing downward through the surficial material and reaching the saturated zone. The raster calculator was then used to multiply gw_suscept by gwhazardsrc, resulting in total groundwater vulnerability, which was reclassified to 1-10 scale with 10 being the most vulnerable.

The reclassified groundwater quality vulnerability and used Zonal Statistics as Table to extract raster mean values based on polygons to a table. This table was joined to the Watershed management units to create a new polygon of Groundwater quality vulnerability on a per watershed basis ("GWQualV_WS").

Problems with data: The first problem encountered was that the OGC well data do not specify volumes of fluid withdrawn or injected; only the operation type and type of fluid in each well. There are also limited data regarding the differences between facility types so it is difficult to determine if any should be considered higher risk.

Table A2: Datasets used to evaluate groundwater quality vulnerability.

Source	Raw Data	Final File Name	Description
OGC GIS data	AWSH_BC	GW_wells	Location of all oil and gas related wells.
GW_wells	---	gw_well_dens (ogcwellsdens)	Spatial density map of groundwater well locations throughout NEBC.
OGC GIS data	AFSIT_BC	OGC_Facilities_bc	Non-oil and gas facilities.
OGC GIS data	AFCLTY_BC	OGC_OG_fac	Oil and gas facilities.
OGC_OG_fac	---	ogc_fac_dens (ogcfacdens)	Raster showing the spatial density of oil and gas facilities.
GW_wells	---	Disposal_well	Disposal well locations. Used for deep injection of waste water.
OGC_OG_fac	---	Disp_facility	Waste water disposal facilities.
Disposal_well + Disp_facility	---	disp_fac_withwell	Disposal facility containing a well within a 50m radius.
GW_wells	---	Injection_Wells	Injection well locations. Used to inject additional fluid to assist fracking wells.
OGC_OG_fac	---	Inj_facility	Location of injection facilities.
Injection_Wells + Inj_facility	---	Inj_fac_withwell	Injection facility containing a well within a 50m radius.
GW_wells	---	Wells_undef	Wells with an undefined operation type.
GW_wells	---	Wells_und_highrisk	Undefined wells that have been completed or abandoned.
OGC GIS data	AWSIT_BC	OGC_well_site	Polygons of well pad locations.
OGC GIS data	ASUMP_BC	wst_sumps	Locations of sump sites used for drilling waste disposal.
OGC GIS data	AAPR_BC	OGC_perm_road	Locations of permanent roads throughout NEBC.
OGC GIS data	AADR_BC	OGC_PetDevRoad	Locations of roads being used for oil and gas development.
OGC_perm_road + OGC_PetDevRoad	---	OGC_roads	All roads used by the OGC.
OGC_roads	---	ogc_road_den (ogcroaddens)	Raster showing the spatial density of OGC roads.

OGC GIS data	aprow_bc	OGC_pipeline	Locations of pipelines throughout NEBC.
OGC_pipeline	---	pline_dens (ogcplinedens)	Raster showing the spatial density of pipelines.
S. Holding D.R.A.S.T.I.C.	drasticrc	gw_suscept	Raster showing the groundwater susceptibility throughout NEBC. The values are based on the D.R.A.S.T.I.C. model.
Raster Calculator	---	gwhazardsfull (gwhazrc)	Raster showing total hazards. Created by multiplying facility, well, road and pipeline rasters with weights of 4, 3, 2, and 1 respectively.
Raster Calculator	---	GW_QualV (gwvulfull, gwvulrc)	Raster showing total groundwater vulnerability throughout NEBC. Created by multiplying gw_tot_hazard by gw_suscept.
		GWQualV_WS	Groundwater quality vulnerability as a polygon shapefile on a per watershed basis.

Groundwater Quantity

The main goal of the Groundwater Quantity Vulnerability mapping is to determine the volume of groundwater being extracted from industry source wells and from each watershed within the NEBC area. First, a layer for the location of source wells (Source_Wells) was created by using the layer containing all the well locations, as described in the previous section. ***These wells will be given a lower hazard ranking than those in the GW Quality section because they are only used for water extraction and do not introduce wastewater or other potential contaminants into the subsurface. A layer for the active sources wells was then created from data in the OGC annual report for 2014, which contains the annual withdrawal volume (m^3) for each well. A density raster was also created for the active source wells with the density values being based on the withdrawal volumes for each well.

Two different data sources were used to display the volumes of groundwater extraction. The layer GW_2013_wthdrw, which contains the volume extracted from each active source well during 2013, and the layer GW_2014_wthdrw, which contains the volume extracted per NEBC watershed during 2014. The 2013 volumes were totalled and displayed per NEBC watershed for easier visual comparison with the 2014 data. The source well density was then determined based on the 2013 abstraction rates per well (srcwelld). This was classified on a 1-10 scale to characterise hazard.

The groundwater productivity was based on the Aquifer Media map from the DRASTIC assessment. The locations of domestic wells were subtracted from the groundwater productivity map to represent reduced groundwater quantity available in these areas. The density of domestic wells was mapped using kernel density to show areas of low/medium/high well presence (welldenkernrc). These areas were subtracted from the aquifer productivity ranking to represent a stressed area (aquifer supply).

We then took the reclassified groundwater quantity vulnerability (GWQuantV) and used Zonal Statistics as Table to extract raster mean values based on polygons to a table. This table was joined to the Watershed management units to create a new polygon of Groundwater quantity vulnerability on a per watershed basis ("GWQuantV_WS").

Problems with data: There are active source wells in the OGC GIS data that are located in watersheds that either have no water withdrawn or have no wells at all according to the 2014 report, such as within the Hay, Chinchaga, Smoky and East Kiskatinaw watersheds. The 2013 withdraw data are more closely correlated with the OGC source well locations but there are still some discrepancies such as the Smoky and East Kiskatinaw watersheds.

Table A3: Datasets used to evaluate groundwater quantity vulnerability.

Source	Raw Data	Final File Name	Description
GW_wells	---	Source_Wells	Location of all the groundwater extraction source wells within NEBC.
OGC_annual report	---	src_well_2014	Locations of active sources wells with their annual withdrawal volume for 2014.
src_well_2014	---	src_well_den**	Raster showing the density of source wells based on their withdrawal volumes.
OGC Water Information	'water source wells' excel output	GW_2013_wthdrw	Volume (m^3) of groundwater withdrawn from source wells during 2013. Displayed per NEBC watershed.
OGC annual report	2014 annual report appendix	GW_2014_wthdrw	Volume (m^3) of groundwater withdrawn for use in oil and gas production during 2014. Displayed per NEBC watershed.
		GWQuantV_WS	Groundwater quantity vulnerability expressed on a per watershed basis as a polygon shapefile.
		GWQuantV	Groundwater quantity vulnerability.
		srcwelld	source well density file
		welldenkernrc	Reclassified domestic well density map
		aquifersupply	Aquifer productivity map (based on aquifer media with welldenkernrc subtracted from the ranking to represent reduced aquifer supply.

Surface Water Quality

Surface water quality was quantified by the overland flow susceptibility. Overland flow susceptibility was mapped based on three land characteristics: the land surface slope, soil media and vadose zone impact. These spatial datasets were derived from the DRASTIC model. The original three rasters are named impactvadose2, soilmedia2 and TopoClip, and were renamed to impactvadose, soilmedia and slope. The three original rasters were also given weights to better represent their influence to the overland flow, with impactvadose being multiplied by 5, soilmedia by 2 and slope by 1. The raster calculator tool was used to add the three weighted rasters together, which was renamed addrunfac.

It is important to note that these rasters had previously been reclassified to a scale of 1 to 10 where a rank of 10 represents the most well drained soil, least overland flow, and lowest slope. They were ranked this way because they represent hazards to groundwater, specifically the ability of water to flow downward into the subsurface. However, to assess surface water quality susceptibility, the flow of water over the land surface is of interest. Therefore, the ranking order (1-10 values) of the final layer (overlandflow) were reversed during the reclassification of the addrunfac layer. Followign reclassification, the layer was renamed overlandflow.

A final raster for vulnerability of surface water was created by multiplying the total hazards (tot_hazard) by the overland flow susceptibility (overlandflow). Total hazards are the same for groundwater and surface water because they are based on the likelihood of contaminants being spilled on the surface or shallow subsurface. The difference is whether the contaminants will flow downward into the saturated zone or remain on the surface and enter surface water bodies.

The raster calculator was used to multiply these two layers and resulted in total surface water vulnerability (SWQualV), which was reclassified to a 1-10 scale. The values were also joined with the water management basins layer so they can be displayed on a per-watershed basis.

Problems with data: When adding the rasters it was difficult to determine the ideal weights to give each one in order to best represent the overland flow. The areas of highest runoff potentially are usually located at the edge of rivers. This could be true, since these areas are often steep, but they may also be an over estimation.

Table A4: Datasets used to evaluate surface water quality vulnerability.

Source	Raw Data	Final File Name	Description
S. Holding D.R.A.S.T.I.C.	Soilmedia2	soilmedia.tif	Raster showing the drainage potential of soil throughout NEBC. Scaled from 1-10, with 10 indicating the most drainage.
S. Holding D.R.A.S.T.I.C.	Impactvadose2	Impactvadose.tif	Raster showing the vadose zone impact on drainage throughout NEBC. Scaled from 1-10, with 10 indicating the highest impact (most drainage).
S. Holding D.R.A.S.T.I.C.	TopoClip	Slope_fin	Raster showing the impact of topography throughout NEBC. Scaled from 1-10, with 10 indicating the lowest slope.
Raster Calculator	---	addrunfac	Addition of soil, vadose and slope impacts. They are given weights of 2, 5 and 1 respectively.
Raster Calculator	---	overlandflow	Reclassifed addrunfac to a 1-10 scale. The values are reversed to account for the impact to surface water. (D.R.A.S.T.I.C. is based on impact to groundwater)
Raster Calcluator	---	SWQualV	Raster showing the total vulnerability of surface water throughout the NEBC area. This is displayed on a per-watershed basis.

Surface Water Quantity

The risk associated with the quantity of surface water is based on the amount withdrawn for various uses versus the amount of recharge entering surface water reservoirs (demand versus supply). The main goal was to determine the volumes extracted from surface water reservoirs, on a point of extraction and per-watershed basis, and the volumes of recharge to these reservoirs.

Demand:

Data for the volumes of surface water extraction were gathered from multiple sources; some are available on a per-watershed basis while others are point sources. The OGC annual water report for 2014 contained per-watershed withdrawal volumes based on short term water licenses (Water Act Section 8), long term water licenses (oil and gas related) and non-oil and gas related licenses **(FLNRO, Forestry Land and Natural Resource Operations).

First, data for the Section 8 Water Act points of withdrawal were acquired. Section 8 refers to short term withdrawal licences and covers all the locations where water is withdrawn from lakes, streams, rivers, water source dugouts or water storage sites. The file contained data for the approved daily and total (yearly) withdrawal amounts but not how much was actually withdrawn over a given time period. For this study, it is assumed that the maximum withdrawal amount is removed. A separate layer was created called OGC_sec8_wtact. This layer contains point source locations for withdrawals rather than per-watershed and only has the approved annual volumes of withdrawal rather than what was actually taken. However, for the sake of hazard assessment, it is assumed that the maximum approved volume will be extracted from each location. For easier comparison with the previous layers the point source data was spatially joined with the water management basins and a new layer was created displaying the approved volumes per-watershed (OGC_sec8_bsn).

Another approach was also used to obtain surface water withdrawal per watershed whereby data were gathered from the OGC annual report from 2014. In the appendix of the report, the actual volume of Section 8 withdrawal (m^3/year) is tabulated along with the volume withdrawn from long term oil and gas related licences. The volumes are per water management basin so they were tabulated in excel and joined with the OGC basins in GIS. The layer containing the section 8 (short term) and long term withdrawals was renamed SW_wthdrw. *the OGC 2014 report also contains data for volumes withdrawn for purposes other than oil and gas, which are displayed in the appendix as FLNRO (forestry, land and natural resource operations) withdrawals. The data were tabulated in excel and joined with the OGC water management basins to be displayed on a per watershed basis in GIS. The layer was renamed FLNRO_wthdrw.

The short and long term withdrawal data were joined with OGC_WtMngBsn as one layer called SW_wthdrw_2014, which also includes columns for the approved annual withdrawal volumes for each watershed.

The data for points of stream diversion was requested and received from the Government of BC Data Distribution Service under the Land and Natural Resources Fresh Water and Marine folder. The data was delivered as a zipped folder initially called BCGW_points_diversion and the GIS shape file was renamed to BCG_pnts_dvrsn. The shapefile is displayed as points and contains information for quantity withdrawn in m3, which can be shown on a color scale to indicate areas of the most withdrawal. These point source volumes were also spatially joined and summed per-watershed for easier visual comparison (pnts_dvrsn_bsn).

Supply:

The data for the supply layer (SW_Supply) were gathered on a per-watershed basis using the OGC North East Water Tool (NEWT). The search by location function was used to obtain an excel file for each watershed, which contained average annual precipitation (mm/year), average annual runoff (m3/year) and average annual discharge (m3/year) for each watershed within the NEBC area. These data were then joined with the watersheds layer (OGC_WtMngBsn) to display the surface water supply per-watershed. This layer will be compared with the demand per watershed to determine areas of high and low risk.

Finally, layers for the current water budget (supply minus demand) were created by finding the difference between surface water supply and the volumes being withdrawn for various uses. The first step was to make a layer showing the volumes extracted from points of diversion for uses other than oil and gas. This was done by editing out the oil and gas licenses from BGC_pnts_dvrsn (PntsDrvsn_NonOil). Next, raster files were created for the average annual runoff, or supply volume (sw_supply) and the volume extracted for use in oil and gas (sw_wthdrw) and non-oil and gas production (pnts_dvrsn). The raster calculator was then used to subtract pnts_dvrsn from sw_supply (swsupply_pod) and again to subtract sw_wthdrw from swsupply_pod. This resulted in a final water budget layer (SWQuantV) showing the recharge volumes remaining after the annual withdrawals had been made, which was displayed on a per-watershed basis and reclassified to a 1-10 scale.

**One problem is that there were no data for the supply to the Peace Arm watershed but there is a large withdrawal volume taken from it. This resulted in the budget for Peace Arm being very negative when it likely isn't. This may be manually changed.

Table A5: Datasets used to evaluate surface water quantity vulnerability.

Source	**Raw Data**	**Final File Name**	**Description**
OGC North East Water Tool (NEWT): search by location	Excel output	SW_Supply	Volume of surface recharge displayed on a per-watershed basis. The layer contains average annual precip (mm), average annual runoff (m^3) and mean annual discharge (m^3).
OGC Annual Report	2014 annual report appendix	SW_wthdrw_2014	Volume (m^3) of surface water withdrawn from each NEBC watershed. This includes short term (section 8) licences, long term (oil and gas related) licenses and their combined total.
OGC Annual Report	2014 annual report appendix	FLNRO_wthdrw	Volume (m^3) of surface water withdrawn from each watershed for uses other than oil and gas development. (Ministry of Forest, Land and Natural Resource Operations)
OGC GIS data	AS8WA_BC	OGC_sec8_wtact	Locations of short term (section 8) withdrawal licenses. Contains the

			approved daily and yearly withdraw volumes (m^3).
OGC_sec8_wtact spatially joined	---	OGC_sec8_bsn	Approved yearly volume of withdraw shown on a per-watershed basis.
B.C. gov Data Distribution Service	WLS_PDL_PS_point	BGC_pnts_dvrsn	Locations of stream diversion and the annual volume withdrawn from each location.
BGC_pnts_dvrsn	---	pnts_dvrsn_bsn	Volumes (m^3) withdrawn from the point of diversion location displayed on a per-watershed basis.
BGC_pnts_dvrsn	---	PntsDvrsn_NonOil	Same values as pnts_dvrsn_bsn with the oil and gas related withdrawals removed.
SW_Supply	---	sw_supply	Raster showing the average annual runoff, or recharge volume (m^3/A) to each NEBC watershed.
PntsDvrsn_NonOil	---	pnts_dvrsn	Raster file showing the annual volume (m^3) of water extracted from non-oil and gas licenses in each NEBC watershed.
SW_wthdrw_2014	---	sw_wthdrw	Raster file showing the annual volume (m^3) approved for withdrawal by oil and gas licenses in each NEBC watershed.
sw_supply – pnts_dvrsn	---	swsupply_pod	Raster file showing the difference between recharge and the volume withdrawn for uses other than oil and gas development on a per-watershed basis.
swsupply_pod – sw_wthdrw	---	SWQuantV	Raster file showing the difference between the surface water supply and the total volume withdrawn, from both oil and gas and non-oil and gas licenses, on a per-watershed basis.