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Risk of Saltwater Intrusion in Coastal Bedrock Aquifers: Gulf Islands, BC

An overview of the assessment of risk of saltwater intrusion in the bedrock aquifers of the Gulf Islands completed as part of a study conducted by Simon Fraser University and BC Ministry of Forests, Lands and Natural Resource Operations as part of a project “Risk Assessment Framework for Coastal Bedrock Aquifers”

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1 Introduction

Simon Fraser University is conducting a study “Risk Assessment Framework for Coastal Bedrock Aquifers” in collaboration with BC Ministry of Environment and the BC Ministry of Forests, Lands and Natural Resource Operations. The project is funded by Natural Resources Canada under the “Enhancing Competitiveness in a Changing Climate” program.

Unlike other water quality risk assessment methodologies used for source water protection that focus on chemical hazards related to contaminants that may be related to land use (agriculture, spills), the more important hazard in coastal aquifers is contamination associated with salinization. Salinization can occur from multiple directions: from above due to inundation or storm surge, laterally due to encroachment of the freshwater/saltwater interface, and from below due to upconing of saline groundwater due to pumping. Because of the diverse pathways of contamination in coastal aquifers, a different approach is required for conceptualize and assess risk to the aquifer.

The overall aim of the study is to develop a risk assessment methodology for source-water protection purposes in coastal bedrock aquifers. The risk framework, highlighted in this report, was tested in the Gulf Islands in coastal British Columbia.

The research was carried out in three Phases. Phase 1 includes a characterization of the hydrogeological system and the various stressors and potential effects of climate change on this system. Phase 2 includes the development of the risk framework, and mapping hazards related to salinity that may be caused by a range of stressors. Phase 3 is involves knowledge translation to government to inform policy. There is overlap between the three phases.

This report is based on research carried out by Jeanette Klassen towards her MSc degree in the Department of Earth Sciences at Simon Fraser University (Klassen 2015). The report provides an overview of the risk assessment framework and the results of the risk mapping carried out in the Gulf Islands, British Columbia. Aspects of Ms. Klassen’s MSc thesis related to assessing chemical indicators of saltwater intrusion are not included, but have been addressed in a companion report (Klassen et al. 2014). Two additional companion reports provide an overview of the hydrogeological system using Salt Spring Island as an example (Larocque et al. 2015), and a summary of the results of drilling, hydraulic testing and sampling (for water chemistry and isotopes) of the monitoring well on Salt Spring Island (Allen et al. 2015).

The scope of work reported upon herein includes:

1. Identifying and mapping the hazards (natural and anthropogenic) that may lead to saltwater intrusion (SWI);
2. Mapping the aquifer susceptibility to SWI;
3. Mapping the aquifer vulnerability to SWI and verifying against the chemical indicators of SWI;

4. Developing an approach to assess loss (consequence); and
5. Mapping the risk of SWI.

2 Coastal Aquifers

In coastal areas, freshwater aquifers are in direct contact with the ocean. The dense seawater typically circulates inland through the sediments or rock, creating a saline zone or “wedge” below the less dense overlying freshwater aquifer (Figure 1) (Bear et al. 1999). The contact between the freshwater and saltwater is referred to as the freshwater/saltwater interface. This interface may be sharp and characterized by an abrupt transition from freshwater to saltwater, but more commonly, it is transitional due to mixing and diffusion processes as shown in Figure 1 (Barlow 2013). Under natural conditions, fresh groundwater flows towards the ocean; flow of freshwater is predominantly driven by topography but is influenced by the aquifer hydraulic conductivity. The position of the freshwater/saltwater interface depends on the magnitude of freshwater discharge, which varies due to natural and anthropogenic factors by moving seaward if the hydraulic gradient increases, or moving landward if the hydraulic gradient decreases (USGS 2000). Changes in the hydraulic gradient impact the natural balance between the freshwater and saltwater.

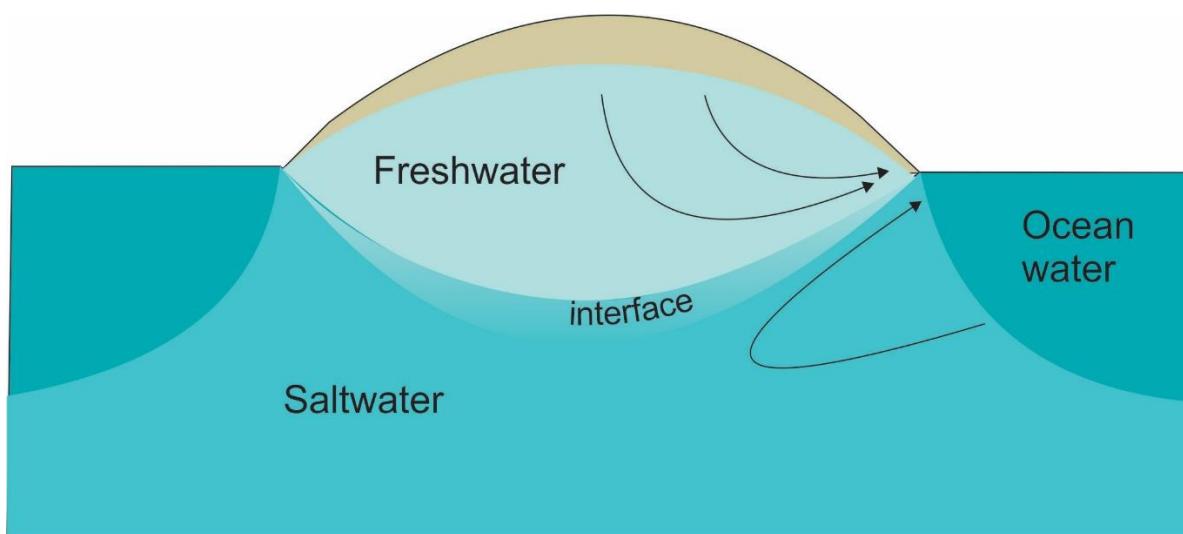


Figure 1. The freshwater/saltwater interface on an island. Freshwater floats on top of seawater due to its lower density. Note: The salinity distribution around the interface typically varies with depth.

Saltwater intrusion occurs when saltwater moves into a freshwater aquifer. In the context of coastal aquifers, technically this process is referred to as seawater intrusion, because “saltwater” can derive from different sources (i.e. septic effluent, landfill leachate, road salt). For the purpose of this study, the common term “saltwater intrusion” (SWI) is used.

One potential driver of SWI is sea level rise (Figure 2). Sea level is currently rising due to changes in atmospheric pressure, thermal expansion of oceans, and melting of ice caps and glaciers. Global sea level is predicted to rise up to 0.6 m by 2100 (Nicholls et al. 2007). A rise in sea level can lead to a

reduction in the hydraulic gradient; particularly in coastal aquifers that are constrained by topography (Michael et al. 2013). A reduction in recharge due to lower precipitation in a warming climate would also likely lead to SWI (Holding and Allen 2015a).

Storm surge is another hazard associated with coastal areas. Storm surge is an abnormal rise in sea level that is associated with a storm event (Danard et al. 2003). Storm surge causes land erosion and flooding; when the surface becomes flooded, the saltwater can infiltrate into the freshwater lens from the land surface and cause localized salinization (Figure 2). Storm surges vary in size based on the morphology of the coastline and the topography of the ocean floor (Stoltman et al. 2007; Debernard et al. 2002). The topography of the ocean floor influences storm surge because currents are obstructed by shallow waters and wave heights increase. The shape of the coastline may also increase the damage potential of storm surge because tidal energy can be focused, and wind and water funnelled to the shoreline (Romanowski 2010; Christiansen 2009).

SWI can also be exacerbated by pumping freshwater at high rates or by pumping numerous wells simultaneously (high well density locations) (Figure 2). Pumping can cause the freshwater/saltwater interface to move inland by reducing the natural gradient to the sea (USGS 2000). Other mechanisms leading to salinization include upconing from depth due to pumping (Reilly and Goodman 1985; Washington State Department of Ecology 2005) and localized intrusion by reversal of the hydraulic gradient near the well or well field (Fetter 2001). In fractured rock, saltwater has been shown to enter wells through discrete fractures (Allen et al. 2002).

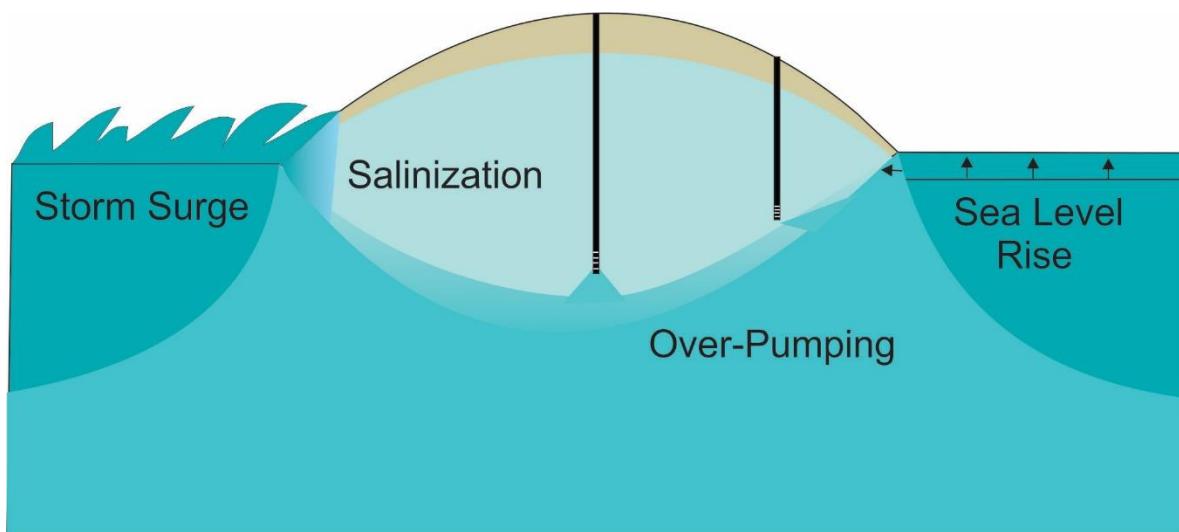


Figure 2. Salinization due to sea level rise, storm surge and over-pumping of groundwater by pumping.

3 The Study Area: The Gulf Islands, BC

The Gulf Islands are located in the Strait of Georgia, between Vancouver Island and the mainland of British Columbia (Figure 3). Locally, there are a few natural lakes on the islands, some of which support domestic and agricultural use. But the majority of residents use groundwater from the fractured

bedrock aquifers as their primary source of freshwater (Denny et al. 2007). The quality of groundwater on the Gulf Islands has been impacted locally by several sources, both natural (i.e. arsenic, manganese, iron) and anthropogenic contaminants (improper disposal of agricultural waste, failed septic systems, pesticides) and saltwater intrusion (Denny et al. 2007). During the summer months, when precipitation is low and water demand is high, the groundwater levels decline and the quality of the water can deteriorate (Allen and Suchy 2001).

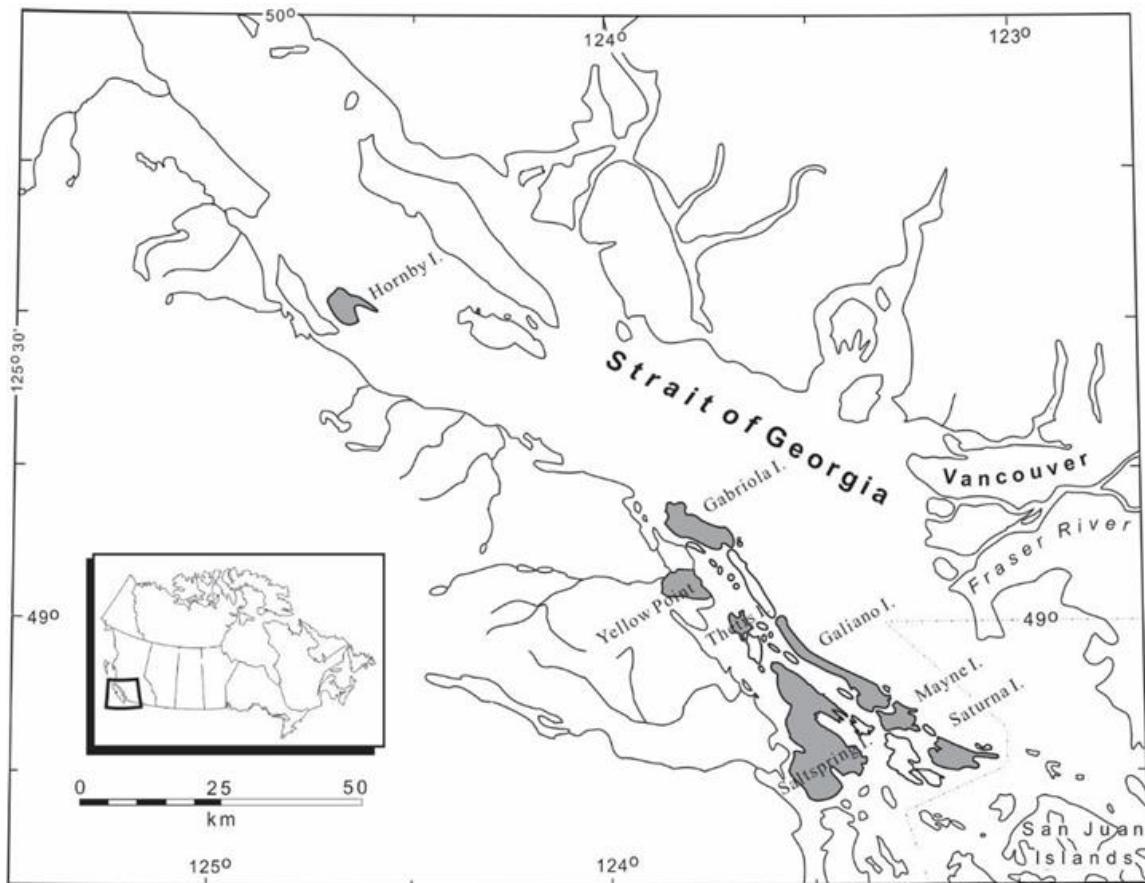


Figure 3. The Gulf Islands, British Columbia. Islands shown in grey have groundwater chemistry data that were used for verifying the results of the aquifer vulnerability assessment.

Surficial materials comprise glacial and/or marine sediments, but form only a thin veneer over the bedrock in most areas. However, these surficial materials may have a significant control on recharge (Denny et al. 2007). The bedrock comprises Paleozoic to Jurassic igneous and sedimentary rocks (Wrangellia Terrain) present only on Salt Spring Island, and Upper Cretaceous rocks of marine origin which form the Nanaimo Group present on all the islands (Denny et al. 2007). The Nanaimo Group consists of interbedded sandstone, shale (mudstone) and some conglomerate (Mustard 1994). During the Eocene, the Nanaimo Group was compressed into a fold and thrust belt and was uplifted and eroded during the Neogene (Mustard 1994). Due to the structural history of the Nanaimo Group, fractures and faults are present throughout the islands at a local and a regional scale (Journeay and Morrison 1999). Hydrogeologically, fractures and faults represent zones of high permeability due to the high density of fracturing, and influence groundwater flow at different scales (Surrette and Allen 2008; Surrette et al.

2008). This fracturing results in a complex groundwater flow system which is more influenced by structure than lithology and stratigraphy (Allen et al. 2003). Consequently, the bedrock aquifers in the Gulf Islands have been divided based on hydrostructural domains (Mackie 2002), which are identified based on their relative permeability. The sandstone-dominant and mudstone-dominant formations of the Nanaimo Group (and the older Wrangellian rocks) have similar hydraulic properties based on discrete fracture network modeling (Surrette and Allen 2012) and aquifer testing (Larocque 2014), and are conceptualized as equivalent porous media, while the fault and fracture zones tend to be more permeable and influence flow at a larger scale (Surrette and Allen 2008).

During the Pleistocene, the Gulf Islands underwent regional depression due to the weight of the overlying glaciers. The land surface was depressed by as much as 300 m below present sea level (Clague 1983). During the period of submergence below sea level (approximately 500-1000 years), there was sufficient time for seawater to intrude into the bedrock aquifers (Allen and Liteanu 2006). Following rebound of the islands, fresh groundwater has gradually displaced the conservative and mobile chloride (Cl) (Allen and Liteanu 2006), but sodium (Na) has been left behind on the clay exchange sites within the mudstone units; these mudstones exist both as massive mudstone, but also as mudstone interbeds within the coarser-grained sandstone. As a result of these geological processes, the groundwater on the Gulf Islands has undergone a chemical evolution (see Klassen et al. 2015 for more details on the groundwater chemistry evolution), which results in groundwater compositions varying spatially due to natural processes.

Saltwater intrusion has been observed on the Gulf Islands, particularly in coastal wells that have been drilled to depths at or near the saltwater interface or in wells where pumping either draws in seawater laterally or from below (upconing). Mixing with seawater can also occur along discrete fractures that connect a well to the ocean (Allen et al. 2002). A complicating factor on the Gulf Islands is that while the Cl originating from submergence is thought to have been flushed from these rocks (Allen and Liteanu 2006), some Cl-rich water may be present in areas or at depths where the rocks were not sufficiently flushed. This means that it is difficult to determine if salinization is due to saltwater intrusion or simply trapped seawater dating back to the late Pleistocene (see Klassen et al. 2015 for the detailed geochemistry results as well as a discussion of indicators of salinity).

4 Overview of the Risk Assessment Framework

Risk assessments determine the risk (probability of a harmful event and its potential consequence/loss) by analysing the potential hazards and the vulnerability of a region. Quantitative risk assessment requires calculations of two components of risk (R): the magnitude of the potential loss (L) and the probability (p) or likelihood that the loss will occur:

$$Risk (R_i) = L_i * p (L_i) \quad (\text{Eq. 1})$$

where the subscript *i* relates to a specific hazard. The total risk is expressed as:

$$Risk_{total} = \sum R_i \quad (\text{Eq. 2})$$

Simpson et al. (2014) defined risk to groundwater quality due to chemical contamination originating at the land surface as:

$$Risk (R_H) = Vulnerability (V_H) * Loss (L) \quad (\text{Eq. 3})$$

This equation differs slightly from Equation 1 in that the probability is embedded in the Vulnerability (V_H) term. Simpson et al. (2014) calculated the spatial risk to groundwater quality (according to Equation 3) using maps of aquifer vulnerability and potential loss. Vulnerability included aquifer susceptibility and hazard threat, and the probability of occurrence was attached to each hazard threat (Simpson et al. 2014):

$$Vulnerability (V_H) = aquifer susceptibility (S_A) * hazard threat (T_H) \quad (\text{Eq. 4})$$

Holding and Allen (2015a) adapted the risk assessment approach for use in small islands. Using the results of a chemical hazard and water use survey, risk to water security was assessed on Andros Island, The Bahamas. Risk due to climate change, encompassing sea level rise, storm surge and a reduction to recharge was also assessed. The approach outlined in this report follows a similar framework as Holding and Allen (2015a) as shown in Figure 4. Aquifer susceptibility is assessed based on specific metrics that may be more suitable for identifying areas that are more susceptible to SWI (distance to coast and topographic slope) rather than according to the aquifer properties that reflect the ease of infiltration of chemical contaminants at surface as conceptualized in traditional aquifer vulnerability mapping. Various hazards related only to salinization (sea level rise (SLR), storm surge, pumping) are then superimposed to assess the aquifer vulnerability. Risk is assessed by considering the consequence of the loss of the groundwater supply. The mapping is carried out in ArcGIS 10 ©.

Each component of the risk assessment is discussed briefly below using examples from the literature that describe how each can potentially be assessed.

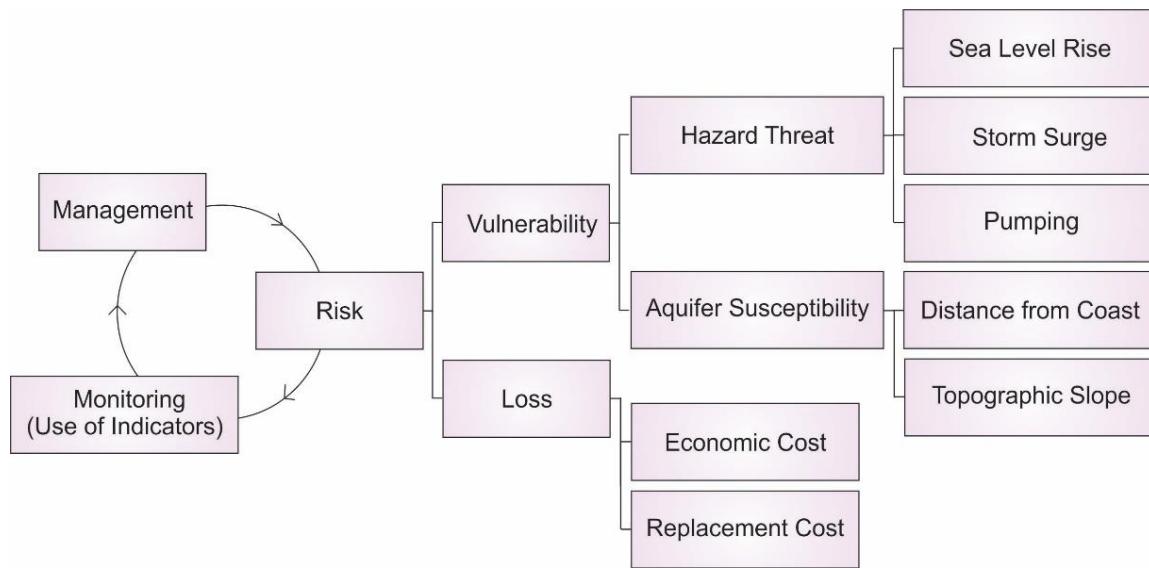


Figure 4. Risk Assessment Framework for coastal aquifers (adapted from Holding and Allen 2015a)

4.1.1 Hazard Threat

In the context of coastal aquifers, hazard threats are related to natural phenomena, specifically coastal hazards, such as SLR and storm surge, and human stressors such as over-pumping. As mentioned above, the position of the freshwater/saltwater interface depends on the magnitude of freshwater discharge, moving seaward if the hydraulic gradient increases, or moving landward if the hydraulic gradient decreases (USGS 2000). This interface can be controlled by natural processes; either a rise in sea level which can push the interface landward, or reduced recharge which permits the interface to move landward. In addition to SLR, tides and storms can result in overtopping or flooding of the land surface by seawater (Holding and Allen 2015b).

Flood hazard maps can be generated to show areas potentially at risk of inundation from SLR and storm surge. In past studies, estimating the flood hazard associated with tides and storms was based on a stationary mean sea level and coastal flood construction level was based on a natural boundary of 1.5 m. The natural boundary represents where the action of water is so common that it begins to leave its mark on soil or edges of the water; for coastal areas the natural boundary is the natural limit of permanent terrestrial vegetation (Auscenco Sandwell 2001). This approach has become problematic because SLR is already occurring, and it is believed that the rate of SLR will increase in the future (Kerr Wood Leidal (KWL) 2011; Nicholls et al. 2007). Therefore, determining a natural (static) boundary has become an inefficient guideline for land use planning and developing floodplain bylaws (KWL 2011). According to the new guidelines and specifications for Coastal Floodplain Mapping (KWL 2011), coastal flooding is due to high tides, storms and tsunamis. The new procedures for floodplain mapping incorporate a combination of parameters; 1) higher high water large tide, 2) allowance for future SLR (1 m by 2100 and 2 m by 2200), 3) estimated storm surge (changes in atmospheric pressure, effects of

strong winds blowing over water surface, waves, changes in ocean currents or temperature), 4) estimated wave effect associated with storms (flooding and erosion) and 5) freeboard (0.6 m of uncertainty) (Ausenco Sandwell, 2011).

Coastal morphology and local wind set-up also influence water levels along coastal regions. Winds may generate local surge in water depths less than 30 m (Ausenco Sandwell 2011). In small areas, such as bays, tidal energy is focused, and wind and water are funnelled to the shoreline. This funnelling of water may cause the local sea level to rise significantly higher than expected (Romanowski 2010). Local surge is typically only generated when there is a substantial body of shallow water depth (<30 m) in front of a shoreline (KWL 2011).

Over-pumping in coastal aquifers represents a significant hazard to groundwater quality because it can cause SWI. SWI can impact an individual well because 1) the well is situated too close to the coast, 2) it is too deep, 3) it pumped at too high a rate, or 4) a combination of two or more of these factors. SWI, however, can impact an aquifer, thereby degrading the freshwater supply. Such larger scale impacts may be caused by a single well for the reasons above, but more often it is caused by concentrated pumping in a location where the well density is too high to be sustained by the amount of recharge received. Kennedy (2012) used civic point (residential density) in a GIS based approach for assessing relative SWI vulnerability in Nova Scotia. Holding and Allen (2015a) assessed water demand hazards on a property by property basis.

4.1.2 Aquifer Susceptibility

The term “aquifer vulnerability” is often used interchangeably with “aquifer susceptibility”. In this report, the term “aquifer susceptibility” is used to describe whether or not the aquifer is susceptible to SWI. Aquifer susceptibility maps have been created for the Gulf Islands (Denny et al. 2007). These maps were constructed using the DRASTIC-Fm methodology (a modification of DRASTIC – Aller et al. 1987). DRASTIC-Fm is an acronym for the following parameters; (D) depth to water, (R) net recharge, (A) aquifer media, (S) soil media, (T) topography, (I) impact of vadose zone media or conductivity of vadose zone, (C) aquifer hydraulic conductivity, and (Fm) fractured media. The aquifer susceptibility mapping method was developed specifically to assess the intrinsic properties of the aquifer in relation to chemical contaminants that may be introduced at the land surface. As mentioned above, in coastal aquifers, salinization is one of the greatest threats to groundwater quality and this can occur from many directions: 1) surface (storm surge and inundation), 2) lateral intrusion due to SLR and pumping or 3) upconing from below due to pumping.

To address the multi-directional pathways for SWI, alternative approaches for mapping aquifer susceptibility in coastal regions are required. For example, Holding and Allen (2015a) mapped aquifer susceptibility based on the location of the freshwater lenses (FWLs) on Andros Island. They used numerical modeling to approximate the location and thickness of the FWLs, verifying the results using available data. If the lens was present and thick, it represented a viable long term source of freshwater

and therefore was susceptible to contamination. Areas with thin or no lenses, were considered less susceptible.

Kennedy (2012) used five parameters to characterize the vulnerability of coastal aquifers. The parameters include: 1) distance from the coastline, 2) topographic slope, 3) civic point (residential) density, 4) large groundwater users (daily non-domestic groundwater withdrawal rates) and 5) water level elevation relative to mean sea level (RMSL).

Erlandson (2014) used the DRASTIC-Fm maps for the Gulf Islands to rate the relative groundwater flux. The C (hydraulic conductivity) and Fm (fractured media) were combined into a composite C. Using two different approaches, Erlandson (2014) combined the composite C with the T (topography or slope) parameter to create a two relative groundwater flux maps. The first method used the topography parameter rating from the original DRASTIC methodology (Aller et al. 1987) and the second method used topography parameter ratings from the Nova Scotia based study (Kennedy 2012). The Fm parameter highly influenced the composite C (hydraulic conductivity) and, consequently, the groundwater flux values.

4.1.3 Loss

Loss can be evaluated in a variety of ways. For example, a risk assessment could consider economic consequences due to the contamination of groundwater supply, impacts to human health if a well is contaminated, or the consequences to ecological systems. In some cases, the contamination of a well impacts more than a single homeowner; for example, a water intensive business such as agriculture (Simpson et al. 2014), commercial developments related to tourism, or a water supply system which provides water to multiple dwellings in a subdivision or area. For agriculture, if no other water resource is available, the business may be required to shut down. For commercial development, rather than closing down, the owner may be required to import large amounts of water or install a rainwater collection system or water treatment facility.

Simpson et al. (2014) identified four potential sources of water if a well becomes contaminated; these include 1) hooking up to municipal water supply where available, 2) drilling a deeper well if the geology allows, 3) importing water, or 4) investing in another expensive long term solution such as water treatment or rainwater harvesting. For islands and coastal aquifers in general, drilling a deeper well will typically not yield freshwater, as saltwater lies below the freshwater lens. Although drilling deeper is not an option for coastal regions, there is the option to drill another shallower well on the same property. For individual homeowners or small businesses in the commercial or industrial sector these may be suitable options, but for larger businesses, such as those in the agricultural sector, they would be impractical.

5 Methodology

The risk assessment framework from Figure 4 was further refined to create a detailed risk assessment framework (Figure 5). This detailed risk assessment framework was used to develop a GIS based Risk Assessment Methodology for coastal aquifers. Details concerning how each variable was mapped and the results are provided in the following sections.

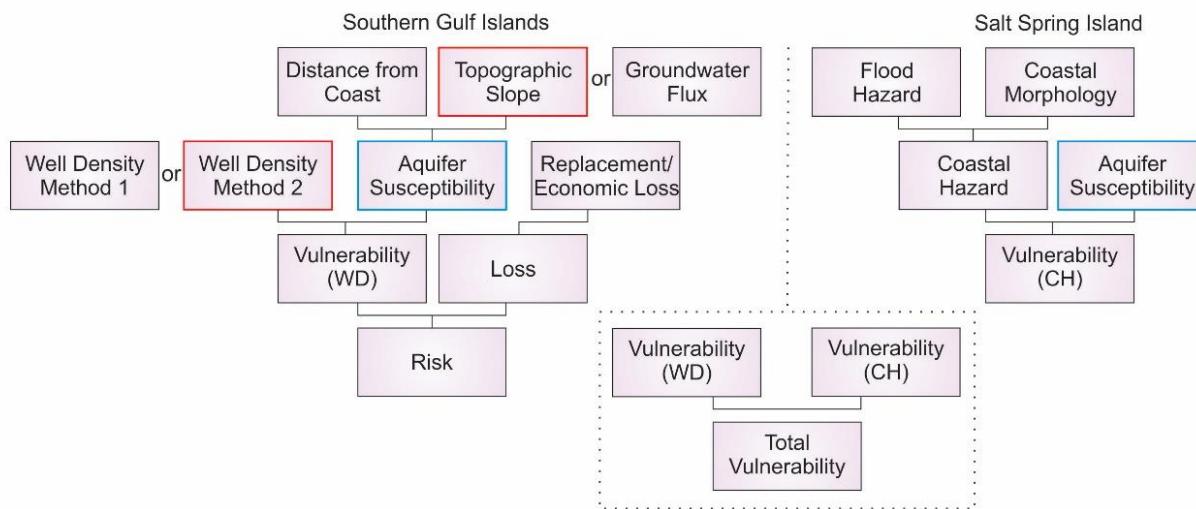


Figure 5. Risk assessment framework (modified from Figure 4). Red outlines indicate which parameter was chosen of the two options evaluated in the risk assessment. Blue outlines show results used in common. Two methods were used to calculate vulnerability (well density (WD) and coastal hazards (CH) - WD was applied to all southern Gulf Islands and CH was applied only to Salt Spring Island.

5.1 Hazard Threat

This section describes the methodologies employed to map hazard threats, and the results, including **pumping** and two **coastal hazards**: 1) flooding, which is associated with sea level rise, tidal fluctuations and storm surge, and 2) coastal morphology. Ultimately, the flood hazard map and coastal morphology map were merged in ArcGIS and rescaled (1 to 5) to create the coastal hazard map for naturally occurring stressors.

5.1.1 Pumping

Pumping was represented by creating a groundwater well density map in ArcGIS. A list of groundwater wells for the Gulf Islands was downloaded from the BC WELLS database (BC MoE 2014). In the province of BC, groundwater wells are reported on a voluntary basis, which results in the WELLS database being

incomplete¹. When the WELLS Gulf Islands dataset was compared with the wells sampled for groundwater chemistry (see Klassen et al. 2014), 200 of 870 sampled wells were not reported in WELLS. There are also 69 water supply system wells (more than one connection). Therefore, the well dataset for this study was enlarged to include all of the sampled groundwater wells and the water supply systems wells. Wells were weighted 1 to 5 to represent low to high water use (relative rating) in order to take into consideration different potential pumping rates (Table 1). Water supply systems were further divided (and weighted) based on number of units/houses they supply. Water supply systems either obtain water through deep or shallow wells, surface water or combined. If a water supply system used surface water, it was assigned a value of 0.

Table 1. Designated weight for different well uses.

Weight	Well Use	
0	Abandoned	
0	Observation	
1	No Label	
1	Other	
1	Private Domestic	
1	Unknown Well Use	
2	Commercial/Industrial	
3	Irrigation	
(3-5)	Water Supply System	# Units
3	Water Supply System	n/a
3	Water Supply System	1
3	Water Supply System	2-14
4	Water Supply System	15-300
5	Water Supply System	301-10,000

Two methods were used to represent well density: Method 1 calculates the density of wells per grid cell (used by Kennedy 2012) and Method 2 calculates a magnitude per unit area from point features that fall within a neighbourhood around each cell (point density). Well density (for both methods) was assigned a rating according to Table 2.

Table 2. Rating table for well density (as described in Kennedy 2012)

Rating	Well Density
5	>20
4	10-20
3	5-10
2	1-5
1	0

¹ It is estimated that 30 percent of all wells in BC are NOT reported in WELLS.
<http://www.rdn.bc.ca/cms/wpattachments/wpID2501atID4277.pdf>

Each method was evaluated based the relationship between the electrical conductivity (EC) indicator for sampled wells (see Klassen et al., 2014) and well density rating. Specifically, groundwater samples above the EC threshold values (95th and 90th percentile were plotted against the rating extracted from the well density map at the well point. Groundwater wells that have high EC values (above threshold) are more likely to experience SWI. As a result, they should coincide with a high well density rating.

Results of the two methods used to create well density maps for the southern Gulf Islands are shown in Figure 6a (Method 1: calculated the density per grid cell) and Figure 6b (Method 2: calculated according to point density).

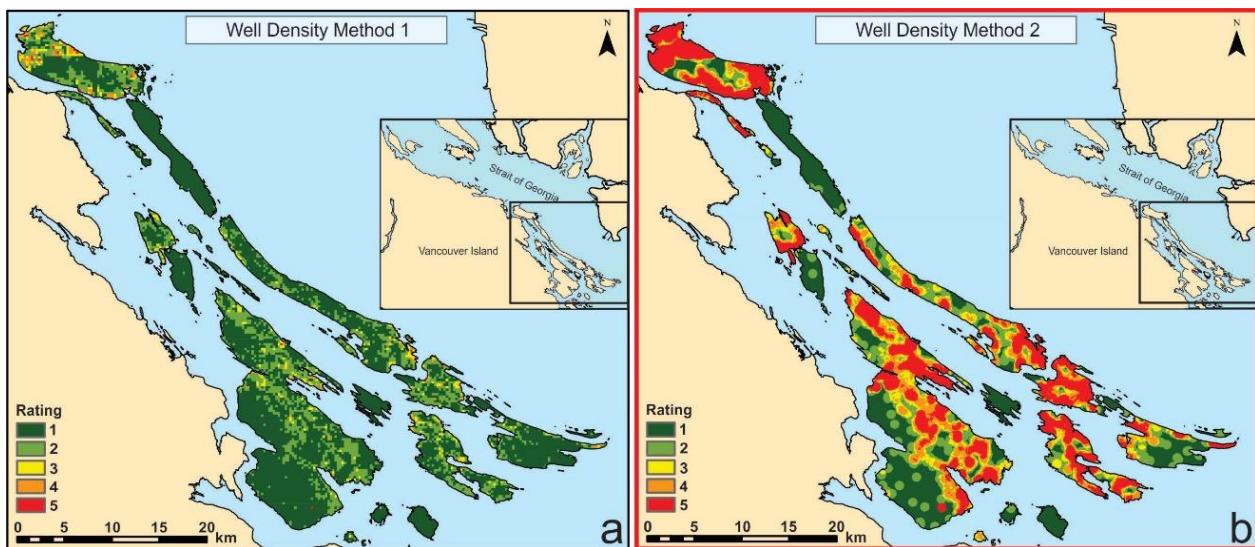


Figure 6. Comparison between (a) Well Density Method 1 and (b) Method 2 (red outline represents the method carried through to the risk assessment)

Well density ratings for sampled groundwater wells with EC above the two thresholds (95th and 90th percentiles) are summarized in Table 3. The well density rating for sampled groundwater wells in Method 1 are between 2 and 3 for both the 95th and 90th percentiles and have mean ratings of 2.6 and 2.7, respectively. Using Method 2, the majority of sampled groundwater wells have a rating of 5 and the mean ratings for the 95th and 90th percentiles are 4.5 and 4.6, respectively. Thus, the method carried through to the risk assessment is Method 2 because the high EC values tend to better coincide with cells with high well ratings. Moreover, Method 1 also has an inverse relationship between well rating and frequency of threshold exceedances; the most frequent rating is 2, and as the rating increases, the frequency decreases (Figure 7).

Table 3. Comparison between well density ratings for Method 1 and Method 2 for sampled groundwater wells with EC values above the 95th and 90th thresholds

Rating	Method 1				Method 2			
	95 th Well Count	95 th %	90 th Well Count	90 th %	95 th Well Count	95 th %	90 th Well Count	90 th %
1	0	0	0	0	0	0	0	0
2	15	51.7	28	50.9	3	10.3	4	7.3
3	11	37.9	19	34.5	1	3.4	2	3.6
4	3	10.3	6	10.9	3	10.3	4	7.3
5	0	0	2	3.6	22	75.9	45	81.8
Mean	2.6		2.7		4.5		4.6	

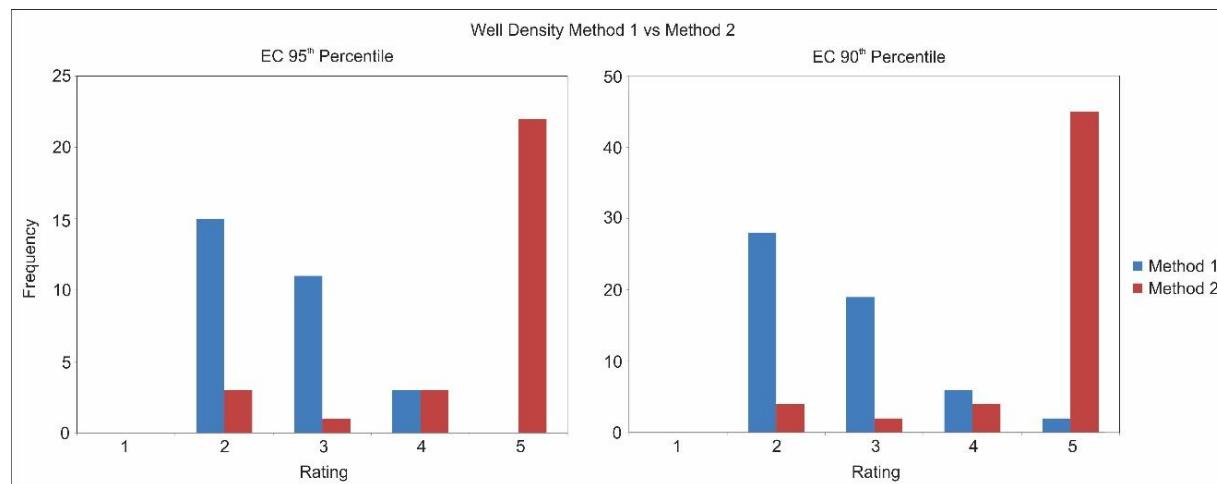


Figure 7. Frequency diagram used to compare well density calculated using Method 1 and Method 2

Limitations of both methods include the incomplete WELLS database. As a result, the well density maps may not be a true representation of the Gulf Islands. The sampled groundwater database is only a partial dataset (556 wells with both map rating and EC value, Hornby and Yellow Point samples, excluded) of the entire groundwater well database (8,754 wells). Finally, the sampled groundwater database may be biased; high salinity wells may have been abandoned and thus not included in the groundwater sampling study.

5.1.2 Coastal Hazards

5.1.2.1 Flood Hazard

Designated Flood Level (DFL) is the appropriate allowance for future sea level rise, tide and the total storm surge expected during the designated flood:

$$DFL = HHWLT + SLR + Storm\ Surge \quad (\text{Eq. 5})$$

Highest high water large tide (HHWLT) is the average of the highest high water levels over approximately 19 years of data, and was obtained through the Canadian Hydrographic Service (CHS) for Fulford Harbour and Ganges Harbour (both tide gauges on Salt Spring Island). The average of the two tide gauges was used to represent the HHWLT on Salt Spring Island (Table 4). Mean and maximum sea level rise (SLR) projections were derived from Thomson et al. (2008). Regional adjustment was added to mean and maximum SLR projections to determine overall SLR (overall SLR is not shown in Table 4).

The storm surge component was assessed based on the results of an analysis of historical (Department of Fisheries and Oceans Canada (DFO) 2014) and predicted (Mike Foreman, direct communication) tide data for Fulford Harbour on Salt Spring Island (Klassen 2015). The residual (or storm surge) was calculated by subtracting the hourly predicted tide data from the hourly observed tide data. In total, there were 344,063 residual tide measurements, spanning from November 1952 to July 1992. These include positive and negative residuals. As the study focused on storm surge, only the 167,615 positive residuals were analyzed. Following the methodology employed by Tinis (2011) for residual tide data at Point Atkinson and Victoria, only residuals >20 cm at Fulford Harbour were considered. As a result, 26,021 positive (>20 cm) residuals were analyzed statistically. The observed tidal range was 4.74 m (max = 4.33 m and min = -0.43 m) at Fulford Harbour. The predicted tidal range was 3.97 m (max = 3.74 m and min = -0.23 m). A frequency analysis for residuals >20 cm indicated that at Fulford Harbour, the 90th and 95th percentiles are 43 and 49 cm, respectively. The largest predicted tide was 3.74 m and the largest residual was 0.92 m. Therefore, the 95th percentile (49 cm) and maximum storm surge height (0.92 m) were carried through this analysis (Table 4).

Table 4. Summary of DFL components for Fulford Harbour and Ganges Harbour on Salt Spring Island

Location	HHWLT (m)	Mean SLR (m)	Max SLR (m)	Regional Adjustment (m)	95 th Percentile Storm Surge (m)	Max Storm Surge (m)
Fulford Harbour	1.57	0.87	1.17	-0.119	0.49	0.92
Ganges Harbour	1.57	0.87	1.17	-0.119	0.49	0.92
Salt Spring Island Average	1.57	0.87	1.17	-0.1	0.49	0.92

Combinations of SLR (mean and maximum) and storm surge (95th percentile and maximum) were added to HHWLT to determine a range in DFL values, which were then assigned a ranking from 1 to 5 (Table 5). The lowest DFL is the most conservative and is assigned the highest rating because it is most likely to occur, whereas the largest DFL is the least likely to occur and therefore has the smallest rating.

Uncertainty, therefore, was incorporated into the hazard rating, resulting in a hazard threat of greater magnitude having an overall lower rating than a hazard threat of smaller magnitude.

Table 5. Rating table for Flood Hazard Map

Rating	SLR	Storm Surge	DFL (m)
5	Mean	95 th Percentile	<2.8
4	Max	95 th Percentile	2.8-3.1
3	Mean	Max	3.1-3.2
2	Max	Max	3.2-3.5
1	Max	Max	>3.5

The DFL values were then represented in ArcGIS using topographic data. The topographic data available for the Gulf Islands includes a LiDAR map (resolution 2 m grid) (Bednarski and Rogers 2012) and a Canadian Digital Elevation Model (CDEM) (25 m grid) (Natural Resource Canada). Because the magnitude of the DFL is small relative to the resolution of the topographic data, the DFL could only be represented for islands with LiDAR data. Of the islands with LiDAR data, Salt Spring Island was the only island with a tidal station with projected SLR, calculated HHWLT and an analysis of historical storm surge. Therefore, coastal hazards were only mapped for Salt Spring Island.

5.1.2.2 Coastal Morphology

The coastal morphology hazard map is intended to capture a greater range of hazards than simply those related to DFL. The parameters included in the coastal morphology map are: 1) depth of ocean, and 2) distance from coast seaward in combination with either the DFL (from the previous section) or the Flood Construction Level (FCL). These parameters were chosen because ground topography influences where inundation will occur (shallow vs steep coastlines), and ocean floor topography and coast morphology influence where and if funnelling of water will occur.

To generate the depth of ocean map, bathymetry data (Carignan et al. 2013) were contoured using a 30 m interval. To represent distance from coast, a 200 m buffer was created along the coast. FCL represents a more extreme DFL:

$$FCL = DFL + \text{Wave Effect and Freeboard} \quad (\text{Eq. 6})$$

Flood construction level adds a wave effect and freeboard to the DFL. Wave effect includes wave run up during a storm event, and freeboard accounts for uncertainties associated with estimation of the calculated water level. For this study, the maximum DFL from the flood hazard map was used. DFL and FCL, associated with coastal topography, were represented in ArcGIS using the available LiDAR data.

Ratings from 1 to 5 were assigned to the coastal morphology map based on combinations of water depth (<30 m), distance from coast (> or < 200 m), and coastal topography (DFL and FCL) (as summarized in Table 6). A high rating (4 or 5) was assigned if there is a substantial body of shallow water

(<30 m depth at a distance >200 m from coastline) along a shallow sloping coastline where inundation would occur (DFL or FCL). The area between the shoreline and DFL was assigned a 5, and the area between the DFL and FCL was assigned a 4 because the DFL was the smaller elevation and therefore more likely to occur (Figure 8).

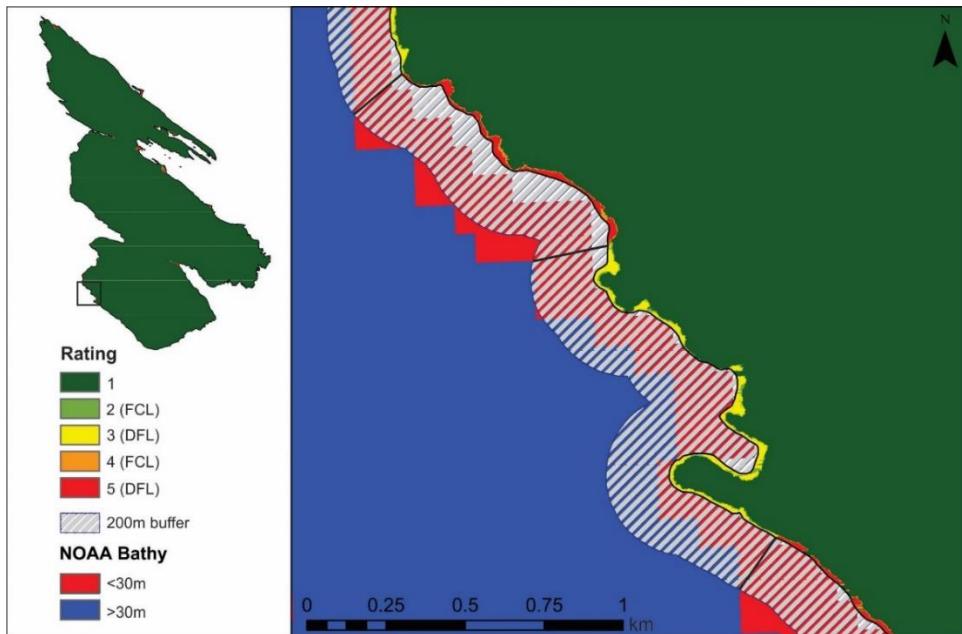


Figure 8. Illustration of how ratings were assigned for coastal morphology

Table 6. Rating table for the Coastal Morphology Map

Rating	Combination
5	<30m water depth at distance >200m beside DFL coastal zone
4	<30m water depth at distance >200m beside FCL coastal zone
3	<30m water depth at distance <200m beside DFL coastal zone
2	<30m water depth at distance <200m beside FCL coastal zone
1	<30m water depth at distance <200m beside steep coastline

5.1.2.3 Coastal Hazard Map

The flood hazard map and coastal morphology map were added together to create the coastal hazards map; all maps are shown in Figure 9. Although the coastal hazard map has a very low rating, there are several regions that are characterized by high ratings, such as around Ganges Harbour and Long Harbour on Salt Spring Island.

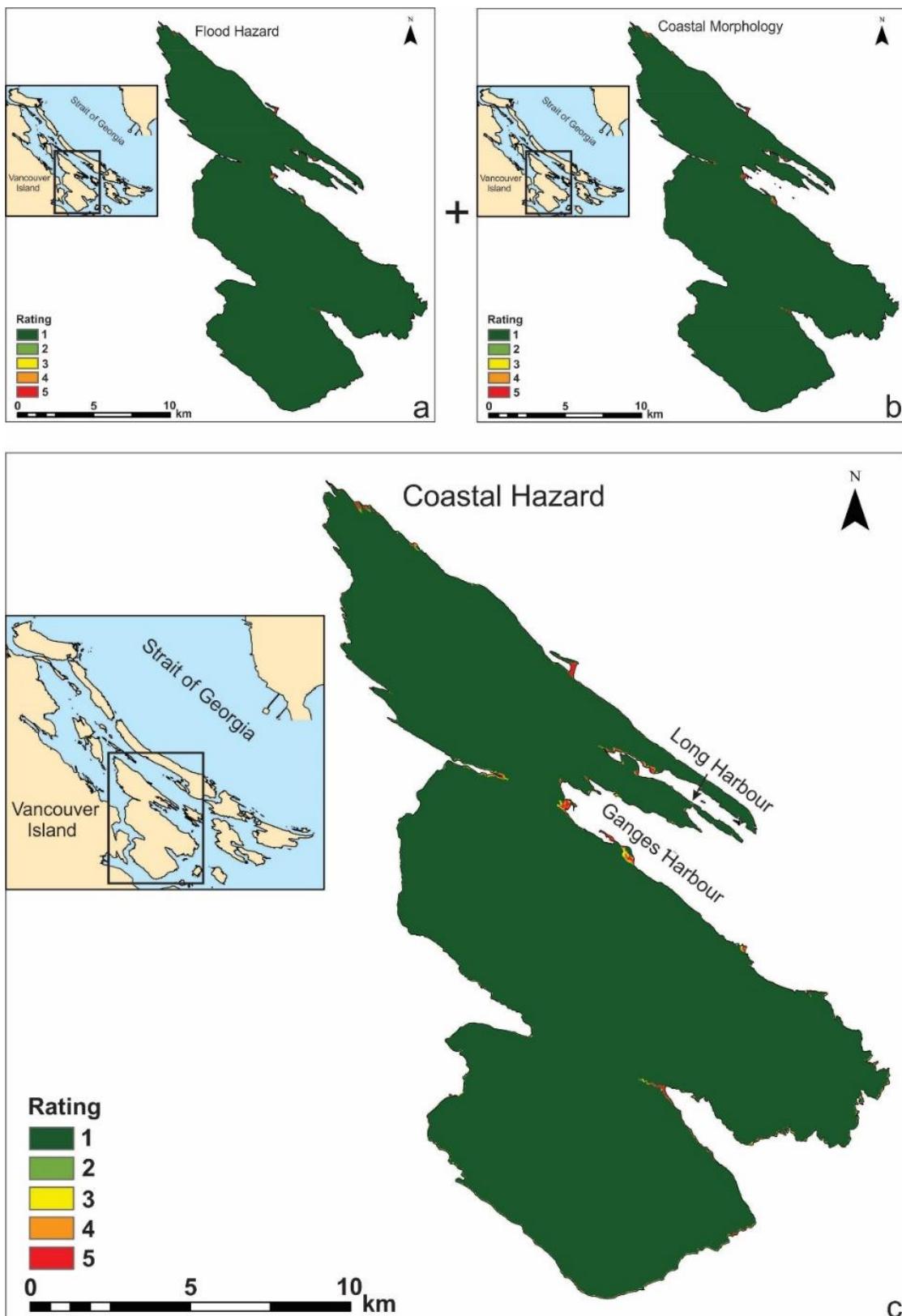


Figure 9. Maps of a) flood hazard, b) coastal morphology and c) resulting coast hazard

The coastal hazards map was overlaid on a land use map for Salt Spring Island (Figure 10) to show the impacts of flooding and storm surge. Arrows point to regions where inundation may occur in agricultural, commercial, community and residential areas.

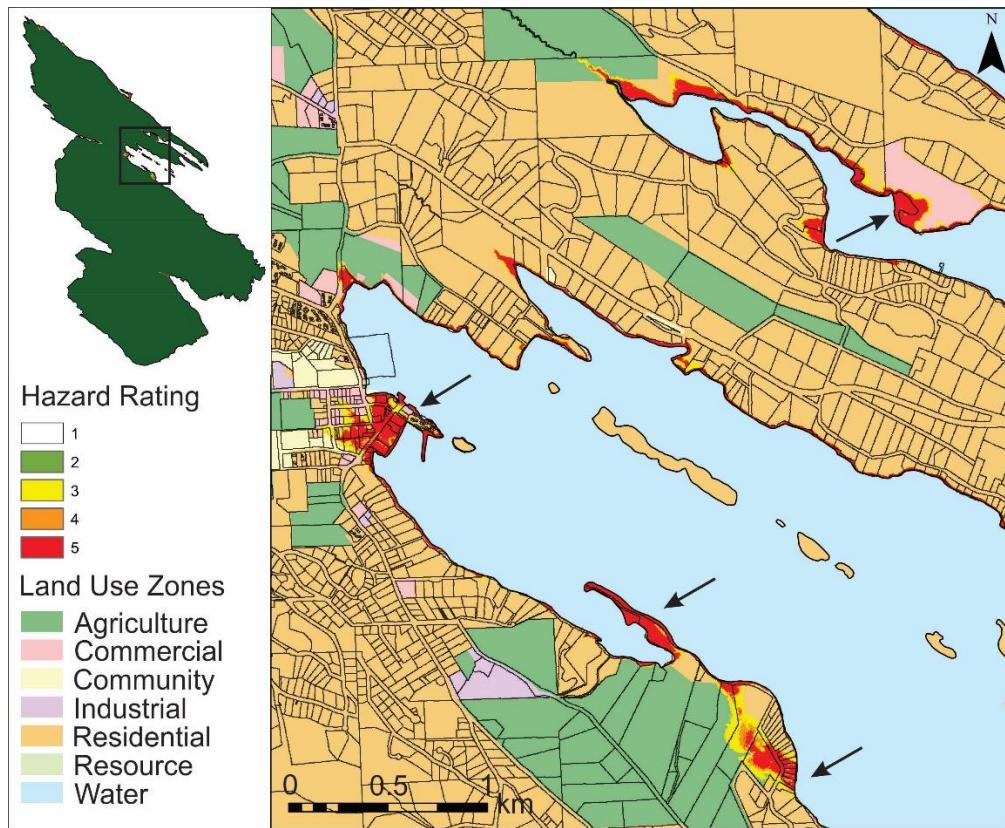


Figure 10. Overlay of coastal hazards onto land use zones near Ganges Harbour, Salt Spring Island

5.2 Aquifer Susceptibility to Saltwater Intrusion

Theoretically, under natural conditions, the freshwater-saltwater interface will extend inland from the coast such that areas closer to the coast will be more likely to become contaminated by saltwater should some disturbance (such as pumping or sea level rise) occur. Similarly, the interface is shallower closer to the coast. Thus, distance from the coast is an important parameter to consider in a SWI aquifer susceptibility map. The position of the saltwater interface is largely determined by the groundwater flux. Where the groundwater flux (from inland to the coast) is high (such as in steep topography), the interface will be closer to coast, whereas if the flux is low (such as in low topography terrain), the interface may be further inland. Therefore, either topography itself or some representation of the flux is important to consider in an aquifer susceptibility to SWI map.

Thus, to characterize aquifer susceptibility to SWI in this study, two parameters were used: 1) distance from coast (Kennedy 2012) and 2) either topographic slope (Kennedy 2012) or groundwater flux (combination of hydraulic conductivity and topography) (Erlandson 2014). Ultimately, distance from coast is added to topographic slope/groundwater flux (depending on which best represents the groundwater chemistry) to create the aquifer susceptibility map.

5.2.1 Distance from Coast

The distance from coast map was created by generating buffers at the assigned distances from the coast in Table 7 and assigned a rating from 1 to 5 based on Kennedy (2012). The distance from coast map is shown in Figure 11. With an increased distance inland, the rating decreases.

Table 7 Rating table for distance from coast (based on Kennedy 2012)

Rating	Distance from Coast (m)
5	0 - 50
4	50 - 250
3	250 - 500
2	500 - 1000
1	1000 - 1500
0	>1500

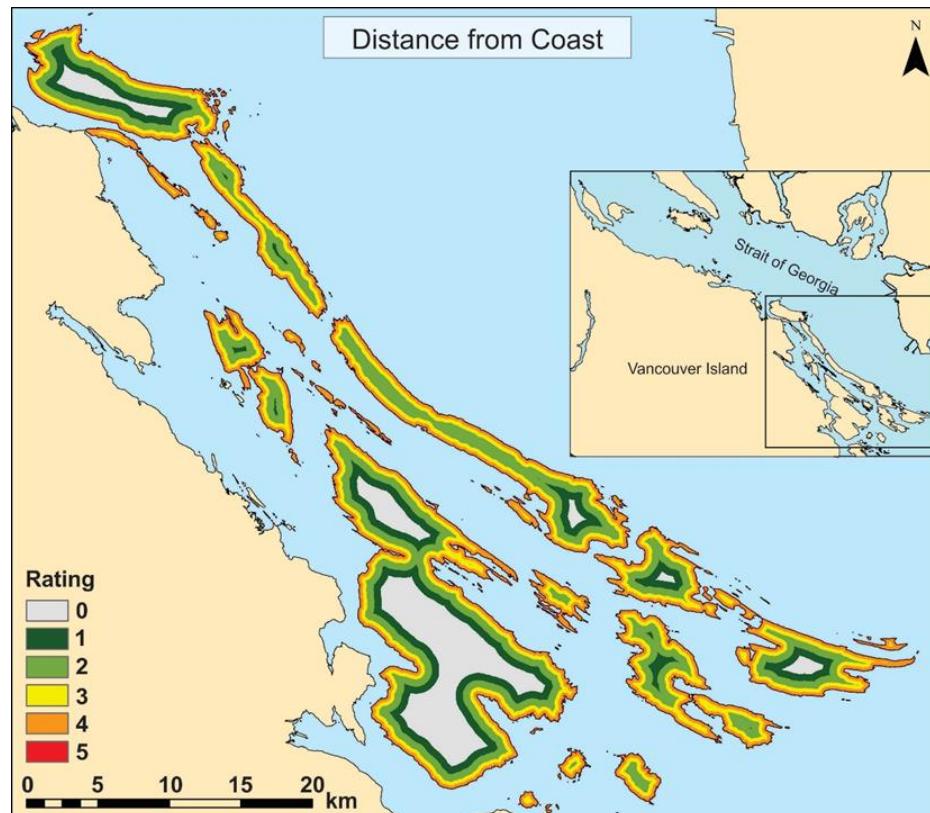


Figure 11. Distance from coast parameter for aquifer susceptibility

Figure 12 shows the relation between well depth and electrical conductivity (EC) measured in a groundwater sample collected from the well. Note: the groundwater sample is considered a mixed sample over the open well and are not depth-specific. Groundwater samples in Figure 12 are coloured based on distance from the coastline (only 32% of sampled groundwater wells have well depth data and could be included in this figure). Groundwater samples with an EC greater than the 95th percentile (2090 $\mu\text{S}/\text{cm}$) are typically within 250 m from the coast (red and orange symbols) (with 1 sample between 250 and 500 m), and groundwater samples with an EC greater than the 90th percentile (960 $\mu\text{S}/\text{cm}$) are within 500 m of the coast (yellow, light green and dark green symbols) (with 1 sample between 1000 and 1500 m). Groundwater samples with EC values above the 90th and 95th percentile are drilled to depths between approximately -6 to -40 m (-20 to -135 ft) below sea level.

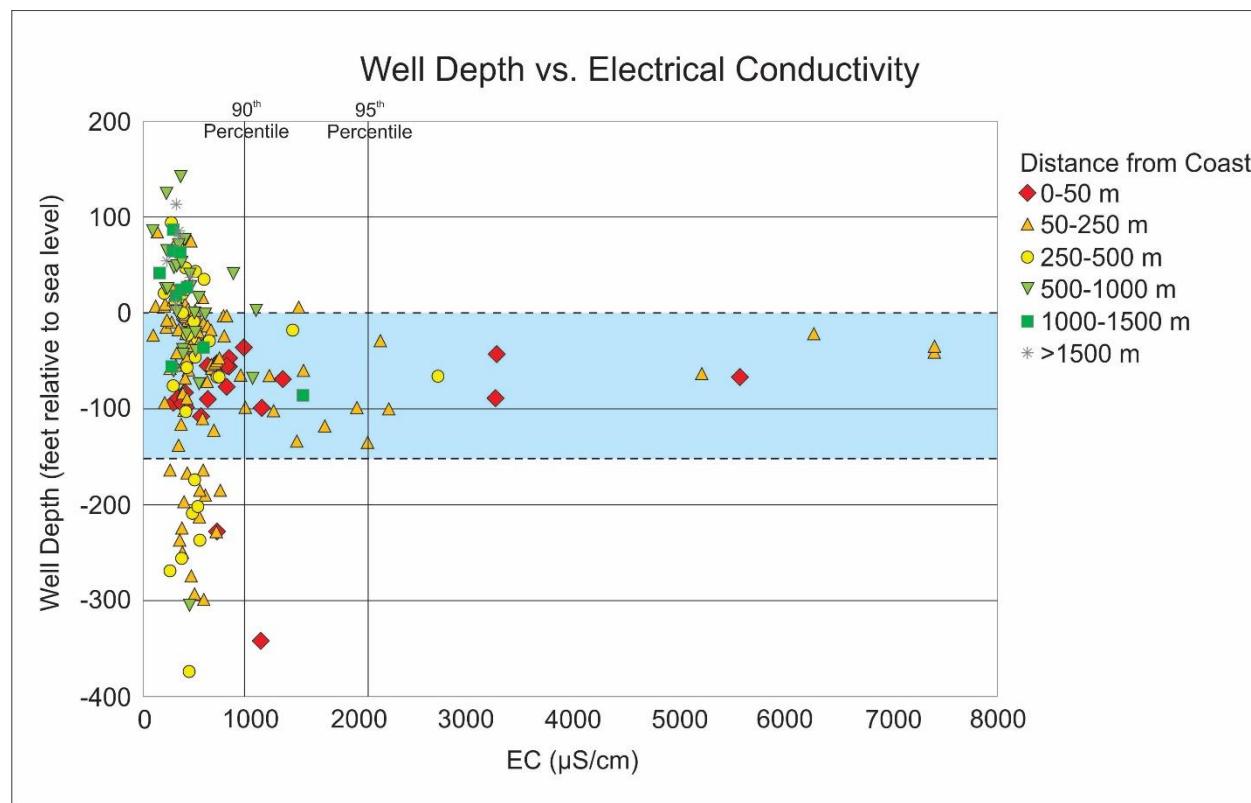


Figure 12. Well depth vs electrical conductivity (EC) for groundwater samples drilled at different distances from the coastline (using the same colours as in Table 7). The horizontal blue section highlights the depth (0 to 40 m) at which groundwater samples have EC values above the 90th and 95th percentile thresholds

5.2.2 Topographic Slope and Groundwater Flux

The topographic slope map was created by calculating the slope from the LiDAR and CDEM maps in ArcGIS. The lower resolution CDEM was available for all of the southern Gulf Islands. LiDAR data were available for North and South Pender Islands, Salt Spring Island, Moresby Island and Portland Island;

however, as Salt Spring Island was a focus for this project the LiDAR data for this island only were used. A rating from 1 to 5 was assigned to the final topographic slope map according to Table 8.

Table 8. Rating table for topographic slope (based on Kennedy 2012)

Rating	Topographic Slope
5	<1°
4	1-5°
3	5-10°
2	10-20°
1	>20°

The groundwater flux map was created by Erlandson (2014) by combining the ground surface topography (i.e. the slope) and hydraulic conductivity of the aquifer. “Percent of slope” data were acquired from the BC Provincial data warehouse as a 25m TRIM DEM. Hydraulic conductivity was estimated by combining the C and Fm parameters from DRASTIC-Fm² maps of the southern Gulf Islands (Denny et al. 2007). Erlandson created two maps, one that used the topography parameter ratings from the original DRASTIC methodology (Aller et al. 1987) and the other according to an approach used by the Nova Scotia Department of Natural Resources (Kennedy 2012).

For this study, the groundwater flux map based on the ratings by Kennedy (2012) was chosen so as to better compare the results with the topographic slope map. Both methods were evaluated based the relationship between topographic slope/groundwater flux and the groundwater chemistry data (extracted rating for sampled groundwater wells); specifically, groundwater samples above the threshold values (95th and 90th percentile) for EC. The approach that best represents the groundwater chemistry data was carried through to generate the final the risk map.

The distance from coast map and the slope/groundwater flux map were added to produce a map with a rating from 1 to 10, which was then rescaled to a rating of 1 to 5 for the final aquifer susceptibility map.

Topographic slope and groundwater flux are compared in Figure 13. Gabriola and Salt Spring Island have the largest difference between the two methods. On Gabriola Island, topographic slope produces high ratings, and groundwater flux produces low ratings, whereas the opposite is observed along the southwestern coastline of Salt Spring Island and coastal areas along Saturna Island (refer to Figure 3 for island names). The fractured media component of the composite C (hydraulic conductivity) heavily influences the groundwater flux, which may be why the two methods produced different ratings for Gabriola and Salt Spring Island.

² DRASTIC maps incorporate seven main characteristics of aquifers to approximate their intrinsic vulnerability to surface contaminants (Aller et al. 1987). Among these seven is the 'C' or hydraulic conductivity parameter. Denny et al. (2007) modified the DRASTIC model by including an additional 'Fm' or fractured media parameter. This Fm parameter characterizes linear zones of higher bedrock susceptibility based on the orientation, length and intensity of fractures (Denny et al., 2007).

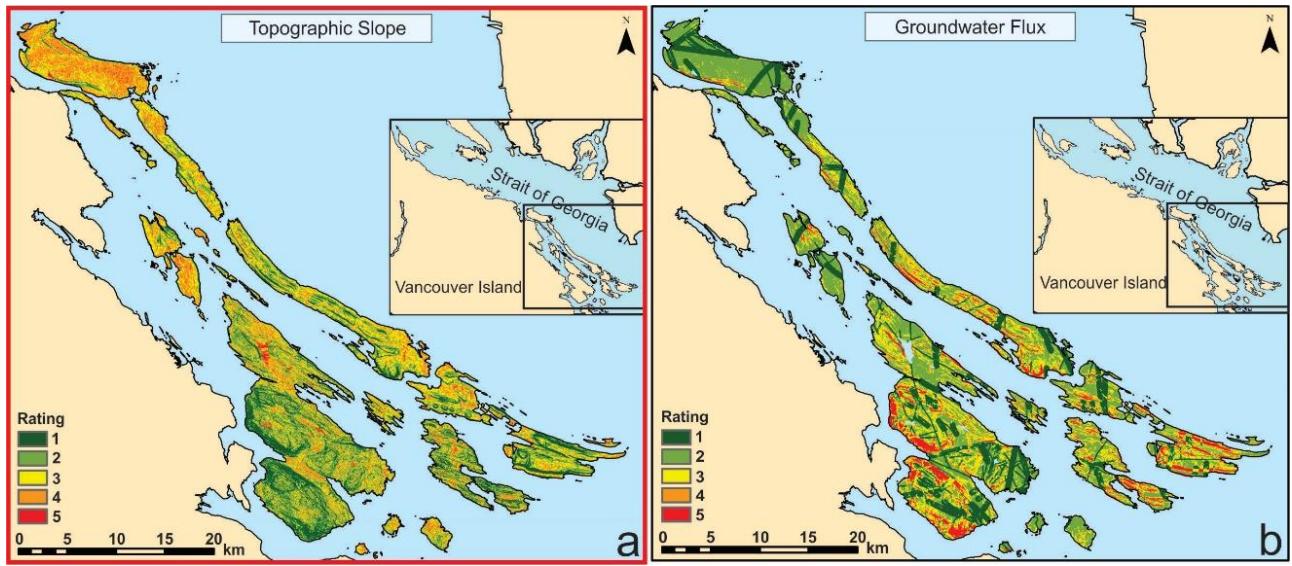


Figure 13. Comparison between topographic slope and groundwater flux. See Figure 3 for map of island names.

Topographic slope and groundwater flux ratings for sampled groundwater wells above the 95th and 90th percentile are summarized in Table 9. Groundwater wells typically have ratings of 3 and 4 for topographic slope and a rating of 2 for groundwater flux (Figure 14). Although groundwater flux is perhaps a better indicator of aquifer susceptibility than simply topographic slope, based on Table 9, topographic slope corresponds to higher ratings for high EC values (above the threshold) and was thus considered to be the more applicable method for this study area.

Table 9. Comparison between topographic slope and groundwater flux ratings for sampled groundwater wells with EC values above the 95th and 90th percentile thresholds

Rating	Topographic Slope				Groundwater Flux				
	95 th Well Count	95 th %	90 th Well Count	90 th %	95 th Well Count	95 th %	90 th Well Count	90 th %	
1	3	10.0	6	10.5	6	21.4	13	24.1	
2	4	13.3	6	10.5	18	64.3	30	55.6	
3	10	33.3	22	38.6	2	7.1	7	13.0	
4	11	36.7	20	35.1	0	0	1	1.9	
5	2	6.7	3	5.3	2	7.1	3	5.6	
Mean	3.2		3.1		2.1		2.1		

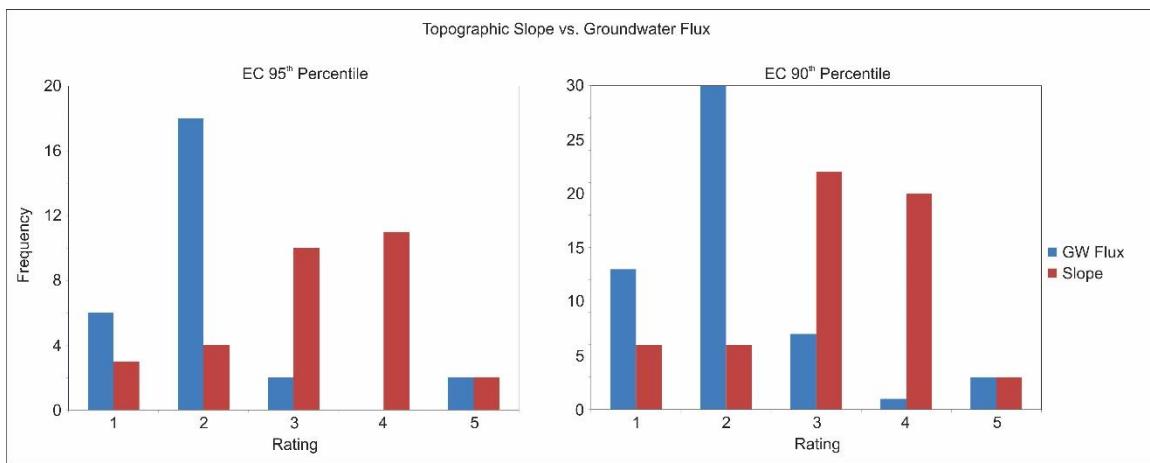


Figure 14. Frequency diagram used to compare topographic slope and groundwater flux

5.2.3 Aquifer Susceptibility to SWI Map

The distance from coast map and topographic slope map were added together to create the aquifer susceptibility map for the southern Gulf Islands (Figure 15).

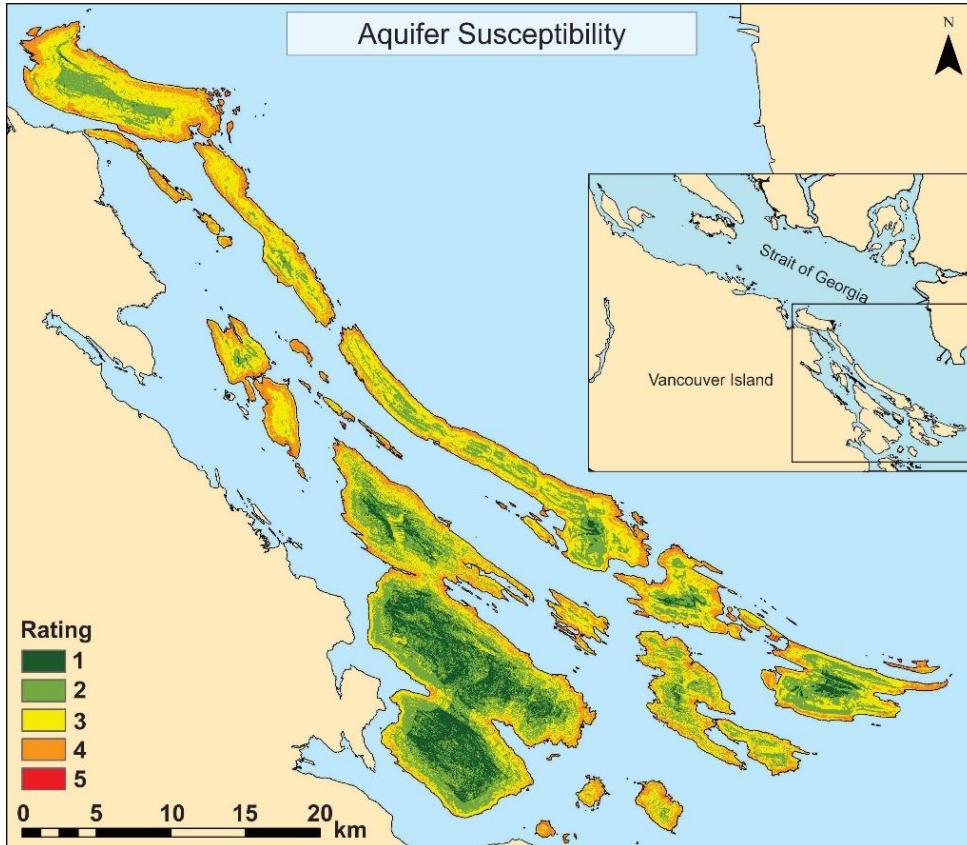


Figure 15. Aquifer susceptibility map calculated from distance from coast and topographic slope for the southern Gulf Islands

5.3 Final Vulnerability Maps

Two hazard threat maps (pumping and coastal hazards) were multiplied with the aquifer susceptibility map to create two vulnerability maps (Eq. 4); one that shows the aquifer vulnerability to pumping (southern Gulf Islands) and the other to coastal hazards (Salt Spring Island). The pumping vulnerability map was created for all of the Gulf Islands, whereas the coastal vulnerability map could only be created for Salt Spring Island (limited based on available LiDAR data). The two vulnerability maps were added to create a total vulnerability map for Salt Spring Island. Because the pumping vulnerability map was for all the southern Gulf Islands, it was used in the complete risk assessment which considers loss.

The aquifer vulnerability based on well density (pumping) is shown in Figure 16 for the southern Gulf Islands. The well density and aquifer susceptibility maps were assigned equal weight in the creation of the aquifer vulnerability map. Features from the well density map are quite prevalent in the aquifer vulnerability map, but the aquifer susceptibility map either reduces the influence of pumping (where aquifer susceptibility rating is low) or highlights areas where the aquifer is highly vulnerable (high susceptibility and high well density).

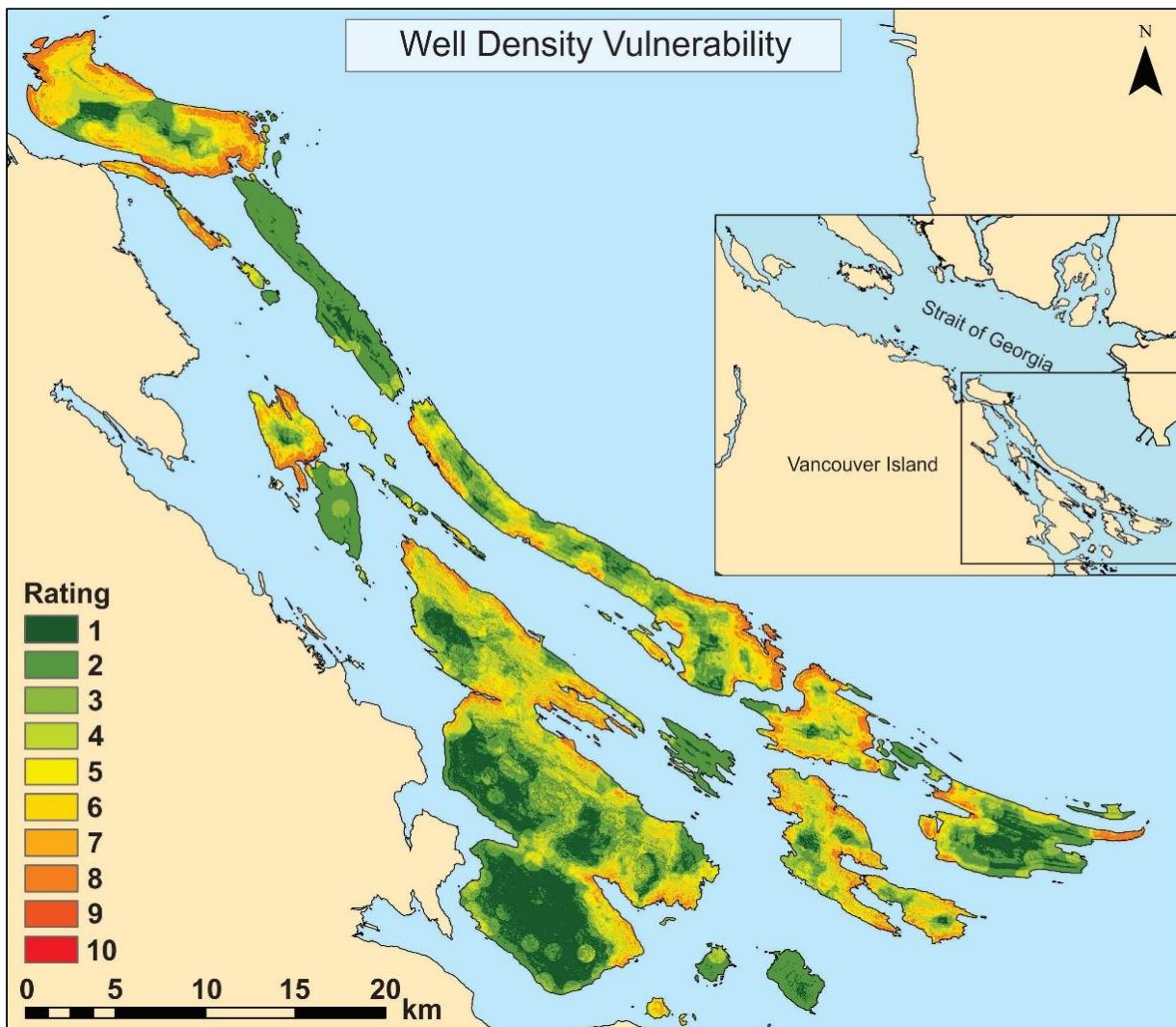


Figure 16. Vulnerability map calculated from pumping and aquifer susceptibility for the southern Gulf Islands

Wells with electrical conductivity (EC) values exceeding the 90th and 95th percentile thresholds were overlaid on the aquifer vulnerability map (Figure 17) to qualitatively assess whether aquifer vulnerability correlates with high salinity. Wells that have EC values above the thresholds are typically found along the coast or in other areas mapped as vulnerable to saltwater intrusion. But there are inconsistencies. For example, East Point (eastern peninsula on Saturna Island) has a high vulnerability, and yet some wells are above the EC thresholds and others are not. Low values of EC could be explained by the occurrence of fractures. Fractures may act as conduits for freshwater (from recharge areas) or saltwater (from the ocean; see Allen et al. 2002), and thus, may locally influence individual wells.

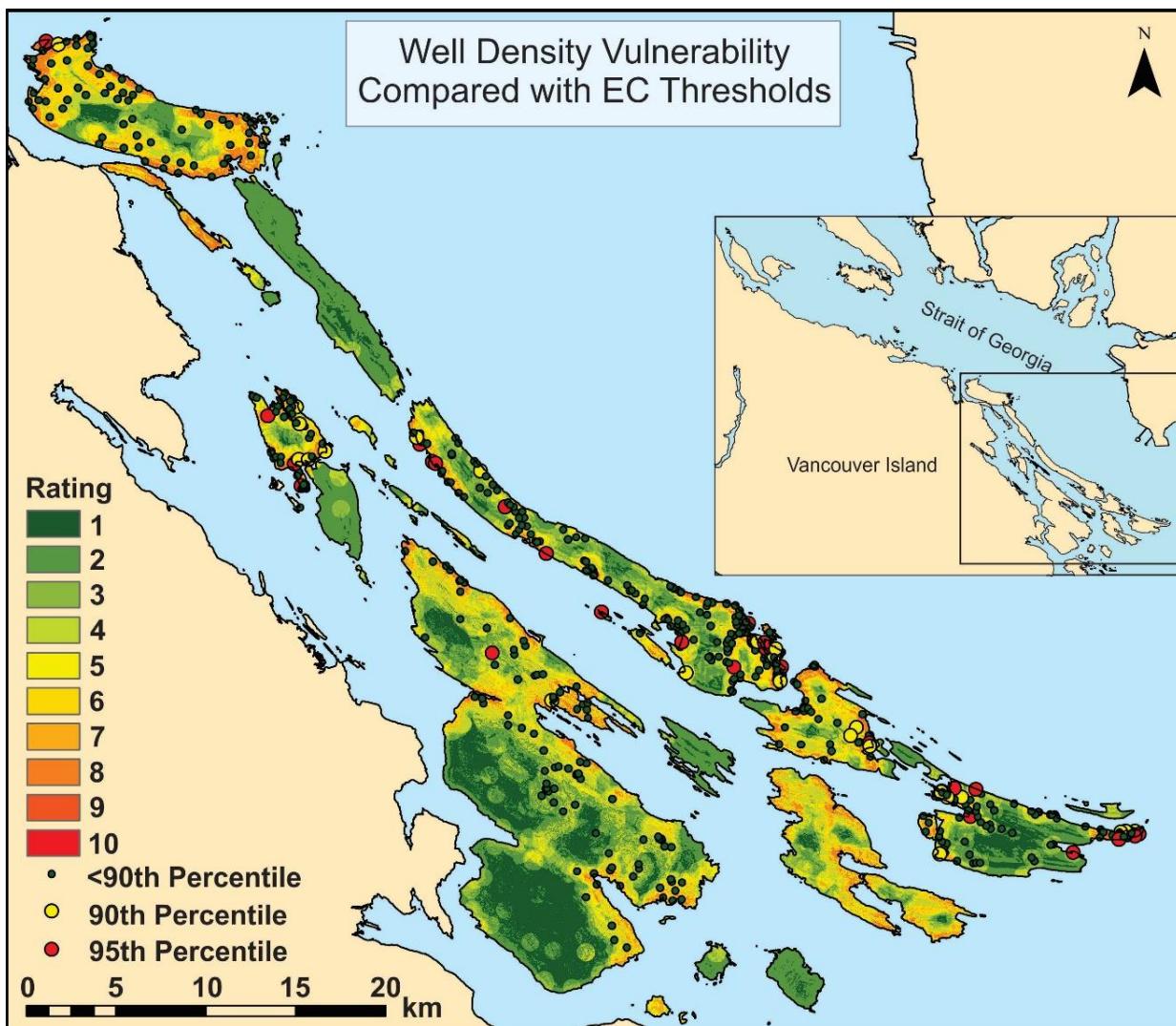


Figure 17. Vulnerability map compared with groundwater chemistry for the southern Gulf Islands

The vulnerability maps for both pumping and coastal hazards are compared in Figure 18 for Salt Spring Island. The pumping vulnerability map has a range of ratings throughout the island (higher ratings in the north/northeast and lower ratings in the south/southwest), whereas the coastal vulnerability map is dominated by ratings of 1 with higher ratings at a few coastal regions.

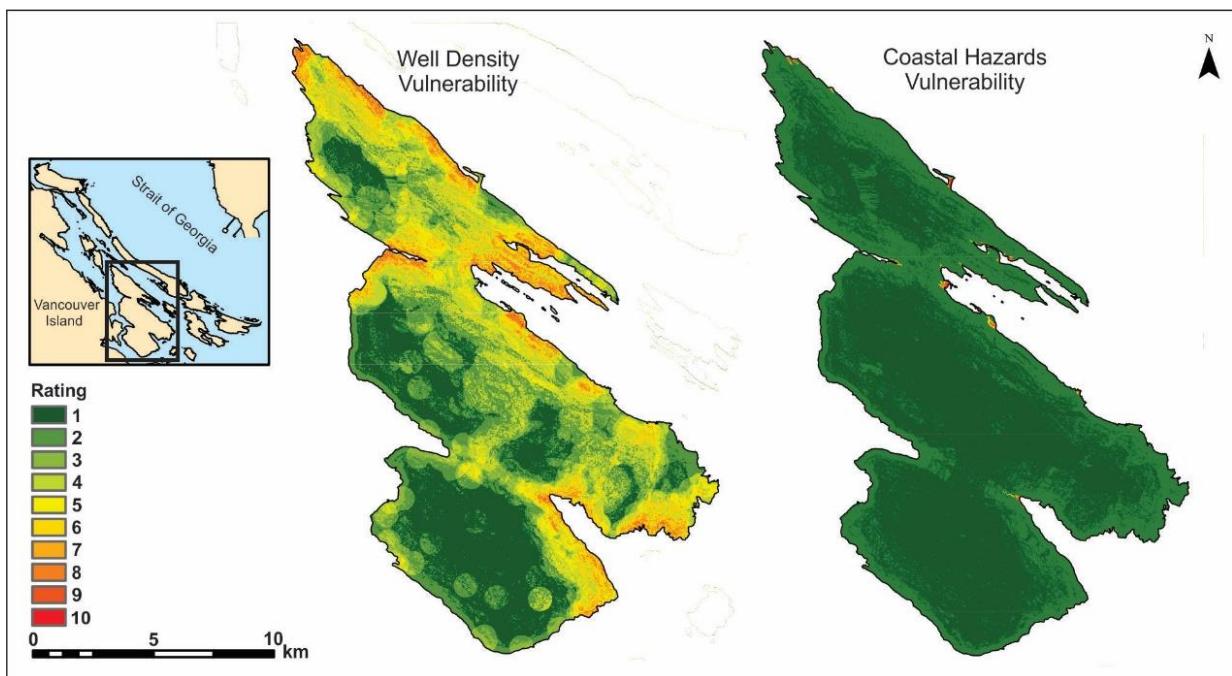


Figure 18. Comparison between pumping vulnerability and coastal vulnerability

The two vulnerability maps were compared with chemistry data from Salt Spring Island. Only two groundwater samples were above the 95th and 90th percentile (1 each). Therefore, all of the chemistry data, regardless of percentile, were included in the analysis (Table 10). The two samples that were above the 95th and 90th percentile had ratings of 4 and 6, respectively, for pumping vulnerability, and 1 and 2, respectively, for coastal vulnerability. The pumping vulnerability ratings are relatively more evenly distributed than the coastal vulnerability ratings, which are dominated by ratings of 1 and 2.

Table 10. Comparison between pumping and coastal vulnerability for all sampled groundwater wells on Salt Spring Island

Rating	Pumping Vulnerability		Coastal Hazards Vulnerability	
	Well Count	%	Well Count	%
1	1	1.1	42	46.2
2	10	11.0	47	51.7
3	0	0	0	0
4	34	37.4	0	0
5	6	6.6	1	1.1
6	22	24.2	1	1.1
7	1	1.1	0	0
8	17	18.7	0	0
9	0	0	0	0
10	0	0	0	0
Mean	5.1		1.6	

There are several limitations with comparing pumping and coastal vulnerability with the chemistry data. First is that the chemistry dataset is a partial dataset of all the wells on Salt Spring Island and the sampled wells are not evenly distributed throughout the island. Second, for coastal vulnerability, most of the high ratings are within 250 m of the coast (see Figure 12). Generally, groundwater samples that are within 250 m of the coast have EC values above the 95th and 90th percentile and out of the 97 groundwater samples for Salt Spring Island, only 24 (25%) are within that distance. As a result, the other 75% control the low ratings for the coastal vulnerability.

The two vulnerability maps were added to create the final vulnerability map for Salt Spring Island (Figure 19).

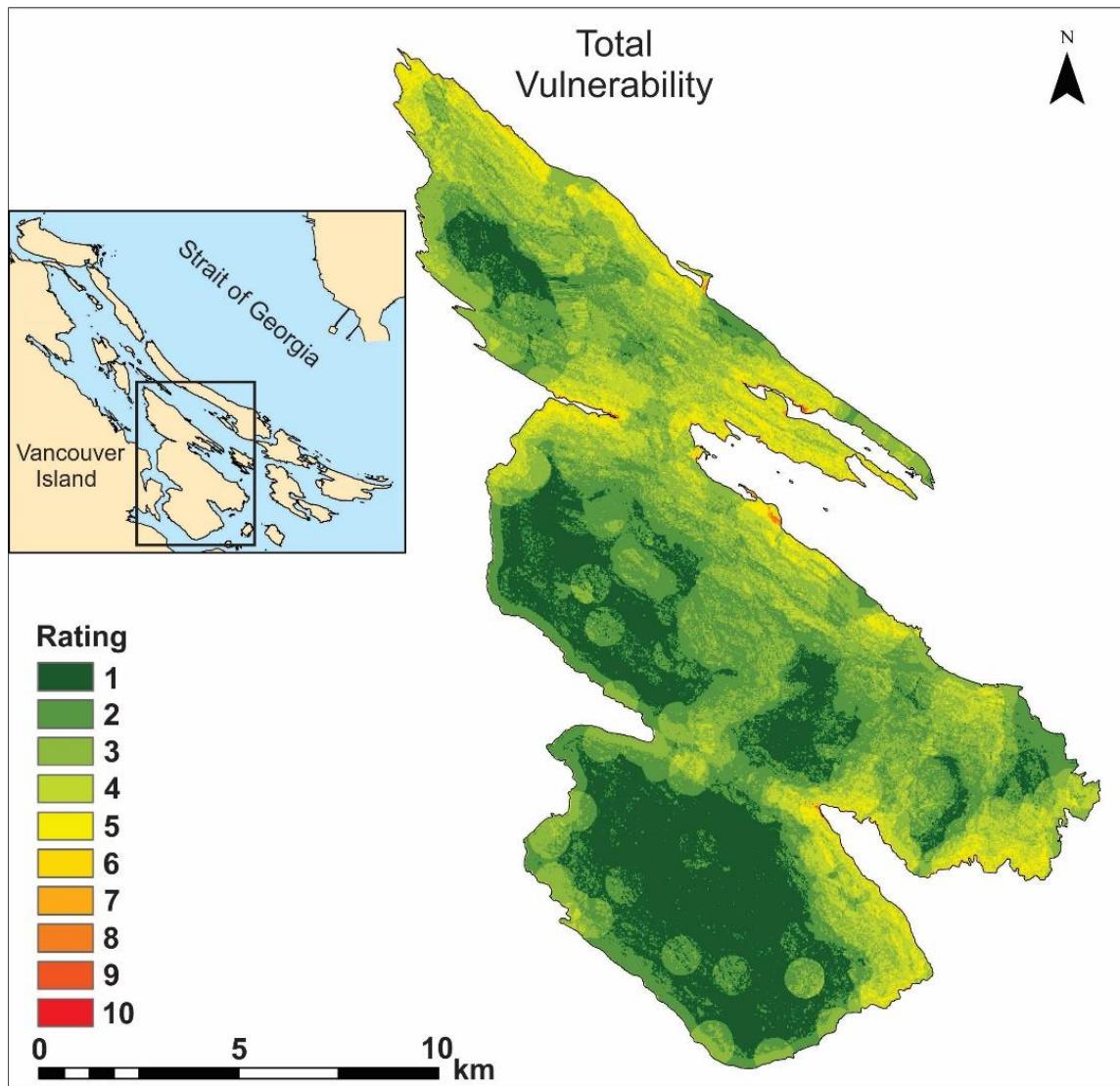


Figure 19. Total vulnerability for Salt Spring Island

5.4 Loss

A land use zoning dataset was obtained through the Islands Trust (Mark van Bakel, Islands Trust, personal communication). The Islands Trust is a federation of small governments serving islands in the Strait of Georgia. Map Islands Trust (MapIT) contains a series of maps which provide information about ecological, property and other valuable mapping information maintained by the Islands Trust Geographic Information System.

A dollar value representing loss was assigned to each zone. If a groundwater supply is lost due to SWI, the water source could be replaced with either a rainwater collection system or water could be imported from the mainland or elsewhere on the Gulf Islands. Installation of a rainwater collection system costs between \$25,000 to \$50,000 (Bob Burgess, Gulf Islands Rainwater Connection Ltd, personal communication) and importing water costs around \$500 per month (\$6,000 per year) for a household of two people (Dan Foley, Summer Rain Water Delivery, personal communication). Financially, the best long term solution would be to install a rainwater collection system; as a result, a conservative value of \$25,000 was assigned to residential, industrial and commercial zones as a conservative estimate for replacement cost.

The method by Simpson et al. (2014) was used to determine the economic loss associated with the loss of a groundwater supply in an agricultural area. Simpson et al. (2014) assigned a loss value based on annual revenue generated by business. Income information on a farm by farm basis was not available, so average annual revenue (\$/acre) was used from Statistics Canada (2007). Simpson et al. (2014) assigned values based on the type of farm (dairy, berries, etc.), but detailed information on the type of agriculture was not available for the southern Gulf Islands. Therefore, an average of \$2,632/acre (value of farmland and buildings) obtained from Statistics Canada (2006) was used to determine the economic loss for agricultural land. The values in Table 11 were used to assign a rating (1 to 10) to the zone codes based on the total loss to create the final loss map.

Land use zones, such as community or resource, which would not necessarily be affected if there were no groundwater resource available were assigned a value of 1 rather than 0 so that when the loss and vulnerability map are multiplied together to create the overall risk map, features are not lost. The replacement cost of \$25,000 was assigned to commercial, industrial and residential land zones and the economic loss was calculated for agriculture land based on a generic value of \$2,632/acre, which results in the loss map for the southern Gulf Islands (Figure 20).

Table 11. Rating table for Replacement and Economic Loss for different zone codes (based on Simpson et al. 2014)

Rating	Replacement/Economic Loss (\$)
10	>5,000,000
9	1,000,000 to 5,000,000
8	500 - 1,000,000
7	250 - 500,000
6	100 - 250,000
5	50 - 100,000
4	25 - 50,000
3	10 - 25,000
2	5 - 10,000
1	1 - 5,000

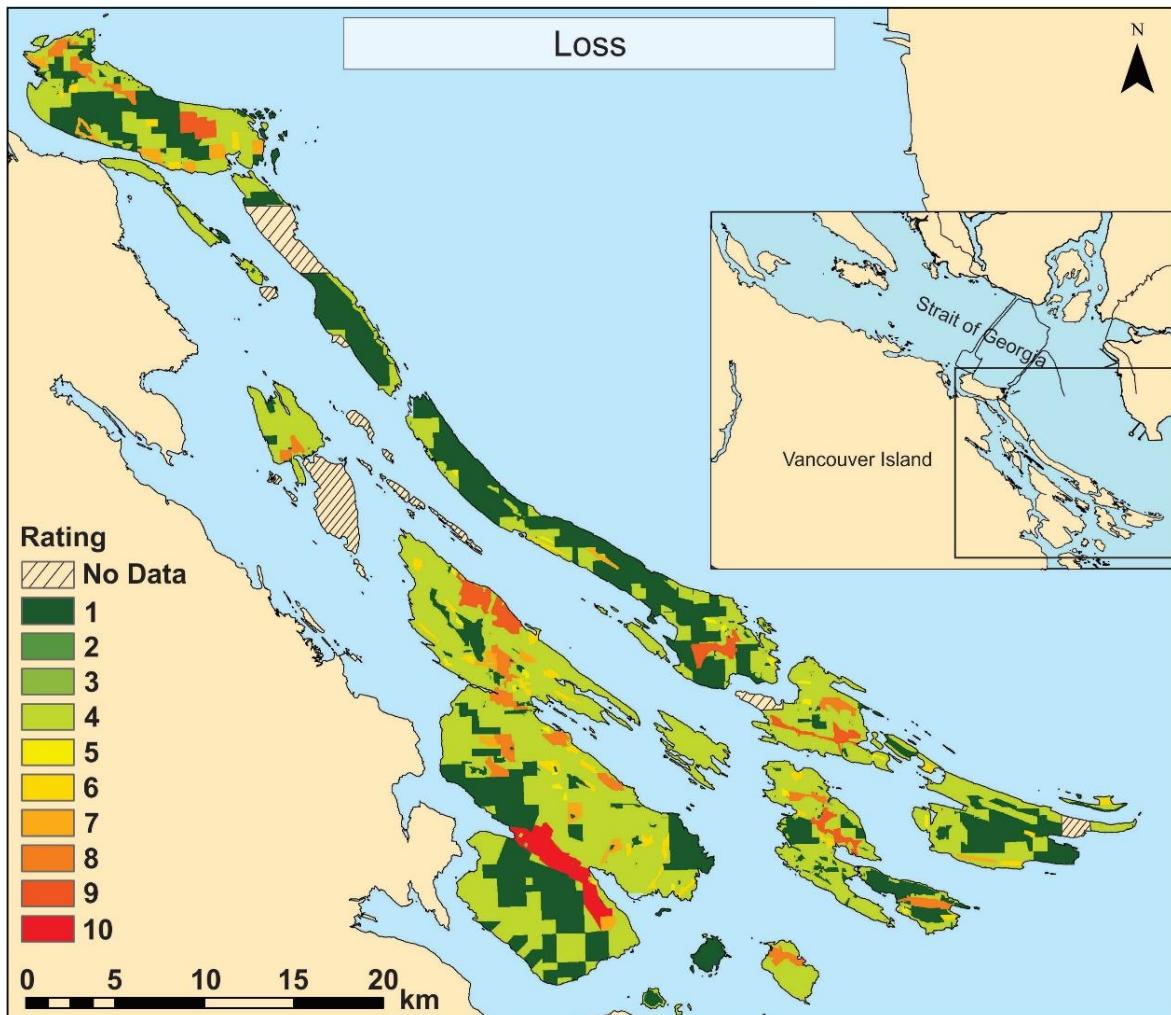


Figure 20. Replacement and economic loss for the southern Gulf Islands

One limitation of the loss map is that it can vary depending on the value assigned to each zone code. For example, a conservative value of \$25,000 was assigned to commercial, industrial and residential zones, but this value could be \$50,000 or larger depending on if the household has more than two occupants or if rainwater harvesting is not a suitable solution for the commercial and industrial sectors. If the value assigned to these zones is increased, it would shift the majority of the ratings from 4, to 5 or 6, which would in turn influence the final risk map.

There are alternative ways of representing loss. For example, loss could also include the change in property value if no water were available or there could be increased cost to a water utility and improvement for district users. Although this study considered some of the financial implications associated with losing a fresh groundwater supply, a more comprehensive evaluation of loss could be undertaken.

5.5 Overall Risk Map

Pumping vulnerability represented by well density (Figure 16) and loss (Figure 20) were multiplied (Eq. 1) to create the overall risk for the southern Gulf Islands (Figure 21). The loss map significantly influences the outcome of the risk map. Therefore, the risk map should be viewed with caution because it reflects a subjective evaluation of loss, as described above. Nevertheless, there is potential value to including loss as it represents (in this case) a potential financial burden to a well owner and a negative economic consequence for agricultural land.

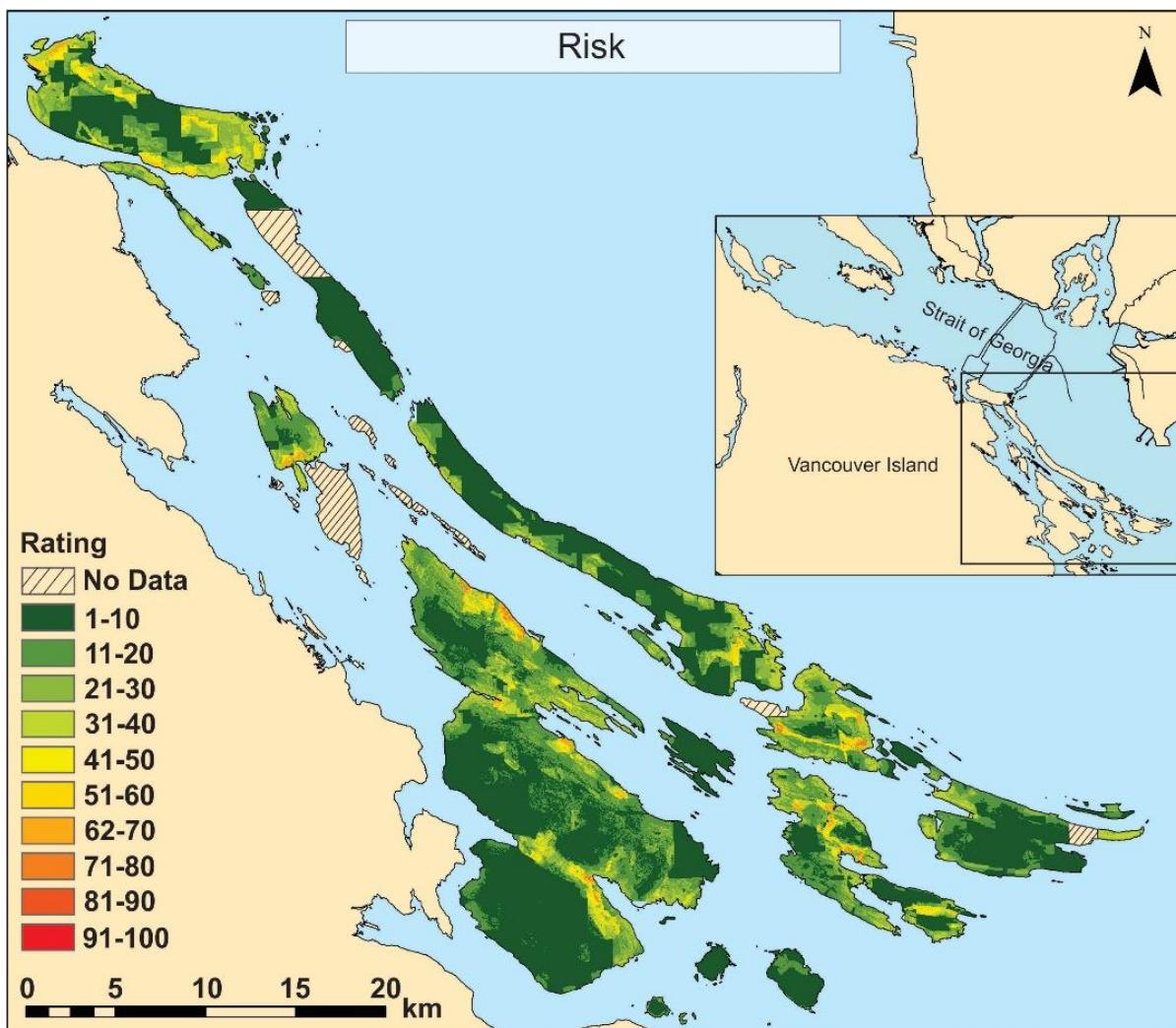


Figure 21. Overall risk for the southern Gulf Islands calculated from pumping vulnerability and loss.

6 Conclusions

This research mapped aquifer vulnerability specific to saltwater intrusion. The approach required mapping coastal hazards, anthropogenic hazards (pumping) and aquifer susceptibility.

Several hazards were identified for this coastal area that have the potential to lead to salinization of aquifers, including storm surge, sea level rise, and pumping. The various coastal hazards were mapped for the Gulf Islands, with greater detail provided for Salt Spring Island where LiDAR data were available. Natural (SLR and storm surge) and anthropogenic (pumping) hazards were mapped separately, employing different datasets and techniques and comparing the results.

The final coastal hazard map (Figure 9c) suggests that coastal hazards are limited to a few areas on Salt Spring Island, particularly in narrow bays and inlets (e.g. around Ganges Harbour); these areas could experience inundation (up to ~400 m inland) related to sea level rise and storm surge. Overall, however,

coastal hazards are relatively limited across most of Salt Spring Island. Other Gulf Islands or portions of islands that are low-lying may be more impacted by coastal hazards. It is recommended to expand LiDAR mapping be carried out throughout the Gulf Islands in order to apply the coastal hazard mapping methods outlined for Salt Spring Island throughout the rest of the region.

Pumping hazards were significant on many islands (Figure 6b). Gabriola and Mayne Islands in particular stand out as having high well density ratings. It should be pointed out, however, that well density was based on wells reported in the provincial WELLS database, plus 69 water supply system wells and some 200 wells that had been sampled for water chemistry but were not reported in WELLS. It is well known that the WELLS database is incomplete – a province wide estimate is that 30% of all wells are not reported. Therefore, it is possible that well density is underestimated for the Gulf Islands. Equally, however, WELLS includes older wells that may not be active. In this study, relative weights were applied to each point for calculation of point density, giving more weight to wells that were reported in WELLS as being for irrigation use and for water supply system wells. This information may be inaccurate. Therefore, it is recommended that an accurate inventory of wells on the Gulf Islands be carried out and that more accurate estimates of water use be obtained to improve the pumping hazard results.

The aquifer susceptibility map was based on distance from coast and topographic slope. Topographic slope was chosen over groundwater flux because there was a stronger relation between high susceptibility ratings and high salinity as reported by Klassen et al. (2014). It is unfortunate that using groundwater flux as a parameter yielded inferior results for susceptibility (when compared with the groundwater chemistry data) because the groundwater flux map incorporates geological variation, and particularly emphasizes large scale fracture zones. These fracture zones act as conduits which could either transport freshwater from recharge areas to areas along the coast, thereby lowering their susceptibility, or alternatively, draw saltwater in to areas that might otherwise not be susceptible. Not including geological variability in the susceptibility rating is a limitation of this study. Nevertheless, the approach used adequately captured areas with high susceptibility close to the coast and where the lens is thin (shallow topography) and lower susceptibility further inland and/or where the lens is thick (steep topography). Additional validation of the susceptibility map is warranted. This could be accomplished by developing three-dimensional density-dependent groundwater flow and solute transport models for each island and comparing the susceptibility map ratings to the model results (which would indicate the depth and thickness of the freshwater lens) (e.g. see Holding and Allen 2015a). Models of this type are currently being developed by SFU for the Gulf Islands.

Each of the two hazard maps (coastal hazards and pumping) was combined with the aquifer susceptibility map to create two aquifer vulnerability maps (for natural and anthropogenic hazards, respectively). For Salt Spring Island, a total vulnerability map was generated. The aquifer vulnerability was compared with the observed chemistry for the Gulf Islands. Generally, wells which have high EC values, fall in areas with high vulnerability, but there are also groundwater wells with high EC in low vulnerability areas or wells with low EC in high vulnerability areas. This variability is likely due to the fact that the aquifer susceptibility map does not take into account geological variability associated with fracture zones as noted above. The variability may also point to differences in geology at the well scale (i.e. individual small fractures) that may influence groundwater flow and chemistry locally.

Notwithstanding, the water chemistry data used to verify the mapping results were not collected for this purpose. As mentioned, only 25% of groundwater samples were collected from wells situated near the coast. To better validate these results, samples should be collected in high vulnerability areas in order to verify the connection between the vulnerability map and observed groundwater chemistry.

Determining loss for the risk assessment considered the financial consequence of a well becoming contaminated. A loss of \$2,632/acre was assigned to agricultural land and a replacement cost of \$25,000 was assigned to commercial, industrial and residential areas where a rainwater harvesting system could be installed. A limitation of this method is that it is controlled by the dollar value assigned to each land use zone. No distinction was made between different types of agriculture on the Gulf Islands, and the replacement cost of \$25,000 was the lower estimate for a rainwater harvesting system; commercial and industrial sectors may require a larger system which could cost up to \$50,000. In order to better characterize loss for the Gulf Islands, several parameters could be introduced, for example, the change in property value if a property were to lose its water supply, the potential increase in cost of water supply systems if more people are required to use them, as well as environmental impacts such as the ecological cost associated with altering the natural hydrological balance if saltwater intrusion were to occur. The various ways of characterizing loss could greatly change the impact on the overall risk.

The final risk to bedrock aquifer map for the Gulf Islands was created by combining the aquifer vulnerability map with the loss map. The risk map shows overall risk throughout the Gulf Islands, but it does not include natural hazards (due to limited LiDAR data). As mentioned above, loss heavily influenced the overall risk map, and depending on how loss is characterised (financial or ecological), the overall risk outcome could be quite different.

Overall, the combination of chemical indicators of saltwater (Klassen et al. 2014) and risk assessment maps (this study) are useful tools which can be used to improve decision-making related to monitoring and community development for this particular coastal area of BC and elsewhere. The aquifer vulnerability map, in particular, is suited for determining areas which are salinized or most likely to become salinized, and therefore is potentially useful for water allocation decision-making or groundwater / land use development planning.

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