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GIS Modelling of Sea Water Intrusion Risk along British Columbia's Coast

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EXECUTIVE SUMMARY

Over-development in coastal areas can cause sea water intrusion into coastal aquifers. Once sea water intrusion occurs, remedial measures can be slow and costly. Mapping sea water intrusion risk helps to ensure these risks are appropriately managed by:

- Identifying areas at risk of sea water intrusion along B.C.'s coast to support statutory decision makers in licensing groundwater use;
- Providing a better understanding of the factors affecting risk of sea water intrusion for statutory decision makers, as well as to local governments, groundwater users and interested public to inform planning of development and promote sustainable groundwater use; and
- Identifying areas for ENV and FLNRORD to conduct more detailed characterization and monitoring.

A geographic information system (GIS) modelling approach employed by Klassen and Allen (2016) to map the sea water intrusion risk of the Gulf Islands has been expanded to map the entire B.C. coast. For this study, Klassen and Allen's (2016) method was updated to consider the following:

1. unconsolidated aquifers along B.C.'s coast, which were not considered in Klassen and Allen (2016) as the Gulf Island study area is predominantly bedrock;
2. the much greater variety of groundwater use along B.C.'s coast compared to the Gulf Islands; and
3. the new groundwater licensing requirements that came into effect in 2016.

The method developed by Klassen and Allen (2016) to assess overall sea water intrusion risk incorporated an assessment of both the vulnerability and the potential for associated resource loss. Vulnerability was determined by evaluating the intrinsic Aquifer Susceptibility and the Pumping Threat with a refined analysis that incorporated a coastal hazard assessment where data were available.

In the present study, the unconsolidated Aquifer Susceptibility is determined using distance from coast and groundwater level (non-pumping) relative to sea level with the grid cells conservatively assigned the maximum rating from unconsolidated wells within that grid cell. The bedrock Aquifer Susceptibility is based on topographic slope and distance from coast. Pumping Threat is determined using a kernel density function weighted to the estimated quantity of groundwater use summed within each model grid cell. Loss, which assesses the magnitude of the consequence if sea water intrusion occurs within an area, was determined by estimating quantities of water used, where larger use quantities imply greater Loss should sea water intrusion occur. Coastal Hazards were determined from Flood Hazard and Coastal Morphology, and are incorporated into Vulnerability to Coastal Hazards only where LiDAR data are available.

This study utilizes well records from GWELLS and licenced groundwater wells as data sources for determination of Pumping Threat and Loss. As the number of water licences increases and the water rights (eLicensing) database grows, this assessment can be updated to improve this analysis.

GIS modelling and mapping showed the following results:

- Low-lying, more recent fluvial and deltaic aquifers (types 1 and 2) can show relatively high Aquifer Susceptibility ratings extending far inland; High Aquifer Susceptibility ratings for confined, unconsolidated aquifers (e.g., Quadra Sands) do not extend as far inland.
- Along the coast where the bedrock topography is steep, high bedrock Aquifer Susceptibility only occurs along the shoreline. Bedrock susceptibility is typically high on rocky, low-lying islets and peninsulas.

- The areas with highest Pumping Threat are associated with very high well density (e.g., Gulf Islands) or higher volume pumping related to municipal or water utility. Pumping Threat is generally lower where residents rely on groundwater solely for domestic use.
- The Pumping Threat is generally highest for unconsolidated alluvial and glacio-fluvial aquifers (types 3 and 4). The percentage of Provincial Groundwater Observation Well Network (PGOWN) wells affected by nearby pumping appears to be significant. The percentage of PGOWN wells experiencing decline appears to decrease with decreasing Pumping Threat rating, as might be expected. This observation is subjective and is based on a limited number of PGOWN wells.
- For both unconsolidated and bedrock aquifers, total dissolved solids (TDS) generally increases with increasing Vulnerability from Pumping Threat rating. Higher TDS results are interpreted to indicate pumping of more brackish water influenced by sea water chemistry.
- Sites of concern documented by the province correlate with areas of higher Aquifer Susceptibility, Pumping Threat, or Vulnerability. Most documented sites of concern have Vulnerability ratings of 3 or above.
- Coastal Morphology in low-lying areas mentioned above contributes to significantly greater Coastal Hazards in those areas. Shallow bathymetry and low-lying areas less than about 3 m elevation are the main attributes contributing to high Coastal Hazard.
- The areas of higher Vulnerability from Pumping Threat tend to be associated with type fluvial, alluvial and deltaic aquifers (types 1, 2, and 3). The Vulnerability from Pumping Threat of Quadra sand (confined glacio-fluvial type 4b) aquifers tends to be highest only immediately adjacent to the coastline.
- The unconsolidated aquifers (fluvial or glacio-fluvial type 1) located along high order streams have high Vulnerability from Coastal Hazards due to low elevation and topographic relief. The Quadra Sands and aquifers associated with alluvial fans that occupy the mouths of smaller coastal creeks have high Vulnerability to Coastal Hazards, but only in the narrow zone along the coastline, and decreasing upgradient.
- In areas where the land is underlain by an appreciable thickness of surficial sediments, the Vulnerability to sea water intrusion into bedrock aquifers from Pumping Threat and Coastal Hazards may be higher than actual because the topographic slope upon which bedrock susceptibility is calculated reflects the slope of the overlying unconsolidated deposits, which is typically less.
- Mapped aquifers underlying the floodplains associated with larger streams have the highest Total Vulnerability. Aquifers associated with alluvial fans that occupy the mouths of smaller coastal creeks have high Total Vulnerability, but only in the narrow zone along the coastline.
- There are additional factors affecting sea water intrusion risk that could not be feasibly incorporated into the GIS model (e.g., availability of alternate water sources, and seasonal water demand). Management of risk in specific areas may need to consider these additional factors, particularly in areas with high Total Vulnerability ratings of 3 and above, so as to adequately mitigate risk. For example, within the Gulf Islands context, moderate to high Total Vulnerability ratings (3 to 5) may require additional consideration to mitigate risk.
- Spatial representation of unconsolidated Aquifer Vulnerability is limited to areas with mapped aquifers. The preliminary spatial representation of Loss is limited to grid cells with reported wells and municipalities that use at least one groundwater source.
- The preliminary Loss mapping is dominated by low ratings because the grid cells correspond with drinking water, irrigation, or some industrial use purposes, with low pumping (less than 30 m^3/day). The highest preliminary Loss ratings are associated with irrigation, water works purposes, and municipal water supply wells.

- As expected, the Overall Sea Water Intrusion Risk for both the unconsolidated and bedrock aquifers is highest in low-lying areas close to the ocean.

We recommend completing the following additional work to add to the findings of this study:

- Acquire additional LiDAR data, especially for low-lying areas with major rivers and/or where more substantial post-glacial sediment deposits exist to allow Coastal Hazards to be modelled along more of B.C.'s coast.
- The mapping layers should be regularly updated potentially every 2-3 years, or more frequently if significant additions, subtractions, or revisions are made to the regional coastal aquifer mapping.
- Consider estimating Loss for smaller municipalities and communities with <300 connections that use groundwater for their supply.
- Consider upscaling the Loss component to allow Loss and Overall Risk to be more comprehensively communicated.
- Explore using the results from this study to develop simple indicators of susceptibility, vulnerability and risk of sea water intrusion for mapped aquifers along the B.C. coast.

As a follow-up to this study, the results should be communicated to promote awareness of coastal aquifer vulnerability and sea water intrusion risk associated with natural physiographic factors and human activities (well drilling and operation), and to encourage implementation of best practices to reduce sea water intrusion occurrence in the coastal setting.

CONTENTS

FIGURES (IN TEXT)

FIGURES B1 THROUGH B17 (IN APPENDIX B)

FIGURES C1 THROUGH C6 (IN APPENDIX C)

TABLES

ACRONYMS

DEM	Digital Elevation Model
DWSS	Drinking Water Supply System
DFL	Designated Flood Level
EcoCat	Ecological Reports Catalogue (B.C. ENV)
EMS	Environmental Monitoring System (B.C. ENV)
ENV	Ministry of Environment and Climate Change Strategy
FCL	Flood Construction Level
FLNRORD	Ministry of Forests, Lands, Natural Resource Operations and Rural Development
GIS	Geographic Information System
GWELLS	Groundwater Wells and Aquifer Database
HHWLT	Higher High Water Large Tide
LiDAR	Light Detection and Ranging
PGOWN	Provincial Groundwater Observation Well Network
SLR	Sea Level Rise
SWE	Static Water Elevation
SWL	Static Water Level
T	Transmissivity
TDS	Total Dissolved Solids
WSA	*Water Sustainability Act*
WTN	Well Tag Number

NOTE ON USE OF THE PHRASE “SEA WATER” INTRUSION

The *Water Sustainability Act* (WSA) uses the specific term “sea water” to distinguish between intrusion of sea water from the ocean versus intrusion of saline water from other sources (e.g., brine from deeply buried sedimentary formations in northeast B.C. or brackish groundwater found in glacio-marine drift in parts of coastal B.C.). While many scientific publications use the term “saltwater intrusion” for intrusion of sea water from the ocean, in this report, we use the phrase “sea water intrusion” instead to reflect the term “sea water” in the WSA. In practice, the phrase “sea water intrusion” and “saltwater intrusion”, when applied to intrusion of water from the ocean (e.g., as a result of well pumping) are analogous.

1. INTRODUCTION

In 2016, the *Water Sustainability Act* (WSA) came into effect and introduced the licensing of groundwater use. This provision addresses a long-standing gap in B.C.'s water management policy to control groundwater use and promote sustainability of the water resource. In particular, Section 58 of the WSA prohibits operation of wells in a manner that causes intrusion of sea water, as well as saline groundwater (e.g., from deep sedimentary formations in NE B.C.) and contaminated groundwater (e.g., from contaminated sites). In making water allocation decisions, decision makers must consider this requirement. The Province of B.C. (2016) has also published best practices guidance on how to operate wells to prevent sea water intrusion. The present study improves the province's understanding of sea water intrusion risk along B.C.'s coast and will provide a resource for statutory decision makers in determining the areas of B.C. where risk of sea water intrusion may require specific consideration.

Characterization of sea water intrusion risk is necessary to inform water management planning and decision making. Previous research completed by Simon Fraser University (Klassen and Allen, 2016) included the development of a method to assess the risk of sea water intrusion in B.C.'s Southern Gulf Islands. This present study expands on and extends the work done by Klassen and Allen (2016) to the remainder of the B.C. coast (Figure 1) to:

- Identify sea water intrusion risk along B.C.'s coast to support statutory decision makers in licensing groundwater use;
- Provide better understanding of the factors affecting the risk of sea water intrusion to support planning, decision making, and raising public awareness; and
- Identify areas for the province to conduct more detailed characterization and monitoring of sea water intrusion.

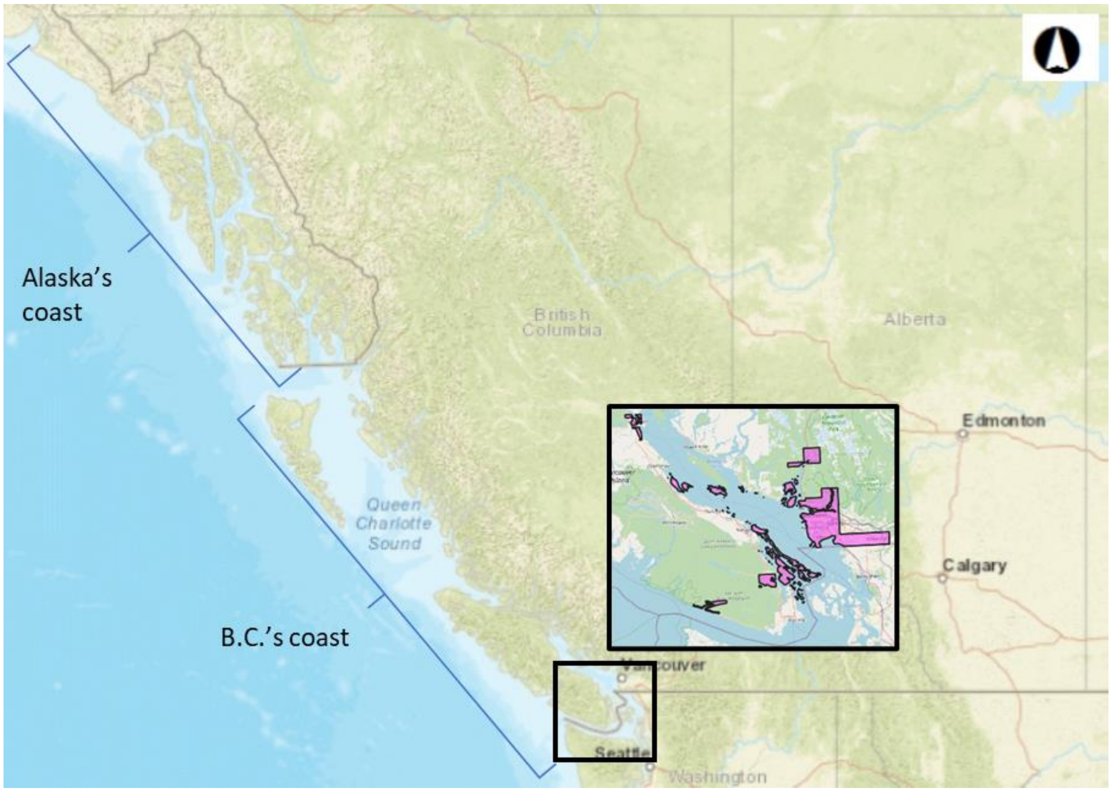

Figure 1. B.C.'s coast showing subset areas where high-resolution LiDAR was available.

2. AQUIFERS ALONG BRITISH COLUMBIA'S COASTLINE

B.C.'s coastline extends over 25,700 km from the State of Washington in the south to the State of Alaska to the north, comprising lowlands, plains, and basins (Holland, 1976). The climate along B.C.'s coast is varied. The windward side of the coast experiences mild wet winters and cool, wet summers (Moore et al., 2010). On the leeward side of the coast (east coasts of Vancouver Island and Haida Gwaii), the winters are mild and wet and the summers are dry.

Aquifers comprising every type of unconsolidated and bedrock aquifer presented in Wei et al. (2009) occur along the coast. In the study area, recharge to unconsolidated aquifers from infiltration of precipitation (recharge-driven aquifer systems – Allen et al., 2010) typically occurs in winter to early spring. Unconsolidated aquifers located adjacent to coastal streams may also receive considerable recharge from streams during the peak winter streamflow period and also in late spring if the stream receives snowmelt from higher elevations (stream-driven aquifer systems – Allen et al., 2010). Recharge to fractured bedrock aquifers typically occurs during the winter months shortly after rainfall events (recharge-driven). Groundwater in coastal aquifers ultimately flows from recharge to discharge areas, to local streams, rivers and even directly to the ocean.

Along the coast, discharging fresh groundwater comes into contact with sea water (Figure 2). This interface between the freshwater and sea water typically exists under a state of dynamic equilibrium. The discharge of fresh groundwater to the ocean keeps the sea water from intruding landward. However, once an aquifer is subject to pumping, pumping reduces the natural hydraulic head and, consequently, the groundwater discharge to the ocean. This reduction causes the interface to move farther landward than under natural pre-pumping conditions. If a coastal aquifer's depth extends below sea level, pumping not only can cause the interface to move landward but also upward below the pumping well as denser sea water is drawn up from depth by a process called *up-coning*. The landward and upward movement of sea water into an aquifer caused by groundwater pumping along the coast is sea water intrusion (Figure 2). Sea water intrusion will result in increasing salinity of the water in the coastal aquifer as well as in the water pumped from wells. Once intrusion occurs, it can take many years or decades for the salinity to decline in response to management actions (e.g., curtailment of pumping). From the standpoint of supplying drinking water, the timeline for reversal of effects may be too great for water suppliers to effectively adapt without resorting to costly treatment or development of alternative supplies.

Groundwater use occurs all along B.C.'s coast, but municipal, industrial (including fish hatcheries) and irrigation uses are heaviest where the population is greatest, such as in the Fraser Lowland and east coast of Vancouver Island. To date, concerns about sea water intrusion from pumping are localized to specific areas. Table 1 lists a number of areas where sea water intrusion concerns have been identified by the province for the purposes of the current study or from historical groundwater reports in the Ecological Reports Catalogue (EcoCat). This list is not exhaustive, and sea water intrusion likely occurs in other areas apart from those listed. The extent of sea water intrusion varies in these areas and may be localized to specific areas.

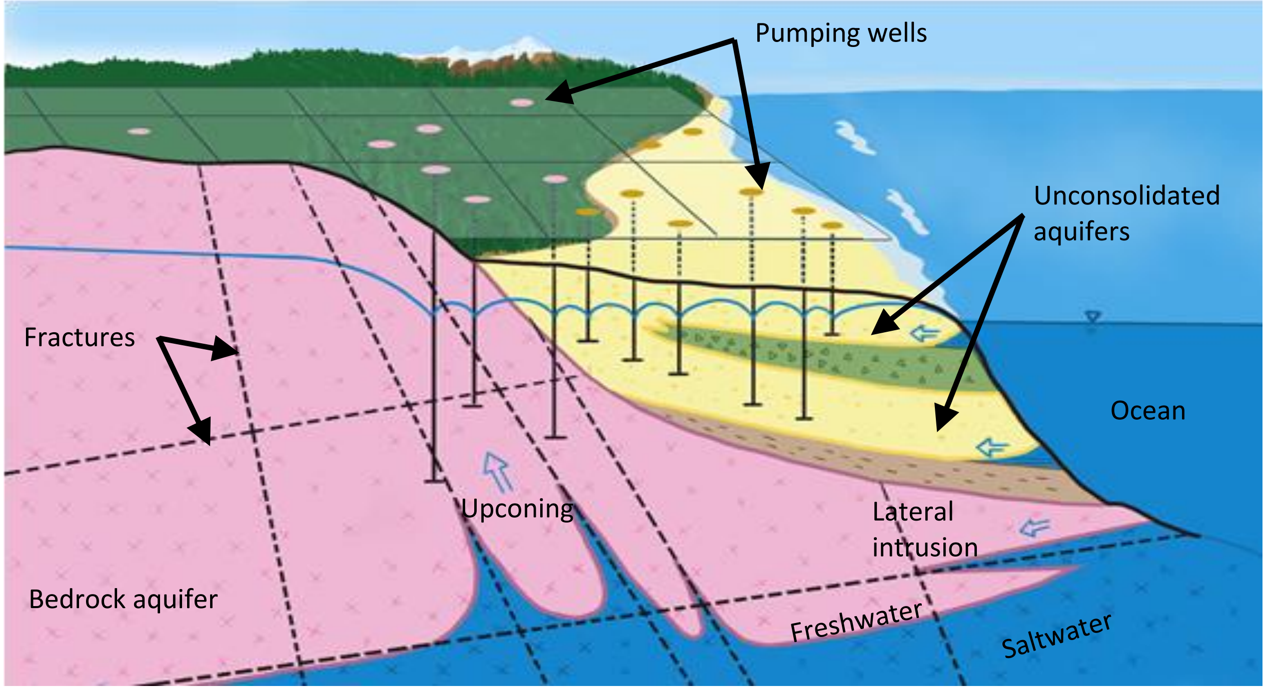

Figure 2. Schematic diagram showing intrusion of sea water in coastal unconsolidated and bedrock aquifers (lateral intrusion and vertical intrusion (up-coning)) due to pumping. The dashed lines represent fractures in the bedrock. The GIS grid cells are shown on the surface.

Table 1. Areas of concerns for sea water intrusion.

Location of Concern (References)	Aquifer(s)
Parksville	221
Little Qualicum River Estuary, Qualicum Beach	664
Savary Island	834, 909
Furry Creek	404
Delta	42
Cowichan River Estuary (Chwojka, 1997; Wei, 1985; Kohut, 1981)	186, 188
White Rock	57
Mill Bay (Kwong, 1987)	204
East Point, Saturna Island (Lapcevic and Kelly, 2010)	735
Scott Point, Salt Spring Island (Tradewell, 1976)	721
Gabriola Island	706, 709
Hornby Island (Allen and Matsuo, 2002)	436, 438
Pender Island	720
Central Saanich (Senanus Drive)	608
Sooke	606
Village of Belcarra (Holt and Allen, 2005)	68

3. METHODOLOGY

3.1 General

This study expands and extends the geographic information system (GIS) modelling approach that Klassen and Allen (2016) applied for the sedimentary bedrock aquifers in the southern Gulf Islands. For this study, the risk framework and mapping method from Klassen and Allen (2016) (modified from the method originally developed by Kennedy (2012)) were reviewed and expanded to address the following:

- existence of unconsolidated aquifers along B.C.'s coast on islands and the mainland, which were not considered in Klassen and Allen (2016)'s Gulf Island study because the island aquifers are primarily bedrock;
- the much greater range of groundwater use along B.C.'s coast compared to the Gulf Islands;
- the groundwater licensing requirements that came into effect in 2016; and
- a measure of Loss which is directly related to quantity of pumping and general water quality requirements.

The approach used in this study is shown in Figure 3. This assessment relies principally on physical factors that are believed to be either drivers or reflect conditions that influence sea water intrusion risk. Because of lack of available data, it was not feasible to assemble and review water quality data from wells except to provide a preliminary check on the reasonableness of the mapping results at this stage.

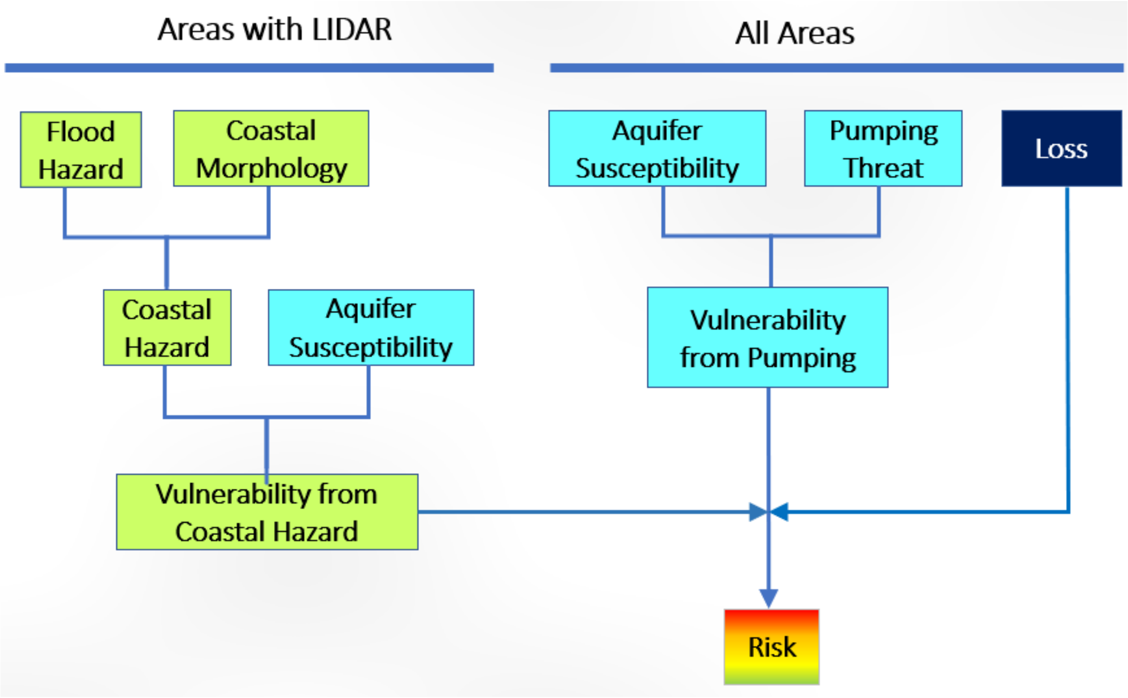

Figure 3. Summary of the approach used in this study (modified from Klassen and Allen (2016)).

The GIS approach was developed in Python 3.7 and QGIS 3.14 with calls to open source modules GeoPandas and NumPy to clean and parse the data, and GDAL (Geospatial Data Abstract Library) to generate the raster mapping. Graphical models are used to facilitate the spatial analysis and raster algebra. The Python scripts and graphical models were provided to the Ministry of Environment and Climate Change Strategy (ENV) as deliverables for this phase of study are summarized in a table located in Appendix A.

A GIS approach was developed to assess Pumping Threat and Aquifer Susceptibility for unconsolidated aquifers, and to have the Loss ratings reflect a greater range of groundwater use. The approach incorporates water licensing information, and as water licensing information improves as WSA implementation progresses, licensing information will become the prime indicator of non-domestic groundwater use in future model updates. The remainder of Section 3 presents and discusses the methods to assess each component in further detail.

As with Klassen and Allen (2016)'s study, Flood Hazard, Coastal Morphology and Coastal Hazard were only determined where Light Detection and Ranging (LiDAR) data were available. In these areas, Coastal Hazard and Aquifer Susceptibility were combined to represent Aquifer Vulnerability from Coastal Hazard (see Figure 3). In areas without LiDAR, we assessed sea water intrusion risk without consideration of Coastal Hazards and estimated Aquifer Vulnerability from Pumping using Aquifer Susceptibility and Pumping Threat. The Aquifer Vulnerability from Pumping was used (together with Loss) to calculate Overall Risk.

3.2 Datasets

3.2.1 Spatial datasets

In completing the analyses herein, we incorporated a series of spatial datasets in various data formats and scale, as summarized in Table 2. The mapping layers that incorporate the LiDAR data have resolutions of 5 m reflecting the scale of the input datasets. All other mapping layers have resolutions of 150 m.

Table 2. Summary of spatial datasets used in study.

Dataset	Format	Scale	Purpose	Reference
GWELLS	Shapefile	-	Used to infer well location and aquifer type	ENV (2019)
Water Rights	Shapefile	-	Licensed volumes used for Pumping Threat module	FLNRORD (2019)
Environmental Monitoring System (EMS)	Shapefile and .CSV	-	Used to reality check model results	ENV (2020)
B.C. Coastline	Shapefile	-	Used as basis for buffers and spatial analysis	GeoBC (2020)
Digital Elevation Model / LiDAR	GeoTIFF	20 m resolution	Used to extract elevations to well points	NRCAN (2011)
LiDAR	GeoTiFF	1-5 m resolution	Used to perform Coastal Hazards analysis	GeoBC (2020); Islands Trust (2020)
Bathymetry	GeoTIFF	20 m resolution	Used as basis for assessment of Coastal Morphology	NOAA (2015)

Water use information from licensed water use was procured from the water rights database. In addition, we were provided MS Excel spreadsheets from the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) that summarized known or assumed water use information for aquaculture facilities on southern Vancouver Island. We also queried the Regional Health Authorities and received water use information for Drinking Water Supply Systems (DWSS) located along the coast. For both hatchery and DWSS wells, we cross-referenced the information to GWELLS by Well Tag Number (WTN), by location, and by well owner. Demand was apportioned evenly between wells if the hatchery or DWSS operated with more than one well and demand from individual wells was unavailable. We assumed an average water demand of 2 m^3/day per residential connection for DWSS. Other types of service connections would use more water (e.g., schools, businesses, multi-family units, etc.) and this was quantified by reported well yield. Metered or assumed quantities were assigned to each WTN based on the provided information.

3.3 Aquifer Susceptibility to Sea Water Intrusion

The term "Aquifer Susceptibility" used here has the same meaning as in Klassen and Allen (2016), that is an aquifer's natural susceptibility to intrusion of sea water, regardless of pumping. In this study, Aquifer Susceptibility considers the susceptibility of unconsolidated and bedrock aquifers because both kinds of aquifers occur along B.C.'s coast. However, susceptibility for both kinds of aquifers were assessed using slightly different approaches. The different approaches for assessing susceptibility of unconsolidated and bedrock aquifers are illustrated in Figure 4 and discussed below. In mapping aquifer susceptibility, all unconsolidated aquifers were treated the same and all bedrock aquifers were treated likewise.

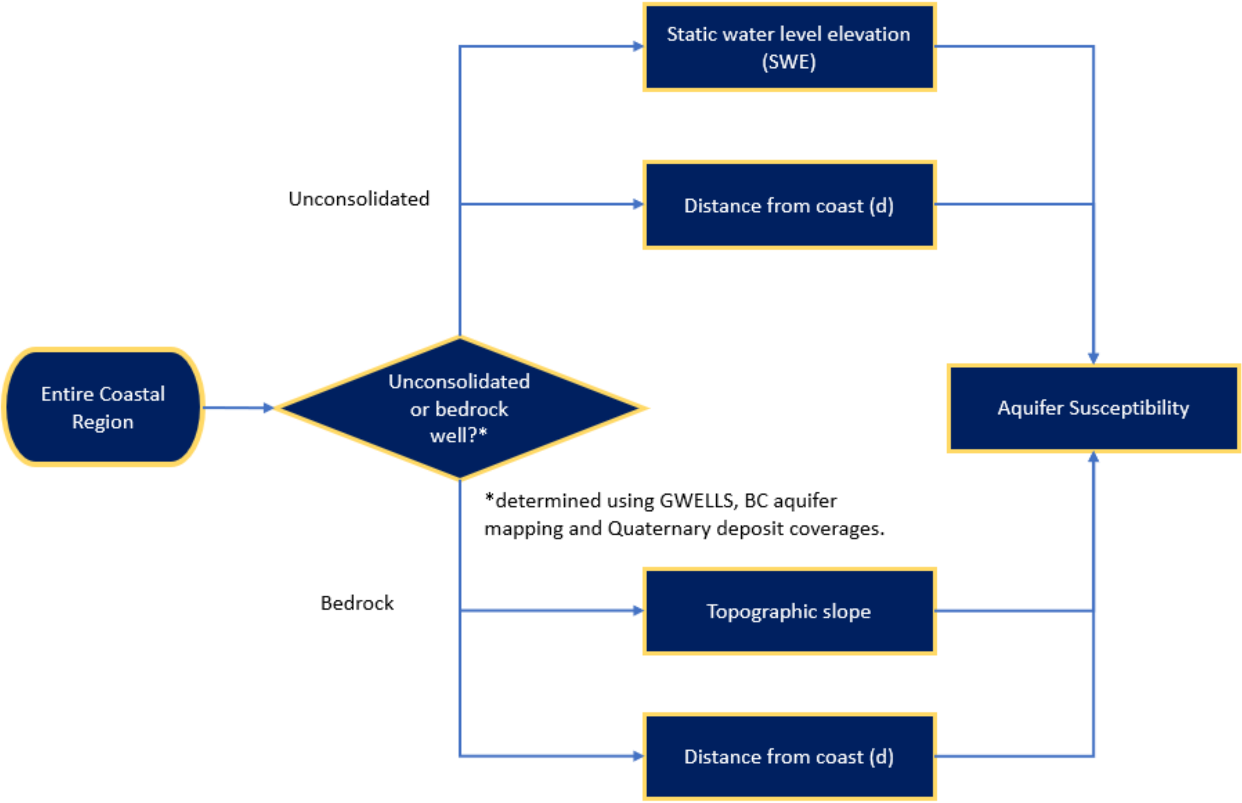

Figure 4. Diagram showing how Aquifer Susceptibility is determined for wells completed into unconsolidated versus bedrock aquifers.

The assessment approach illustrated in Figure 4 assumes:

- hydraulic connection between a coastal aquifer and the ocean exists,
- the greater the static water level elevation (for unconsolidated aquifers) and topographic slope (for bedrock aquifers), the greater the amount of groundwater discharge or flux to the ocean (less susceptible), and
- the greater distance a location is away from the coast, the less susceptible that location is to sea water intrusion.

3.3.1 Natural groundwater flux to the ocean

Natural groundwater flux to the ocean at any given location along the shoreline is dependent upon the transmissivity (T) of the aquifer and the ambient hydraulic gradient. In B.C. however, data on aquifer transmissivity and hydraulic gradient are lacking for most places. For bedrock aquifers, Klassen and Allen (2016) used topographic slope (to infer gradient) and distance from coast (intrusion progresses inland from the ocean) as practical parameters to infer groundwater flux, assuming bedrock transmissivity is uniform. Klassen and Allen's (2016) approach seems reasonable and has essentially been adopted here for bedrock aquifers (see Section 3.3.3).

One potentially important factor is that use of topographic slope and distance from coast to infer groundwater flux may not capture the size of the recharge area contributing groundwater flux to local bedrock peninsulas. Past studies in southern Vancouver Island and the Gulf Islands (e.g., Scott Point on Salt Spring Island (Tradewell, 1976), Senanus Drive in Central Saanich, and East Point on Saturna Island (Lapcevic and Kelly, 2010) suggest where the recharge or contributing watershed area is limited, groundwater flux to the local bedrock peninsula is also limited and the risk of sea water intrusion from groundwater pumping on the peninsula is of heightened concern. Results of Susceptibility mapping will be viewed with these known areas of limited recharge in mind.

Unconsolidated aquifers typically have much higher transmissivities (10 to greater than 1000 m^2/day) than bedrock aquifers, and often have lower hydraulic gradients due to being located in low-lying areas along the coast. For this reason, topographic slope was not used to infer flux for unconsolidated aquifers because given the accuracy of the digital elevation model (DEM), the measured range of slopes is likely too imprecise. Instead, we estimated susceptibility of sea water intrusion based on the static water level elevation and distance from coast (see Section 3.3.2).

3.3.2 Susceptibility ratings for unconsolidated aquifers

Susceptibility ratings for unconsolidated aquifers were based on static water elevation (SWE) and distance from coast. The SWE was calculated by subtracting the depth to static water level (SWL) reported in the well record from the local ground elevation. The lower the SWE and the closer the well is to the coast, the higher the Susceptibility Rating (Table 3). Note the distance to coast categories in Table 3 are not equal. The distance category at the coast is 1 grid cell wide and increases to 10 grid cells wide at 1.5 – 3 km distance from the coast, implying changes in Susceptibility is highest at the coast and decreases more rapidly at greater distances away from the coast. The SWE categories in Table 3 have equal elevation intervals. The intervals were selected recognizing the variation of the reported SWLs through the years and different seasons, the accuracy of the DEM, and professional judgement.

In a preliminary assessment, Susceptibility of unconsolidated aquifers was determined based on elevation of the base of the unconfined aquifer and distance from the coast. That method proved impractical for the following main reasons:

- data on bottoms of unconsolidated aquifers was much more sparse than data on reported SWLs,
- the heterogeneous nature of geologic contacts made interpolation of the bottom of unconsolidated aquifers questionable, and
- many wells drilled into unconsolidated aquifers are not drilled to the bottom of the aquifer and this often causes the depth of the bottom of the aquifer and susceptibility to be under-estimated.

By relying on reported SWEs, the Susceptibility rating was assigned only for grid cells where SWL is reported for a well. The SWE and the corresponding distance from a well to the coast within a grid cell were used in Table 3 to determine the Susceptibility rating for that grid cell. If a grid cell contained more than one well, susceptibility ratings were determined for each well based on each well's SWE and distance to coast. Then, the highest susceptibility rating was adopted for the grid cell. If a well did not have a reported SWL, a Susceptibility rating was also determined assuming a SWL at the bottom of the well. In addition, a Susceptibility rating of 5 was set at the intersection between the mapped aquifer polygon and the coastline to provide more data points for contouring of Susceptibility, especially in local data-sparse areas.

Susceptibility ratings determined for each grid cell with well data were then contoured over the areas where mapped aquifer polygons exist within 3 km from the coast, thus allowing Susceptibility to be interpolated between grid cells without wells. In areas where an unconsolidated aquifer has not been mapped by the province, Susceptibility was determined for the grid cell with well data but contouring was not done.

Table 3. Susceptibility rating scheme for unconsolidated aquifers.

		Distance from coast (m)				
		< 500	500-1000	1000-1500	1500-2000	2000-3000
SWE (m asl)	≥40	2	1	1	1	1
	40 -> 30	3	2	2	1	1
	30 -> 20	4	3	3	2	1
	20 -> 10	5	4	4	3	2
	≤ 10	5	5	5	4	3

3.3.3 *Susceptibility for fractured bedrock aquifers*

For this study, we modified the rating scheme for bedrock aquifers from Klassen and Allen (2016) (Table 4). In this scheme, Susceptibility is based on a well's distance from the coast and the local topographic slope (to reflect groundwater flux). Since distance from coast for a grid cell and topographic slope can be calculated everywhere, bedrock Susceptibility was determined for all grid cells within 3000 m from the coast. The effect of distance on bedrock Susceptibility was not linear but decreased with increasing distance from the coast. The distance categories differ from Klassen and Allen (2016) to match the grid cell size used in the current study. The result of this modification is that the highest Susceptibility rating at the coast extends farther inland to 150 m, rendering the Susceptibility mapping more conservative.

Table 4. Susceptibility rating scheme for bedrock aquifers.

		Distance from coast (m)				
		<150	150-300	300-900	900-1500	1500-3000
Topographic slope	<1°	5	4	3	3	2
	1-5°	4	4	3	2	2
	5-10°	3	3	3	2	1
	10-20°	3	2	2	2	1
	>20°	2	2	1	1	1

3.4 Pumping Threat

Despite the fact that storm events and sea level rise can cause intrusion of sea water into aquifers by overtopping of the aquifer, pumping can be the most significant cause of intrusion because it can reduce groundwater flux to the ocean significantly, and because pumping is typically of longer duration than a storm event and can cause larger changes in water levels within aquifers adjacent to the ocean (Ferguson and Gleeson, 2012). Pumping (regulating groundwater use) is also one factor affecting sea water intrusion that can be directly regulated under the WSA.

In this study, we did not use well density to infer Pumping Threat as Klassen and Allen (2016) did for the Gulf Islands because of the wide range of groundwater use along B.C.'s coast. Instead, we relied on information on pumping rate to inform Pumping Threat. Total pumping within a grid area was inferred from various sources because groundwater licensing in B.C. is still in the early stages of implementation and there is currently no reporting system for groundwater use. The various sources used to infer pumping were prioritized to infer groundwater use of any given well. The order of priority (and certainty) of information to infer pumping is listed in Table 5, starting from the highest priority. In the future, as groundwater licensing in B.C. becomes established, Pumping Threat can be based more on the licensed quantity or any use measured and reported to the province as a condition of a water licence or regulation.

Table 5. List of how pumping rate is inferred from the various data sources.

Non-Domestic Groundwater Use	Domestic Groundwater Use (not currently licenseable)
Licensed quantity from the Provincial eLicensing database	Assigned 2 m^3/day if a well is identified from the "intended use" field in GWELLS as "domestic" (unspecified use in the well record was also interpreted to be domestic)
Measured quantities reported for select fish hatcheries (mainly based on effluent discharge permits)	
If the well is identified as supplying a private water utility, pumping based on authorized number of lots for private water utilities	
If a well is identified as supplying a water supply system, pumping estimated from water supply systems information supplied by regional health authorities (e.g., number of connections)	
Otherwise, pumping rate is assumed based on the well yield from the well record in GWELLS	

In addition to the pumping rate, Pumping Threat also recognizes the role that ambient groundwater flow has in resisting intrusion of sea water. Pumping Threat ratings were developed based on the following:

$$Pumping\ Threat\ rating = \left(\log\left(\frac{\Sigma Q}{T \times i \times cell\ width}\right)\right) + 4 \qquad \text{(Equation 1)}$$

where ΣQ is the sum of the total pumping rate within a grid cell, T is the aquifer transmissivity, i is the hydraulic gradient, and 4 is an empirical scaling factor that shifts the rating values to within a range of between 1 and 5. In this study, pumping quantities assigned for each well were summed within each grid cell (ΣQ). A kernel density function was applied to the grid cells, weighted towards pumping quantity to interpolate pumping quantity in grid cells where there are no wells present. Aquifer transmissivity and hydraulic gradient were assigned based on values in Table 6. The transmissivity values were selected based on typical values reported in Wei et al. (2009) for the aquifer types. The hydraulic gradients were assigned based on the average topographic gradients of the mapped aquifers.

Table 6. Aquifer types and their assigned transmissivity and hydraulic gradient values to inform Pumping Threat ratings.

Aquifer Types	Assigned Transmissivity (T)	Assigned Gradient (i)
1a, 1b, 2	2000 m^2/day	0.01
1c, 3, 4	200 m^2/day	0.03
5, 6	10 m^2/day	0.10

Values were calculated using equation 1 for specific pumping rates (i.e., 2, 10, 30, 100, 300, 1,000, 3,000, and 10,000 m^3/day) and the assigned transmissivity and hydraulic gradient values in Table 6. These calculated values helped to scale the Pumping Threat ratings for each category of aquifers shown in Table 7.

Table 7. Pumping Threat ratings for each aquifer type.

Aquifer Types	**Pumping (Q)**								
	<2 m^3/d	2-10 m^3/d	10-30 m^3/d	30-100 m^3/d	100-300 m^3/d	300-1000 m^3/d	1000-3000 m^3/d	3000-10000 m^3/d	>10000 m^3/d
Unconsolidated aquifers 1a, 1b and 2	1	1	1	2	3	3	4	4	5
Unconsolidated aquifers 1c, 3, and 4	1	1	2	3	3	4	4	5	5
Bedrock aquifers 5a and 6b	1	2	3	3	4	4	5	5	5

The Pumping Threat rating ranges from 1 to a maximum of 5. For grid cells that did not have any reported wells (pumping of <2 m^3/day), a pumping threat rating of "1" was assigned to the grid cell.

Table 7 shows the following:

- The range of pumping rates is not linear, but rather implies that impact of pumping is influenced by aquifer transmissivity, which is assumed to be log-normally distributed.
- The typically lower transmissivity of bedrock aquifers (assigned T of 10 m^2/day) means for any given pumping rate, the Pumping Threat rating is (up to 2 points) higher than for unconsolidated aquifers.

- Similarly, for any given pumping rate, the Pumping Threat rating is (up to 1 point) higher for unconsolidated type 1c, 3, and 4 aquifers (typical T of 200 m^2/day) than for the more productive types 1a, 1b, and 2 aquifers (typical T of 2000 m^2/day).

3.5 Flood Hazard

In a preliminary assessment, LiDAR, and tidal stations with calculated Higher High Water Large Tide (HHWLT) and storm surge were only available for Salt Spring Island and Metro Vancouver. Therefore, Flood Hazards, Coastal Morphology and Coastal Hazards were only determined in these areas. Subsequently, we acquired additional LiDAR for Campbell River and Cowichan Bay.

Designated Flood Level (DFL) is the allowance for future sea level rise, storm surges and extreme tides (Klassen, 2015, Klassen & Allen, 2016). Klassen (2015), Klassen and Allen (2016), CRD (2013), and FLNRORD (2011) describe the methods for determining DFL. Tidal data was used from a tidal station near Campbell River to determine HHWLT and Storm Surge. For all areas we used estimated Sea Level Rise (SLR) from GSC (2014). We applied the methods described in Klassen (2015), which used DFL to represent Flood Hazard, where:

$$DFL = HHWLT + Sea\ Level\ Rise\ (SLR) + Storm\ Surge \qquad \text{(Equation 2)}$$

The parameters used to calculate DFL are described in the following subsections.

3.5.1 Highest High Water Large Tide (HHWLT) and Storm Surge

HHWLT is the average of the annual maximum HHWLT (extreme tides) from 19 years of predicted tidal data, and represents the average annual high tide level. Given how there were only small areas with available LiDAR data for the current study, we used literature values of HHWLT for the southeast Vancouver Island region from Klassen and Allen (2016), for Vancouver Coastal Region from Tinis (2017), and calculated values for Campbell River as part of this study. HHWLT was calculated using 19 years of recent tidal data for the southern Gulf Islands by Klassen and Allen (2016) and the Vancouver region by Tinis (2017), respectively, which are similar and therefore reasonable for our purpose.

Storm surge was assessed by Klassen and Allen (2016) and Tinis (2017) using an analysis of residuals from predicted and observed tidal data. Storm surge was determined using similar methodology for the Campbell River area. Values for storm surge used in the model are shown in Table 8.

Table 8. Summary of parameters for Flood Hazard ratings.

Parameter	Southern Gulf Islands (Victoria and Fulford harbour)	Vancouver (Point Atkinson)	Campbell River
Highest High Water Large Tide (HHWLT)	1.57 (1)	2.0 (2)	1.63
Sea Level Rise (SLR)	Mean: 0.87 m (1) Maximum: 1.17 m (1)	Median: 0.62 m (3) Maximum: 0.94 m (3)	Median: 0.28 (3) Maximum: 0.60 (3)
Storm Surge	95th percentile: 0.49 m (1) Maximum: 0.92 m (1)	90th percentile: 0.45 (2) Maximum: 1.03 (2)	95th percentile: 0.52 Maximum: 0.87
Regional Adjustment	-0.119 m (1)	-	-

(1) from Klassen and Allen (2016)
(2) values for Point Atkinson in Vancouver Harbour from Tinis (2017)
(3) from GSC (2014), pg 12 and other places

3.5.2 *Sea Level Rise (SLR)*

We used the projected SLR for the southern Gulf Islands as provided in Klassen and Allen (2016). Projections for sea level rise (SLR) were not readily available for the Vancouver area, and therefore were assessed using relative sea level projections for coastal B.C. from the Geological Survey of Canada (GSC, 2014). The work summarized in GSC (2014) provides relative sea level projections for points along the B.C. coast based on contributions from thermal expansion of the ocean, isostatic adjustment, and anthropogenic projections for the high-emissions global warming scenario (see page 66 in GSC 2014).

We combined HHWLT, SLR and storm surge (see Table 8) to determine the DFL as summarized in Table 9. The variance in SLR shown in Table 8 is likely attributed to local effects from tidal gauges, different data sources, and usage of median vs. mean. No regional adjustment was applied to the parameters for Vancouver or Campbell River. The Flood Hazard ratings are presented in Section 3.5.3, and results are discussed in Section 4.3.

3.5.3 *Flood Hazard Ratings*

Using the information described in the sections above, we estimated DFL for the southern Gulf Island and Vancouver areas, which is presented in Table 9. HHWLT is not explicitly included in the table, but it is used in the determination.

Table 9. Flood Hazard Ratings based on Designated Flood Level (DFL) for the southern Gulf Islands and Vancouver areas.

Rating	Sea Level Rise (SLR)	Storm Surge	Designated Flood Level (DFL) for Southern Gulf Islands (m)	Designated Flood Level (DFL) for Vancouver (m)	Designated Flood Level (DFL) for Campbell River (m)
5	Mean or Median	> 90th percentile	< 2.8 m	<3.1 m	<2.4 m
4	Max	> 90th percentile	2.8 – 3.1 m	3.1 – 3.4 m	2.4 – 2.7 m
3	Mean or Median	Max	3.1 – 3.2 m	3.4 – 3.7 m	2.7 – 2.8 m
2	Max	Max	3.2 – 3.5 m	3.7 – 4.0 m	2.8 – 3.4 m
1	Max	Max	>3.5 m	> 4.0 m	> 3.4 m

3.6 Coastal Morphology

Coastal Morphology is intended to include wave effect and free board hazards, influenced by the topography of the sea floor close to the coast. The parameters include: depth to ocean, and distance from coast in combination with the Designated Flood Level (DFL) or Flood Construction Level (FCL). Coastal Morphology considers near-shore bathymetry and distance from coast. Coastal Morphology is estimated using FCL, where:

$$FCL = DFL + Wave\ Effect\ and\ Freeboard \qquad \text{(Equation 3)}$$

FCL represents a more extreme DFL condition that accounts for wave effect and freeboard. Site-specific coastal engineering studies are required to assess local wave effects. A 0.6 m freeboard value was considered as an acceptable nominal value in other studies (Klassen and Allen, 2016; CRD, 2013; FLNRORD, 2011).

We employed the same methodology as Klassen and Allen (2016) to determine the influence of Coastal Morphology on sea water intrusion. Ratings of 1 to 5 were assigned based on combinations of water depth (<30 m), distance from coast (> or < 200 m), and coastal topography (DFL or FCL). For areas next to deep and steep zones, the effects of Coastal Morphology are less likely to induce inundation so they are given ratings of 4 and 3. For areas next to shallow and gentle zones, the likelihood of inundation due to Coastal Morphology is greater so they are given higher ratings of 5 and 4. The rating table is summarized in Table 10 from Klassen and Allen (2016). DFL is assigned a higher rating than FCL because it is more likely to occur. The Coastal Morphology results are discussed in further detail in Section 4.4.

Table 10. Summary of hazard ratings for Coastal Morphology.

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

3.7 Coastal Hazard

Coastal Hazard is the combination of Flood Hazard and Coastal Morphology, and was only estimated in areas with high resolution LiDAR data. The Coastal Hazard results are discussed in further detail in Section 4.5.

3.8 Aquifer Vulnerability to Pumping Threat

Aquifer Vulnerability to pumping is the geometric mean of the product of Pumping Threat and Aquifer Susceptibility:

$$Aquifer\ Vulnerability\ to\ Pumping = \sqrt{Pumping\ Threat\ \times Aquifer\ Susceptibility}$$

(Equation 4)

Aquifer Vulnerability to Pumping Threat was calculated for unconsolidated and bedrock aquifers as described above in Sections 3.3.2 and 3.3.3, respectively. The geometric mean was used to retain the rating scheme to be between 1 and 5. The rating scheme for Aquifer Vulnerability to Pumping Threat is summarized in Table 11.

Table 11. Rating scheme for Aquifer Vulnerability to Pumping Threat.

		Pumping Threat				
		1	**2**	**3**	**4**	**5**
Susceptibility	**1**	**1**	**1**	**2**	**2**	**2**
	2	**1**	**2**	**2**	**3**	**3**
	3	**2**	**2**	**3**	**3**	**4**
	4	**2**	**3**	**3**	**4**	**4**
	5	**2**	**3**	**4**	**4**	**5**

3.9 Aquifer Vulnerability to Coastal Hazards

In areas with LIDAR, Aquifer Vulnerability to Coastal Hazards was estimated as shown below in (Equation 5). The study used DEMs extracted from the LiDAR data to represent topography, at 1 to 5 m resolution in 2017 and 2018 (GeoBC, 2020; Islands Trust, 2020). For each grid cell, Aquifer Vulnerability to Coastal Hazards was estimated to be the geomean of Coastal Hazard and Aquifer Susceptibility of the unconsolidated and bedrock aquifer. The geomean retains the rating scheme to be between 1 and 5.

$$Aquifer\ Vulnerability\ to\ Coastal\ Hazards = \sqrt{Coastal\ Hazard\ \times Aquifer\ Susceptibility}$$

(Equation 5)

3.10 Total Vulnerability

Total Vulnerability is the combined vulnerability of the aquifer to sea water intrusion from well pumping and from coastal hazard (flooding, wave runup and inundation). Aquifer Vulnerability to Coastal Hazards is added to the Aquifer Vulnerability to Pumping Threat to create the Total Vulnerability maps (Equation 6). Total Vulnerability is divided by 2 and rounded to the nearest integer to retain the rating scheme to be between 1 and 5.

$$Total\ Vulnerability = \left.\begin{pmatrix} Aquifer\ Vulnerability\ to\ Pumping\ Threat\ + \\ Aquifer\ Vulnerability\ to\ Coastal\ Hazards \end{pmatrix}\middle/ 2\right.$$

(Equation 6)

3.11 Loss

Unlike Klassen and Allen (2016), in this study Loss was not quantified in absolute dollar values because the much more varied types of groundwater use (i.e. municipal, industrial, agricultural) along B.C.'s coast makes that exercise extremely complicated. Rather, Loss was evaluated more simply and directly to water use.

3.11.1 Loss of the well supply

In this study, Loss was related to quantity of water pumped and general water quality requirements related to water use purpose. A larger pumping quantity implies a larger enterprise that would suffer a greater economic Loss should sea water intrusion occur. A larger pumping quantity also implies a replacement source of supply is more difficult to develop. Water quality requirements can also affect Loss. For example, water quality for mineralized water is unique; mineralized water, if lost, can not be replaced by other water sources. Water for drinking water and food production, for example, generally requires higher quality than water for resource extraction or dewatering, so may impose more limitations on the type of source and expense of water treatment.

Table 12 presents the pumping quantity and water use purposes and the associated Loss ratings. The larger the pumping quantity, the greater the Loss rating. The quantity categories are similar to those for Pumping Threat.

For a given pumping quantity, however, some water use purposes are given higher ratings than others because of general water quality requirements (Table 12). Differentiating water use purposes in the Loss ratings general water quality requirements for different water use purposes to be considered. For any given range of quantity, we gave highest priority to: 1) uses that have unique water quality requirements or for protecting the aquatic environment, 2) uses that require higher water quality like for drinking water, many industrial operations and irrigation, and 3) all remaining uses with generally less stringent water quality requirements:

A. Mineralized or conservation use purposes: Only the elicensing database can provide this information with any degree of reliability. Since groundwater licensing is still in its infancy, a search of eLicensing yielded no groundwater use for these purposes.

B. Drinking water, irrigation, many industrial use purposes: Drinking water uses include domestic purpose, waterworks purpose, irrigation purposes and industrial purpose except items 13 (miscellaneous industrial), 19 (vehicle and equipment), 20 (waste management), and 21 (well drilling and transportation or corridor management) in Schedule A of the Water Sustainability Regulation. Water use purposes in this category are expected to be present in most grid cells where groundwater pumping occurs because these uses are by far the most common.

C. Other water use purposes: Water for land improvement, mining and oil and gas purposes, as well as the industrial uses excluded from the above category fall into this lowest category for general water quality requirements.

Table 12. Loss rating scheme (numbered items for "Industrial" refer to specific industrial water use purposes listed in Schedule A of the Water Sustainability Regulation).

Water use purpose*	Category	Loss rating by total pumping and water use purpose category within grid				
		<30 m^3/day	30-100 m^3/day	100-300 m^3/day	300-1000 m^3/day	>1000 m^3/day
Domestic	B	2	3	4	5	5
Waterworks	B	2	3	4	5	5
Industrial (all items except items 13, 18-21)	B	2	3	4	5	5
Irrigation	B	2	3	4	5	5
Mineralized water	A	3	4	5	5	5
Mining	C	1	2	3	4	5
Industrial (items 13, 18-21 only)	C	1	2	3	4	5
Oil and gas	C	1	2	3	4	5
Conservation	A	3	4	5	5	5
Land improvement	C	1	2	3	4	5

Power and storage use purposes were not included in the assessment of Loss. Power generation is only applicable to surface water. Storage should not involve a net Loss of water.

The same rating scheme in Table 12 was used to rate Loss of well supply for both unconsolidated and bedrock aquifers. However, Loss was calculated separately for unconsolidated and bedrock aquifers within the study area to recognize the two broad sources of groundwater supply.

The approach for determining Loss uses GWELLS, water licences, and Drinking Water Supply Systems (DWSS) and hatchery information compiled as part of this study. In assigning Loss related to a well supply, the total pumping within a grid cell is summed separately for the unconsolidated and the bedrock aquifer. The total pumping quantity and water use purpose category determine which column in Table 12 applies. Next, the highest water use purpose associated with a well within the grid cell determines the Loss rating. For example, if there are 2 wells within a grid cell and one well is pumping 250 m^3/day for dewatering a construction site (category C above) and the other well is a domestic well (2 m^3/day – category B above), the total pumping from the cell is 252 m^3/day. Since groundwater within the grid cell is used for domestic (albeit one well), the Loss rating from Table 12 would be “4”. Water use purpose, even if its proportion to total pumping is smaller could increase the Loss rating for a grid cell. If there are no wells in a grid cell, Loss is null.

3.11.2 Assigning Loss to an area

For many smaller groundwater uses or groundwater use for private farms, the area that the Loss is attributed to is assumed to be the grid cell where the well is located. This approach of attributing Loss works because in many instances where the well is located on the property is where the water is used (the appurtenant property). However, the assumption becomes less valid for larger water supply systems or irrigation districts where water diverted from a well or well field is purveyed to other areas beyond the immediate grid cell. There are no irrigation districts within the study area but there are a number of improvement districts, waterworks districts (Civic Info, 2021-accessed February 10, 2021) and municipalities supplied by groundwater within the study area. Given the large number of improvement and waterworks districts within the study area, it was beyond the scope of this study to identify the appurtenant property for these water supply systems.

For the purposes of this study, we maintained the assumption of attributing Loss to the grid cell where the well is located, except if the well is associated with a municipality (via eLicensing information, name of the well in the well record). For wells that are associated with a municipality, the Loss is still attributed to the grid cell but is also noted to supply water to land within the municipality. As groundwater licensing progresses, Loss can be re-attributed to the appurtenant property or properties described in eLicensing.

In this preliminary assessment of Loss, we attributed Loss to within the grid cell as described above. Upscaling of Loss may be possible but was not within the scope of the current study.

3.12 Overall Sea Water Intrusion Risk

Overall Sea Water Intrusion Risk is calculated using Aquifer Vulnerability to Pumping Threat and Loss, as shown in Equation 7 below. In this preliminary assessment of Overall Sea Water Intrusion Risk, Risk is attributed to the grid cell and by area (See Section 3.11 above). Similar to Aquifer Vulnerability to Pumping and Coastal Hazards (see Sections 3.8 and 3.9), the geomean was calculated to retain the rating scheme to be between 1 and 5.

$$Risk = \sqrt{Aquifer\ Vulnerability\ to\ Pumping\ Threat\ \times Loss} \qquad \text{(Equation 7)}$$

3.13 Data & Analysis Limitations, and Sources of Uncertainty

The mapping coverages are limited to areas within 3 km of the coastline where data are available, as discussed in Sections 3.2 through 3.7 for Aquifer Susceptibility, Pumping Threat and Coastal Hazards, and Section 3.11 for Loss, respectively.

The GWELLS Application formed our main hydrogeological data source. The main assumptions (and limitations) in using GWELLS are:

- The well database contains records that are incomplete and/or contain missing or erroneous data, including incomplete lithology, missing static water level (SWL) and inexact well locations; and further, are subject to error on the part of the well driller or error on database entry.

- The inventory of wells is not complete because well record submission was voluntary until 2016 (and even after 2016, compliance with well record submission is not 100%); and,
- GWELLS does not reflect present status of well use; for example, a well may be used intermittently, or use may have occurred over a certain period of time and discontinued. We assume that well use is enduring through time.

A large amount of geospatial data previously compiled by others formed the basis of this desktop study. It was not part of the scope of work to conduct any validation or quality control checks on the spatial datasets provided; unless otherwise stated, the spatial datasets were taken at face value for analysis and interpretation. Combining geospatial datasets generated at different scales can also produce errors in positional accuracy and precision.

A limitation of the GIS method is that groundwater flow between cells cannot be modelled, and as such it is not a physical model of the groundwater flow system. For example, the GIS model may indicate a grid cell as having high vulnerability from pumping but not identify grid cells directly down-gradient to the coast as having the same vulnerability. However, intrusion of sea water from the pumping would impact those down-gradient grid cells.

Another limitation of the raster-based approach is that in some areas there is a gap between the grid cells and the coastline due to the variable extents of the spatial datasets used in the study, and/or edge effect from the raster manipulation. The gap was reduced by extending the Pumping Threat mapping by one grid cell to overlap with the coastline. However, the polyline representing the coastline may not overlap with the DEM, resulting in small segments of coastal area where no mapping is shown. Intrusion from sea water may still impact those areas where gaps are shown in the mapping.

GIS-based maps of information derived from water well records, such as groundwater elevations and sediment thicknesses, can create an illusion of high degree of accuracy. The information on the maps is better constrained in areas of higher well density, and more uncertain in areas of lower well density.

4. RESULTS

Due to the large study area, it is not feasible to display the GIS modelling results for the entire B.C. coast within the report. Instead, results are shown in two primary areas: the southern Gulf Islands and corresponding southeast Coast of Vancouver Island, and Vancouver and the Fraser River Delta and surrounding areas (unconsolidated aquifers only). Results are displayed in the following maps in Appendix B:

- Figure B1 – Susceptibility of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B2 – Susceptibility of unconsolidated aquifers in the Vancouver area.
- Figure B3 – Susceptibility of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B4 – Pumping Threat of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B5 – Pumping Threat of unconsolidated aquifers in the Vancouver region.
- Figure B6 – Pumping Threat of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B7 – Flood Hazard, Coastal Morphology and Coastal Hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B8 – Flood Hazard, Coastal Morphology and Coastal Hazards in the Vancouver area

- Figure B9 – Vulnerability of unconsolidated aquifers to pumping along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B10 – Vulnerability of unconsolidated aquifers to pumping in the Vancouver area.
- Figure B11 – Vulnerability of bedrock aquifers to pumping along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B12 – Vulnerability of unconsolidated aquifers from coastal hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B13 – Vulnerability of unconsolidated aquifers from coastal hazards in the Vancouver area.
- Figure B14 – Vulnerability of bedrock aquifers from coastal hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B15 – Total Vulnerability of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B16 – Total Vulnerability of unconsolidated aquifers in the Vancouver area.
- Figure B17 – Total Vulnerability of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.

Preliminary results for Loss and Overall Risk are shown in the following maps in Appendix C.

- Figure C1 – Loss in unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C2– Loss in unconsolidated aquifers in the Vancouver area.
- Figure C3 – Loss in bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C4 – Overall risk from sea water intrusion in unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C5 – Overall risk from sea water intrusion in unconsolidated aquifers in the Vancouver area.
- Figure C6 – Overall risk from sea water intrusion for bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.

These figures provide a basis for presenting and discussing the GIS modelling results within two main areas of groundwater use. Observations from these two areas help us understand modelling results in other parts of the study area, including the more remote areas. Bedrock results are not shown for the Vancouver area because that area is mostly underlain by relatively thick unconsolidated sediments. The data layers can be queried to produce maps for any area of interest within the study area.

4.1 Aquifer Susceptibility

4.1.1 Susceptibility of Unconsolidated Aquifers

Figures B1 and B2 depict Susceptibility of unconsolidated aquifers. As noted above, the Susceptibility of unconsolidated aquifers is based on existing well information. To estimate Susceptibility in areas with no wells, the Susceptibility was interpolated between grid cells, but only within the mapped aquifer polygons. For reported unconsolidated wells located outside the mapped aquifer polygons, Susceptibility was determined only in the grid cells where wells are reported and no interpolation was applied.

Figures B1 and B2 show that Susceptibility for unconsolidated aquifers is highest at the mouth of streams where the distance to sea is shortest and groundwater elevation is lowest (e.g., Cowichan River estuary, Chemainus River-Bonsall Creek estuary, Nanaimo River estuary, Capilano and Seymour Rivers, and Furry Creek). These most susceptible areas are underlain by fluvial, alluvial and deltaic sand and gravel aquifers.

Along the coast of the Georgia Depression where confined Quadra Sands aquifers occur, the groundwater levels tend to rise rapidly from the coast (as a result of isostatic adjustments) so the most susceptible areas occur only along the coast and do not extend as far inland as for the fluvial, alluvial and deltaic aquifers. The areas along Cobble Hill between Mill Bay and Duncan, between Chemainus and Ladysmith, and at White Rock are examples of such areas (Figure B1). The most susceptible areas occupied by the Quadra Sands at UBC extend farther inland but that is because of the general lack of well data in the area to constrain the contours (Figure B2).

Figure B2 also shows that much of Lulu Island, Richmond, and Delta are susceptible. The extensive susceptible area is partly because it is the Fraser River delta and also because the sea water wedge along the Fraser River distributaries extends from the mouth to as far as upstream as Annacis Island (Leung et al., 2018; Thompson, 1981) and the coastline was modified to include the Fraser River to the Port Mann Bridge. This, in effect, extends the susceptible coastline up the Fraser River.

The glacio-marine aquifer underlying the Nicomekl-Serpentine River floodplain was deposited during glaciation and at a sufficient depth in the ocean such that the aquifer is still below present-day sea level and is susceptible to sea water intrusion (Figure B2).

Unconsolidated Aquifer Susceptibility on the southern Gulf Islands is not an issue except for Salt Spring Island where mapped unconsolidated aquifers exist (Figure B1). Figure B1 shows that there are many areas with wells drilled into unconsolidated aquifers but Susceptibility can not be extrapolated beyond the grid cells in the absence of aquifer mapping. Development of aquifer mapping in the future would allow for extrapolation of results.

Finally, Aquifer Susceptibility is a characteristic intrinsic to the aquifer, but characterizing Susceptibility is limited to areas with well data. In areas where data are lacking, the Susceptibility of unconsolidated aquifers can be inferred by examining Susceptibility ratings in areas of similar hydrogeology where Susceptibility has been characterized. For example, there are many alluvial fans that occupy the mouths of smaller coastal creeks where Susceptibility has not been mapped because no wells exist. However, the Susceptibility rating for these small, coastal fans is expected to be similar to ratings for the fans at Porteau Creek and Furry Creek, for example, where well data exist.

4.1.2 Susceptibility of Bedrock Aquifers

Along the coast where the bedrock topography is steep, high Susceptibility only occurs along the shoreline (Figure B3). Bedrock Susceptibility is typically high on rocky, low-lying islets and peninsulas.

In areas of appreciable unconsolidated sediment thickness, like the Cowichan River estuary, bedrock is buried and bedrock Susceptibility is not based on the bedrock topography but rather the topography of the unconsolidated sediments. In estuaries at the mouth of rivers like the Cowichan, Chemainus or Nanaimo (Figure B3) where the topography is flat, the bedrock Susceptibility has been mapped as high.

As mentioned in 3.3.1, although the method used here does not explicitly consider the size of recharge areas draining to local bedrock peninsulas as a contributing factor in Susceptibility, mapping did identify local bedrock peninsulas as having high bedrock Susceptibility. For example, Scott Point on Salt Spring Island, East Point on Saturna Island, and Belcarra in Indian Arm where sea water intrusion concerns have been documented all have been mapped as having high Susceptibility. It appears that distance to coast and bedrock topographic slope adequately reflect bedrock Susceptibility in these localized areas of limited bedrock relief with a small contributing drainage area.

4.2 Pumping Threat

4.2.1 *Pumping Threat in Unconsolidated Aquifers*

Figures B4 and B5 show the Pumping Threat ratings for unconsolidated aquifers along the southern east coast of Vancouver Island, on the southern Gulf Islands and in the Vancouver area. The highest Pumping Threat ratings appear to be associated with aquifer 197 (type 4b), compared to the aquifers located at the mouth of the Cowichan River (type 1b). This is because there are more wells reportedly located within aquifer 197, and the aquifer subtypes were used to scale the Pumping Threat ratings based on the intrinsic properties of the aquifers (see Section 0). Aquifers at the mouth of the Chemainus River and Bonsall Creek near Crofton and along the Nanaimo River (types 1c) also have lower Pumping Threat because of their expected relatively higher productivity of those types of aquifers.

High Pumping Threat wells are located in White Rock in aquifer 57 (type 4b), but otherwise are not found in the Vancouver area, likely because high capacity pumping wells have not been recorded (even though major dewatering projects are known to exist). Information on pumping would be needed to assess the pumping threat associated with dewatering projects.

4.2.2 *Pumping Threat in Bedrock Aquifers*

Figure B6 shows the Pumping Threat ratings for bedrock aquifers along the southern east coast of Vancouver Island and on the southern Gulf Islands. The highest Pumping Threat ratings are associated with very high well density (e.g., Gulf Islands) or higher volume pumping related to drinking water supply system use (e.g., Mill Bay area, Mayne Island). Most cell grids rated less than 2 or 3 reflect bedrock pumping where residents rely on groundwater for domestic use and where unconsolidated aquifers are not present.

4.2.3 *Assessing the Reasonableness of Pumping Threat Results*

The reasonableness of Pumping Threat results was checked against the responses of Provincial Groundwater Observation Well Network (PGOWN) wells within the study area. There are currently 89 active and inactive observation wells with groundwater level monitoring data within the study area; 42 are completed in unconsolidated aquifers and 47 completed in bedrock. Most of these observation wells (86) are located on Vancouver Island, Gulf Islands and other islands in the Strait of Georgia. We reviewed groundwater level hydrographs for all 89 observation wells to identify:

1. Which observation wells show (or have shown) a decline in groundwater level over the years, and
2. Which observation wells show evidence of being significantly affected by nearby pumping.

Observation wells showing groundwater level declines: Determining groundwater level decline is somewhat subjective. However, the following main criteria were used here to identify groundwater level decline in the observation well hydrographs:

- Observation wells that Environmental Reporting BC shows either a moderate or large rate of decline over the long term (>10 years – see, for example, Observation Well No. 345 Cobble Hill (Arbutus Ridge).
- Observation wells monitoring fractured bedrock aquifers where groundwater level decline is only reflected in the late summer-early fall period (because of the low storativity of fractured bedrock, groundwater levels typically recover fully with winter precipitation). Since

Environmental Reporting BC measures trends from year-to-year, declines that occur only during the late summer-early fall season may not always be recognized (see, for example, Observation Well No. 283 Pender Island).

- Observation wells where the groundwater level may have declined years ago and stabilized. The recent stabilized groundwater level may prevent a declining trend from years ago to be recognized by Environmental Reporting BC (see, for example, Observation Well No. 303 Qualicum Beach). A declining trend in groundwater level from years ago was counted as a decline because the Pumping Threat map lumps pumping cumulatively over the decades.
- Observation wells where trends are evident but not reported in Environmental Reporting BC because the data comprised manual month-end data, the well is no longer active, there are gaps in the record, or there is not sufficiently long-term data set (see, for example, Observation Well No. 323 Hornby Island and Observation Well No. 319 Saturna Island.

Figure 5 shows the percentage of PGOWN wells with groundwater level decline over time, for each Pumping Threat rating. While the total number of wells for Pumping Threat low or very high ratings (1, 2, and 5) are very few (5 wells or fewer), Figure 5 implies the percentage of PGOWN wells in bedrock showing a decline appears highest for very high Pumping Threat (rating 5) and decreases with decreasing Pumping Threat rating, as might be expected. The pattern for unconsolidated aquifers appears similar, except no observation wells in grid cells with very high Pumping Threat (rating of 5) show a decline. This may be due to the fact that three of these have 5 years of data or less and one (Observation Well No. 350) was established prior to the start of heavy pumping and is now decommissioned.

It should be noted that the number and distribution of PGOWN wells is limited, and monitoring trends may not be indicative of conditions over the whole aquifer. In the future, increasing monitoring in coastal areas at high or very high risk of intrusion should be considered. This could be accomplished by expanding the PGOWN network or collecting data from private wells through terms and conditions placed on water licenses or volunteer networks.

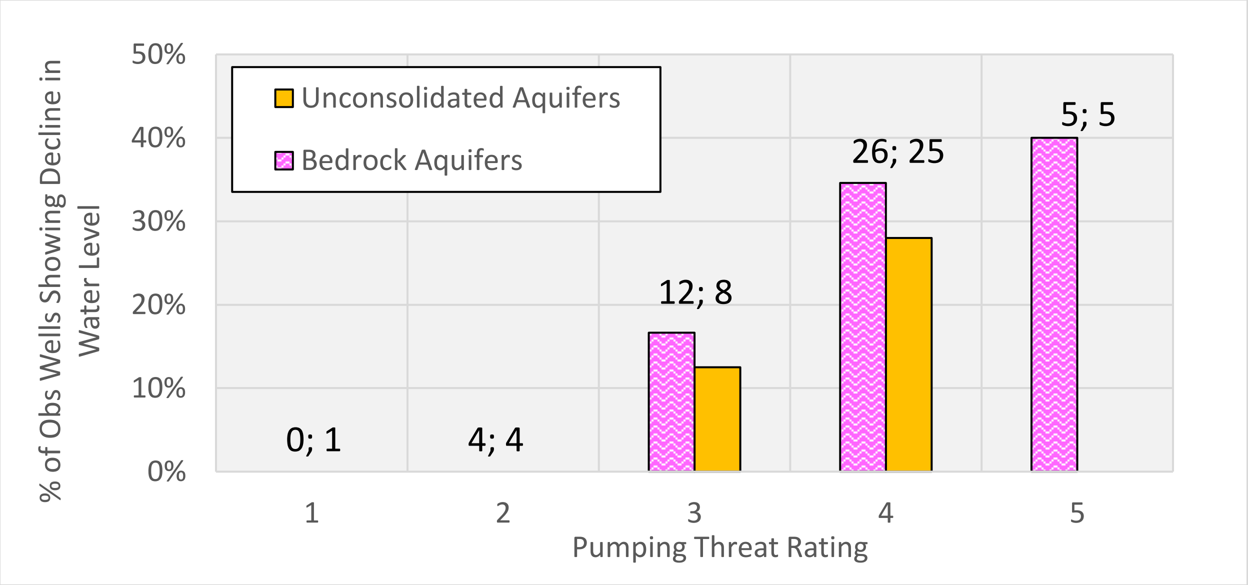

Figure 5. Bar graphs showing the percentage of PGOWN wells showing a declining trend. The total number of observation wells in bedrock and unconsolidated aquifers, respectively, are labelled for each Pumping Threat rating category.

Observation wells that are significantly affected by nearby pumping: We also assessed whether there is any relationship between the observation wells that are significantly affected by nearby pumping and Pumping Threat rating. "Significantly affected by pumping" is subjective, but is taken here to mean where pumping appears to have significantly altered the natural (expected) hydrograph to the extent that drawdown and recovery spikes are evident in the data. Specific evidence for this includes:

- hydrographs where there is marked recovery at the end of the summer pumping season (see, for example, Observation Well No. 295 Qualicum Beach,
- for unconsolidated aquifers, hydrographs that show the groundwater level recovering before the expected recharge season, indicating recovery from pumping (recharge to unconsolidated aquifers typically occurs weeks to months after the arrival of the rainy season – see, for example, Observation Well No. 232 Lantzville, and
- hydrographs that show constant pumping interference year-round (see, for example, Observation Well No. 392 Nanoose).

Minor interference that does not change the expected natural hydrograph are not considered "significant". Figure 6 shows the percentage of observation wells in each Pumping Threat rating category that are significantly affected by pumping nearby. Unfortunately, no pattern is evident, except that in all Pumping Threat categories, the percentage of observation wells affected by nearby pumping appears to be significant. This may be because of the biased distribution of the Observation Well Network, which has historically established wells in areas of nearby pumping. For example, some of the older observation wells were inherited from test-drilling programs and are located in specific wellfields.

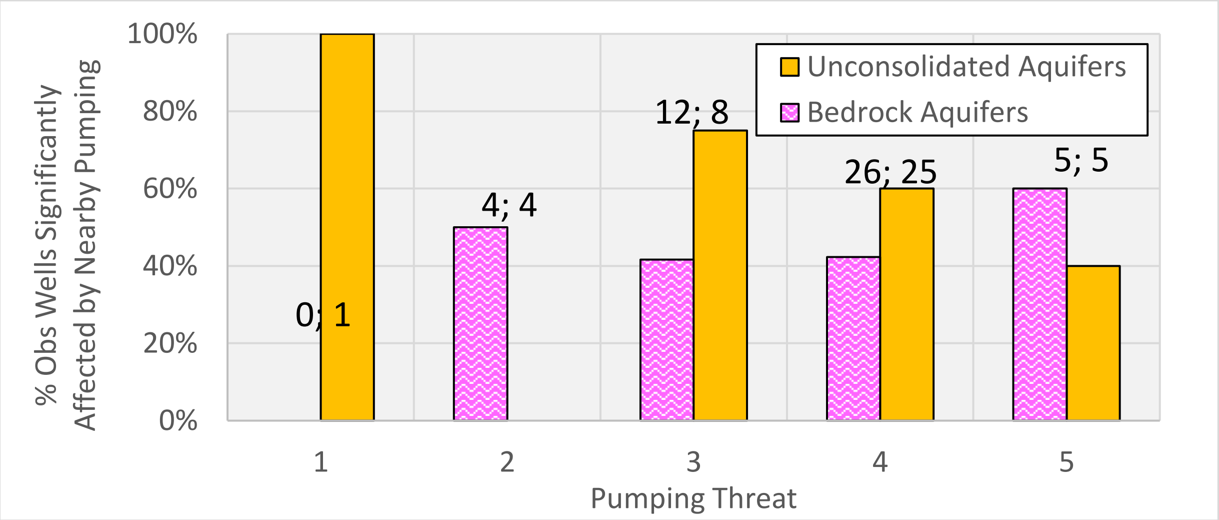

Figure 6. Bar graphs showing the percentage of PGOWN wells deemed significantly affected by nearby pumping. The total number of observation wells in bedrock and unconsolidated aquifers, respectively, are labelled for each Pumping Threat rating category.

In checking the reasonableness of Pumping Threat against observation well data, the following limitations are recognized:

Low number of observation wells in some Pumping Threat rating categories: The number of PGOWN wells, especially for Pumping Threat ratings of low and very high (1, 2 and 5) are few. Therefore, the percentages are not taken as statistically representative for those Pumping Threat rating categories.

Biased distribution of wells: The high percentage of PGOWN wells significantly affected by nearby pumping for all Pumping Threat rating categories may also reflect the biased distribution of the PGOWN in areas of groundwater development concerns.

Grid cell size and rating scale: The grid cell size of 150 m by 150 m may not be large enough to represent pumping within a given area for confined, unconsolidated and bedrock aquifers (typically low storativity). Heavy pumping beyond the grid cell within which an observation well is located will not be reflected in the Pumping Threat rating beyond that grid cell.

Pumping volume is only inferred: Inferred pumping within grid cells may not reflect actual pumping over the years. Records in GWELLS do not document all pumping wells, particularly in the Parksville-Qualicum area where submission of well records from local drillers has historically been far from complete. As previously noted, pumping rates for many non-domestic wells are largely inferred from the well record and this may not reflect actual pumping, which may be less than the driller's estimated yield. Reporting of actual pumping over time of licensed uses should improve in the future as pumping information is derived more from direct information of licensed use. As well, enforcement of unauthorized pumping would eliminate Pumping Threat that can not be accounted for within the study.

4.3 Flood Hazard

Most of the areas on Figure B7 (southern Gulf Islands) are rated very low (1), showing that Flood Hazard in the area is generally low, with a few exceptions as follows:

- The small islets within the Shoal Island group;
- Long Harbour;
- Cowichan Bay;
- Burgoyne Bay;
- The unnamed islets near Parker Island; and,
- Tumbo Island off the north shore of Saturna Island.

The Flood Hazard results for Vancouver are shown on Figure B8. Most of the Fraser River delta is rated 5 south of the Fraser River and north of the Nicomekl River. There are a few rectangular areas which are likely built-up land and rated very low (1) (see Delta, Point Roberts, Tsawwassen Ferry Terminal and an area in Richmond on Figure B7). Most of the surrounding areas are rated very low (1).

4.4 Coastal Morphology

Most of the Coastal Morphology in the study area comprise deep water and steep slopes within 200 m of the coast, except the following which have high ratings of 4 and 5:

- Cowichan Bay (see Figure B7);
- Low-lying areas around Salt Spring Island and other southern Gulf Islands (see Figure B7);
- Richmond, White Rock and other low-lying areas on the Fraser River delta (see Figure B8)
- at the deltas of Capilano River, Lynn Creek, and Seymour River in North Vancouver; and,
- The low-lying areas around Hornby, Gabriola and Denman Islands (not shown).

Coastal Morphology in low-lying areas mentioned above contributes to significantly greater Coastal Hazards in those areas.

4.5 Coastal Hazard

The majority of the Coastal Hazards map for the southern Gulf Islands (Figure B7) is rated very low (1), excluding low lying areas discussed above in Section 4.4. This is because the coastline is typically steep and Coastal Morphology is steep and deep within 200 m of the coastline. The designated flood level (DFL) was different for the southern Gulf Islands and Vancouver, and it is unlikely that the difference between the highest ratings (2.4 m for Campbell River and 3.1 m for Vancouver) have significant impact on these results. Coastal Hazards is rated very high (5) in the Fraser River Lowlands (see Figure B8), because the area is low-lying and, relatively flat. Shallow bathymetry and low-lying areas less than about ~3 m elevation are the main attributes contributing to high Coastal Hazard.

4.6 Aquifer Vulnerability to Sea Water Intrusion

4.6.1 Vulnerability of Unconsolidated Aquifers from Pumping

The areas of highest vulnerability (ratings of 5) for unconsolidated aquifers are localized around large pumping wells very near the coastline, such as at the mouth of Rosewall and Wilfred Creeks located between Qualicum Beach and Courtenay where heavy pumping is occurring, the mouth of Kokish River at Telegraph Cove, and other areas. Within Figures B9 and B10, the Cowichan Estuary, mouth of the Capilano and Seymour Rivers, and localized areas of pumping within the Fraser River delta have ratings of 5. Localized areas on Salt Spring Island also have ratings of 4 or 5.

The areas of higher vulnerability (ratings of 4 and 5) tend to be mostly associated with fluvial, alluvial and deltaic aquifers (types 1, 2, and 3). The vulnerability of Quadra Sands (4b type) aquifers tends to be highest (ratings of up to 4) only adjacent to the coastline (e.g., at Malcom and Cormorant Island near Port McNeill).

4.6.2 Vulnerability of Bedrock Aquifers from Pumping

Results indicate that many areas with bedrock aquifers have moderate vulnerability to sea water intrusion ratings of 3 (see Figure B11). Localized areas near Active Pass, East Point on Saturna Island, and Long Harbour on Salt Spring Island have high ratings of 4.

In areas where the land is underlain by appreciable thickness of surficial sediments, the vulnerability to sea water intrusion into bedrock aquifers is also high because the topographic slope upon which bedrock susceptibility is calculated reflects the slope of the overlying unconsolidated deposits, which is typically less. Bedrock underneath these estuaries occurs at depths below sea level.

4.6.3 Vulnerability of Unconsolidated Aquifers from Coastal Hazards

Mapping shows that vulnerability is dominated by lower ratings except in low-lying areas along the coastline (see Figures B12 and B13). As previously noted, the Vulnerability to Coastal Hazards is mapped only where LiDAR is available. For other areas, refer to Section 4.6.2.

For the southern Gulf Islands and southeast Vancouver Island coastal area, the results indicate that areas of high vulnerability to Coastal Hazards are located close to the coastline in Cowichan Bay (aquifers 186 and 188), Long Harbour, and Fulford Harbour (aquifers 157 and 156).

The floodplains of the Cowichan River, Fraser River, Nicomekl have high vulnerability to Coastal Hazards extending far inland. The floodplain along the Squamish River (aquifer 399) also has high vulnerability, extending inland. The aquifers located along high order streams have high vulnerability from Coastal Hazards due to low elevation and topographic relief.

The alluvial deposits in North Vancouver (aquifers 66 and 67) and Squamish (aquifer 402) have high vulnerability to Coastal Hazards, but only in the band along the coastline, and moderate to low vulnerability moving up from the coastline due to the topography.

4.6.4 Vulnerability of Bedrock Aquifers from Coastal Hazards

Mapping results (see Figure B14) are similar to the Vulnerability of unconsolidated aquifers to Coastal Hazards (see Section 4.6.3 above). Localized areas where the Vulnerability to Coastal Hazards is high include:

- Tumbo Island near East point;
- Long Harbour on Salt Spring Island; and,
- Localized areas on Gabriola Island.

In areas where the bedrock is overlain by unconsolidated sediments (for example, see Cowichan Bay), the Vulnerability to Coastal Hazards is high. This is because the Vulnerability to Coastal Hazards is calculated using the topographic slope of the overlying sediments, and not of the bedrock.

4.6.5 Total Vulnerability of Unconsolidated Aquifers

In the southern east coast of Vancouver Island and southern Gulf Islands (Figure B15), the mapping shows that the aquifers underlying the Cowichan Bay estuary have ratings up to very high (5). The unconsolidated aquifers on Salt Spring Island (aquifers 155, 156, 157 and 1148) have moderate to high ratings of 3 or 4.

The mapping shows areas along the bank of the Fraser River having very high ratings of 5 (Figure B16). Other localized areas with very high ratings (5) include parts of Tsawwassen, White Rock, and in North Vancouver. The Total Vulnerability of mapped aquifers underlying the floodplains associated with high-order streams tend to have the highest Total Vulnerability, which is expected.

4.6.6 Total Vulnerability of Bedrock Aquifers

The Total Vulnerability of bedrock on the southern Gulf Islands is dominated by ratings of 1 or 2, except the areas along the coastline which have ratings of 3 or greater (Figure B17).

4.6.7 Assessing the Reasonableness of Aquifer Vulnerability

The reasonableness of the Vulnerability results was checked in two different and subjective ways. First, the results were compared to total dissolved solids (TDS) concentrations from historically sampled wells. Reasonableness of the Vulnerability results was also checked against where the province had knowledge of sea water intrusion concerns.

Total Dissolved Solids (TDS): TDS is a measure of the overall salinity of the groundwater. In coastal areas, groundwater with higher TDS may reflect influence of sea water in an aquifer. Available TDS results from historical samples collected from water wells within the study area and stored in the Province's Environmental Monitoring System (EMS) database were compiled and plotted against Vulnerability results for unconsolidated and bedrock aquifers to check for any patterns.

Water samples are collected by the province on a set schedule for the PGOWN wells. In addition, area-specific water quality studies have also been completed in the Cowichan River estuary (to monitor for sea water intrusion), Cobble Hill area, Chemainus Aquifer, various Gulf Islands, Mill Bay, as well as in local areas with water quality concerns. TDS values were available for 286 wells within the study area. TDS values from EMS for monitoring wells at permitted waste discharges sites were not included.

TDS results date back to 1985. Most wells have only one TDS result. For wells (typically PGOWN wells) that have been sampled multiple times, the historical TDS values were averaged for that well. There is usually not enough historical data to assess water quality trends over time. One study area (the Cowichan Estuary) where there were annual testing showed that none of the Ambient Groundwater Quality Monitoring & Assessment wells in the network at the Cowichan Estuary, including Observation

Wells No. 297 and No. 298 monitored between 1985 to 1996, showed any long-term upward trends in TDS, specific conductance, and chloride (Chwojka, 1997). For an observation well completed in bedrock, only water samples collected after 1991 were considered. Prior to 1991, the province collected water samples from observation wells using a trip bailer. For coastal PGOWN wells completed into bedrock, the TDS results from samples collected by a bailer without purging the well typically reflect the fresher water at the top of the stratified water column in the well.

Figure 7 shows the TDS statistics for the Vulnerability ratings for unconsolidated (Figure 7a) and bedrock (Figure 7b) aquifers. For both types of aquifers, the median and geomean TDS generally increase with increasing Vulnerability rating as expected. Generally lower TDS is observed in unconsolidated aquifers which may reflect the limited depth of unconsolidated aquifers, greater flux of fresh groundwater through unconsolidated aquifers and possibly greater hydraulic influence from surface water (with low TDS).

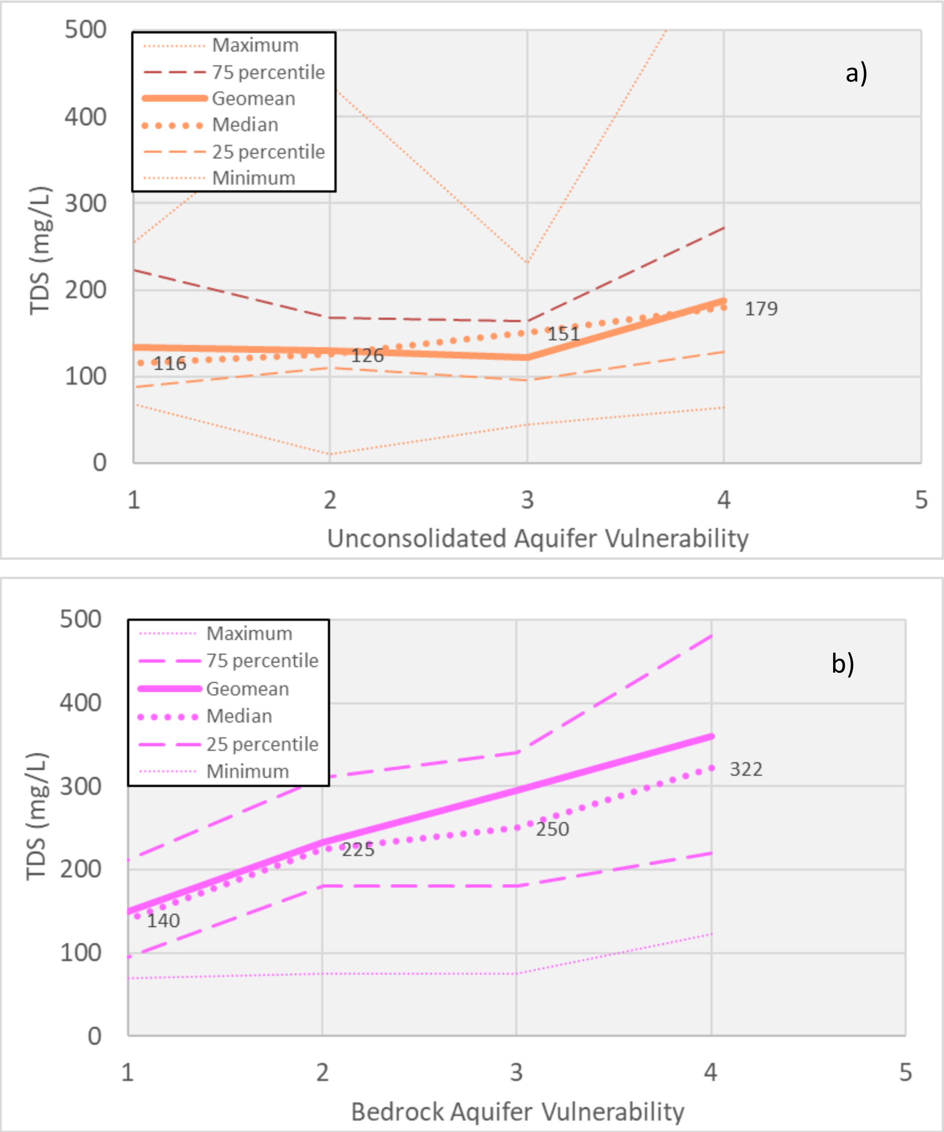

Figure 7. TDS statistics for unconsolidated (a) and bedrock (b) aquifer vulnerability ratings. Median TDS values are labelled.

As with using observation well data to assess the reasonableness of Pumping Threat results, limitations exist with using water chemistry data from EMS:

- TDS results span 35 years and over different seasons; historical data from years ago may not represent current conditions;
- For bedrock wells, the various depths to water-bearing fractures can affect TDS results; and
- The distribution of wells is biased towards areas where there are water quality concerns.

Sea Water intrusion concerns: As part of this study, the province documented sites where concerns of sea water intrusion from groundwater use exists. These concerns include past complaints from local residents as well as concerns identified through licensing applications.

Figure 8 shows the sites of concerns and their corresponding Susceptibility and Pumping Threat ratings. Sites concerning bedrock aquifers are restricted to moderate to high ratings of 3 and 4 and moderate to very high Pumping Threat ratings of 3 to 5. Sites concerning unconsolidated aquifers cover the entire range of Pumping Threat ratings. The one site of concern (in Delta) with a very low rating for Pumping Threat (1) is a site where groundwater use (dewatering) is proposed, but has not yet been licensed. Both sites concerning unconsolidated aquifers (in White Rock) with a Susceptibility rating of very low (1) correlate with productions wells located a sufficient distance from the coast. The scatter plot does seem to show sites of concern are generally in areas of higher Susceptibility or Pumping Threat or both.

Similarly, Figure 9 shows documented sites of concern for unconsolidated and bedrock aquifers to range from low to high (2 to 4 and 3 to 4, respectively). Most documented sites of concern have Vulnerability ratings of 3 or greater. These Vulnerability ratings do not contradict the documented sites of concern by the province.

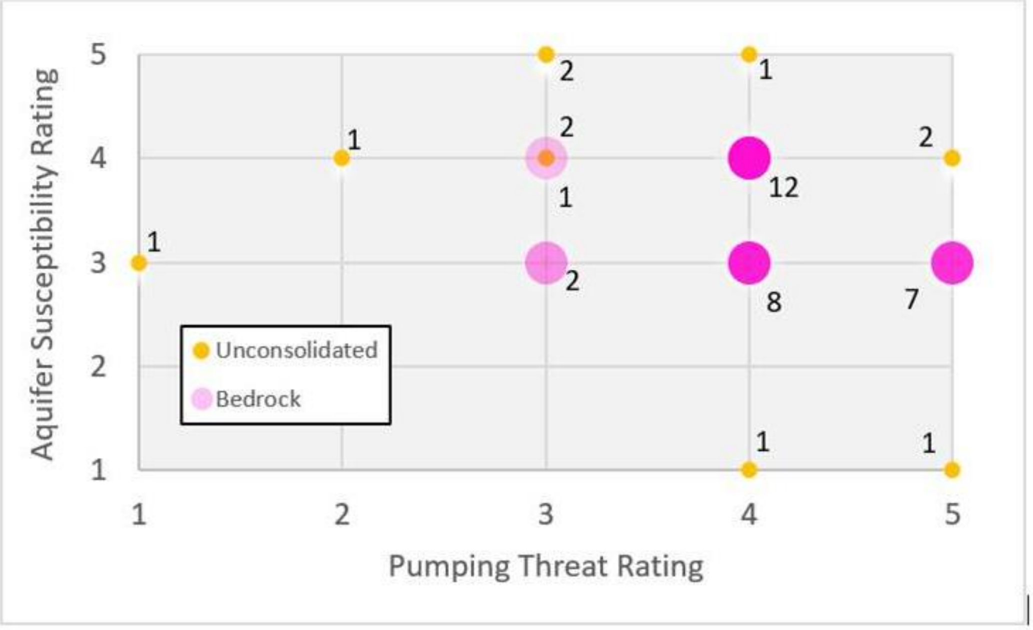

Figure 8. Scatter plot of sites of concern documented by FLNRORD. Sites concerning unconsolidated aquifers are coloured yellow and sites concerning bedrock aquifers are coloured in purple. Number of sites are labelled.

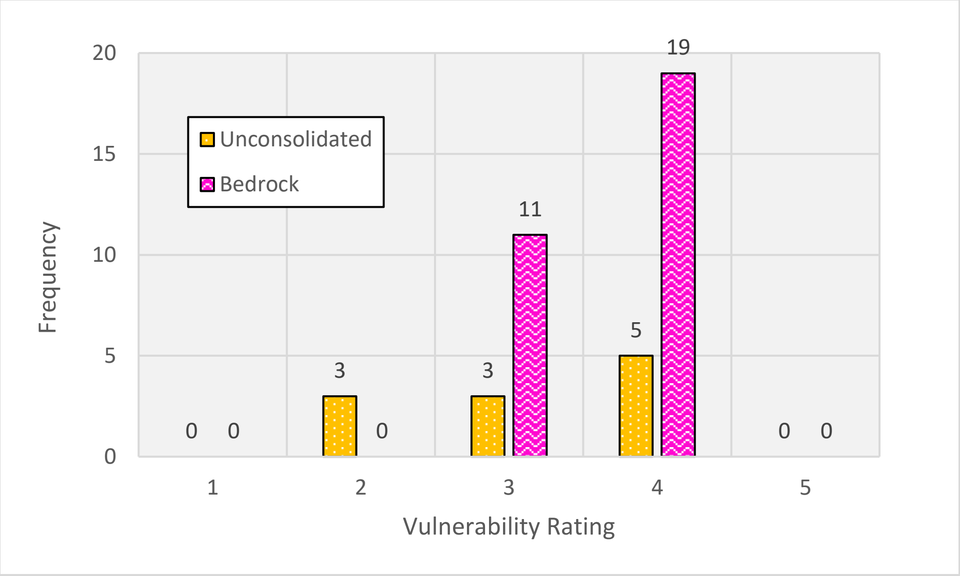

Figure 9. Bar graph of aquifer vulnerability of sites of concerns documented by FLNRORD.

4.7 Loss

Figures C1 and C2 show the preliminary mapping for Loss for unconsolidated aquifers in the southern east coast of Vancouver Island and southern Gulf Island, and Vancouver areas, respectively. Figure C3 shows preliminary Loss mapping for bedrock aquifers in the southern east coast of Vancouver Island and southern Gulf Islands. Loss within a municipality is shown as a coloured polygon, with the colour corresponding to the Loss rating. As previously noted, the preliminary mapping for Loss is limited to grid cells with reported wells, water licences, and Drinking Water Supply Systems (DWSS) and hatcheries that were included in this study.

In the southern Gulf Islands and the Vancouver area, the mapping shows that the most common rating for Loss is low (2). This is because most grid cells correspond with drinking water, irrigation, many industrial use purposes (category B in Table 12) with low pumping (less than 30 m^3/day). Prioritizing water use limits the Loss ratings to no lower than 2 for both unconsolidated and bedrock aquifers because most of the grid cells where data is available contain domestic wells.

In the southern Gulf Islands and south east Vancouver Island area (Figure C1), the highest Loss ratings (ratings of 5) are associated with irrigation, water works purposes, and municipal wells. North Cowichan (Figure C1), Parksville, Qualicum and Lantzville (not shown) are ratings of very high (5) because they are heavy groundwater users. In the Vancouver area, the highest loss ratings are associated with the municipal wells for White Rock which have Loss ratings of very high (5).

Duncan (Figure C1) and Bowen Island (Figure C2) are shaded with hatch patterns. Loss is not applicable to these areas because the municipal wells are > 3 km from the coastline (Duncan), or there are no reported large producing wells for the municipality (Bowen). Most large municipal areas in B.C. (i.e., Metro Vancouver and Greater Victoria) are supplied by surface water so they have no Loss ratings.

While attributing Loss to specific grid cells where the well is located may be appropriate for smaller groundwater uses, the reader should be aware that for many larger uses associated with moderate-sized drinking water supply systems, improvement districts and private water utilities where water is purveyed to a number of parcels, Loss can extend to beyond the immediate grid cell where the well is located. As groundwater licensing advances, the eLicensing database can help pinpoint the appurtenant properties on which water from a particular well is being used.

4.8 Overall Sea Water Intrusion Risk

The Overall Sea Water Intrusion Risk is calculated by multiplying Aquifer Vulnerability from Pumping and Loss (see Equation 7 in Section 3.12). The results are discussed for unconsolidated and bedrock aquifers below.

4.8.1 Overall Sea Water Intrusion Risk for Unconsolidated Aquifers

Figures C4 and C5 show the preliminary Overall Sea Water Intrusion Risk mapping for unconsolidated aquifers in the southern east coast of Vancouver Island and southern Gulf Islands and Vancouver, respectively.

In the southern Gulf Islands, Overall Risk of sea water intrusion into unconsolidated aquifers have low ratings (2). Near Duncan and Cowichan Bay, there are Overall Risk ratings of high (4). Cowichan has an Overall Risk of high (4), because the supply wells have Loss and aquifer Vulnerability from pumping ratings of very high and high (5 and 4), respectively.

Qualicum Beach, Parksville, and Lantzville have Overall Sea Water Intrusion Risk ratings of high (4) because they have Loss ratings of very high (5) and at least one of their municipal wells are located within grid cells with Vulnerability of aquifer from Pumping Threat rating of moderate (3).

In Vancouver, the Overall Sea Water Intrusion Risk for unconsolidated aquifers is highest in White Rock, where the Overall Risk to Sea Water Intrusion is very high (5), due to aquifer Vulnerability from Pumping and Loss. Overall Risk in the Fraser River delta and within 3 km of the coast have ratings up to moderate (3), excluding a few high (4) rated cells in Tsawwassen. The Overall Sea Water Intrusion Risk for unconsolidated aquifers is highest in low-lying areas close to the oceans and where heavy pumping is inferred to be occurring, as expected.

4.8.2 Overall Sea Water Intrusion Risk for Bedrock Aquifers

The Overall Sea Water Intrusion Risk for bedrock aquifers in the southern Gulf Islands are shown in Figure C6.

For the southern Gulf Islands, the grid cells immediately adjacent to the coastline have ratings of at least 3 (see north shore of Gabriola Island, Mayne Island, parts of Galiano Island and Salt Spring Island), due to the vulnerability of the bedrock aquifer. The East Point of Saturna Island has several grid cells with ratings of moderate to high (3 and 4).

Between Nanaimo and south of Cowichan Bay, there are mostly low risk to moderate risk grid cells. These cells are moderate (rating of 3) due to the moderate Pumping Threat from bedrock wells. There are only a few wells completed into the bedrock aquifer in Vancouver, therefore a map of sea water intrusion risk for bedrock in the Vancouver area wasn’t produced for this report.

The Overall Sea Water Intrusion Risk for the bedrock aquifers is greatest in areas closest to the coast where the Aquifer Vulnerability is highest and pumping is occurring. The high risk areas on the Vancouver Island mainland are predominantly due to the vulnerability of the bedrock aquifer and the moderate ratings for Pumping Threat in these cells.

5. CONCLUSIONS

The main conclusions of this study are as follows:

- This interim approach incorporates well records from GWELLS and licenced groundwater wells in the mapping. As the number of water licences increases and the water rights (eLicensing) database grows, the groundwater use and Pumping Threat can be better characterized.
- The Aquifer Susceptibility for the Quadra Sands, an advance outwash deposited at the onset of the last glaciation is highest only at the coast. Low-lying, more recent fluvial and deltaic aquifers (types 1 and 2) can show relatively high Aquifer Susceptibility ratings extending far inland.
- Along the coast where the bedrock topography is steep, high bedrock Aquifer Susceptibility only occurs along the shoreline. Bedrock susceptibility is typically high on rocky, low-lying islets and peninsulas.
- Although the method used here does not explicitly consider the size of recharge areas draining to local bedrock peninsulas as a contributing factor in Susceptibility, mapping identified local bedrock peninsulas as having high bedrock Susceptibility.
- The areas with highest Pumping Threat are associated with very high well density (e.g., Gulf Islands) or higher volume pumping related to municipal or water utility. Pumping Threat is lowest where groundwater is not in use or residents only rely on groundwater for domestic use.
- The Pumping Threat is highest for unconsolidated aquifers corresponding with locations of alluvial or colluvial fan and glacio-fluvial outwash or ice contact sand and gravel (Type 3 and 4) aquifers. The percentage of PGOWN wells affected by nearby pumping appears to be significant. The percentage of PGOWN wells experiencing decline appears to decrease with decreasing Pumping Threat rating, as might be expected. This observation is subjective and is based on a limited number of PGOWN wells.
- For both unconsolidated and bedrock aquifers, TDS - a measure of water salinity - generally increases with increasing Vulnerability from Pumping rating. Higher TDS results are interpreted to indicate pumping of more brackish water influenced by sea water chemistry.
- Sites of concern documented by the Province are in areas of higher Aquifer Susceptibility, Pumping Threat, or Vulnerability. Most documented sites of concern have Vulnerability ratings of 3 or above.
- Coastal Morphology in low-lying areas mentioned above contributes to significantly greater Coastal Hazards in those areas. Shallow bathymetry and low-lying areas less than about ~3 m elevation are the main attributes contributing to high Coastal Hazard.
- The areas of higher aquifer Vulnerability from Pumping Threat tend to be associated with type fluvial, alluvial and deltaic aquifers (types 1, 2, and 3). The Vulnerability from Pumping Threat of Quadra Sand (4b type) aquifers tends to be highest only immediately adjacent to the coastline.
- The unconsolidated aquifers (type 1) located along high order streams have high Vulnerability from Coastal Hazards due to low elevation and topographic relief. The Quadra Sand (type 4b) and aquifers associated alluvial fans that occupy the mouths of smaller coastal creeks have high Vulnerability to Coastal Hazards but only in the narrow zone along the coastline, and decreasing upgradient.
- In areas where the land is underlain by appreciable thickness of surficial sediments, the Vulnerability to sea water intrusion into bedrock aquifers from Pumping Threat and Coastal Hazards is high because the topographic slope upon which bedrock susceptibility is calculated reflects the slope of the overlying unconsolidated deposits, which is typically less. Even so, bedrock underneath these estuaries occurs at depths below sea level.

- Mapped aquifers underlying the floodplains associated with high-order streams have the highest Total Vulnerability. Aquifers associated with alluvial fans that occupy the mouths of smaller coastal creeks have high Total Vulnerability but only in the narrow zone along the coastline.
- There are additional factors affecting sea water intrusion risk that could not be feasibly incorporated into the GIS model (e.g., availability of alternate water sources, and seasonal water demand). Management of risk in specific areas may need to consider these additional factors, particularly in areas with high Total Vulnerability ratings of 3 and above, so as to adequately mitigate risk. For example, within the Gulf Islands context, moderate to high Total Vulnerability ratings (3 to 5) may require additional consideration to mitigate risk.
- Spatial representation of unconsolidated aquifer Vulnerability is limited to areas with mapped aquifers, and grid cells with reported wells. The spatial representation of Loss is limited to grid cells with reported wells and municipalities that use at least one groundwater source.
- Loss is dominated with low ratings because the grid cells correspond with drinking water, irrigation, many industrial use purposes, with low pumping (less than 30 m^3/day). The highest Loss ratings are associated with irrigation, water works purposes, and municipal wells.
- As expected, the Overall Sea Water Intrusion Risk for both the unconsolidated and bedrock aquifers is highest in low-lying areas close to the ocean.

6. RECOMMENDATIONS FOR FURTHER WORK

The following are recommendations for further work to refine the model:

- Acquire additional LiDAR data, especially for low-lying areas with major rivers and/or where more substantial post-glacial sediment deposits exist to allow Coastal Hazards to be modelled along more of B.C.’s coast.
- The mapping layers should be regularly updated potentially every 3 years, or more frequently if significant revisions are made to the regional coastal aquifer mapping.
- Revise Loss to consider potential future water needs due to population expansion, climate change or emergencies. Refine consideration of impacts on groundwater dependent aquatic ecosystems.
- Consider estimating Loss for smaller municipalities and communities with less than 300 connections that use groundwater for their supply.
- Consider upscaling the Loss component to allow Loss and Overall Risk to be more comprehensively mapped.
- Explore using the GIS modelling results from this study to develop a simple indicators of susceptibility, vulnerability and risk of sea water intrusion for mapped aquifers along the B.C. coast.

As a follow-up to this study, the results should be communicated to promote awareness of coastal aquifer vulnerability and sea water intrusion risk associated with natural physiographic factors and human activities (well drilling and operation), and to encourage implementation of best practices to reduce sea water intrusion occurrence in the coastal setting.

SIGNATURES

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GLOSSARY

Alluvial: Process by which sediments are deposited (in the form of a fan-shaped deposit) by a stream as the stream enter a larger valley.

Aquifer: A geological deposit that is permeable and saturated that allows a sufficient supply of water to flow to wells and to springs.

Bathymetry: The mapping of depth of water in oceans, lakes, rivers.

Fluvial: Process by which unconsolidated sediments (mostly sandy, gravelly sediments) are deposited by stream (moving) water.

Glacio-marine: Process by which unconsolidated sediments are deposited in the ocean during glacial times.

Hydraulic gradient: The amount the groundwater level decreases over a specific distance in a specific direction (e.g., vertical hydraulic gradient; horizontal hydraulic gradient). Hydraulic gradient is usually expressed as a dimensionless fraction (e.g., 0.0005).

Isostatic adjustments: The vertical shifting of the earth's crust due to change in loading on the crust (from ocean rise, erosion, melting of ice sheets, etc.).

LiDAR: Light Detection and Ranging is a remote sensing method that uses pulsed lasers to map the surface of the earth or bottom of the ocean to with high accuracy.

Morphology: Study of shape or form.

Recharge: Process where water (from rain, snow, surface water) percolates to the aquifer.

Sea Water (or saltwater) intrusion: The incursion of saltwater into freshwater aquifers located in coastal areas. Well pumping, sea level rise from climate change and from storm surges can cause significant incursion of saltwater into freshwater aquifers to occur.

Static water elevation (SWE): The elevation (above mean seal level) of the groundwater level in the well, when the groundwater level is not affected by pumping activities in the well.

Storativity (S): Volume of water stored or released from a column of aquifer with unit cross section under unit change in groundwater level. Storativity determines how quickly (or slowly) an aquifer responds to hydraulic changes and is reported as a dimensionless number (e.g., 0.0001).

Stream order: A hierarchy within a stream network where the uppermost streams in the watershed are called first-order streams. A stream attains a higher order when two streams of the same order join. For example, two first-order streams join to become a second-order stream and so on. The order of a stream also reflects the size of a stream; higher order streams are larger than lower-order streams.

Total Dissolved Solids (TDS): The total weight of all minerals dissolved in water, usually expressed in mg/L; represents the mineral content of the water.

Transmissivity (T): The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is commonly expressed as metres squared per second or day, feet squared per second or day, or gallons per day per foot. Transmissivity reflects the permeability of the aquifer integrated over the thickness of the aquifer.

Unconsolidated sediments: A geological material comprising loose sediments, e.g., sand and gravel. Synonymous with "Surficial sediments".

Up-coning (of fresh water/saltwater interface): When well pumping (of fresh groundwater) occurs within a coastal aquifer above where a freshwater-saltwater interface occurs at depth, the equilibrium that exists between a body of fresh groundwater and salt water is disturbed such that the freshwater-saltwater interface will move upward, bringing the body of saltwater closer to the pumping well.

Well tag number (WTN): the file number assigned in the government's GWELLS database to the record of a particular well.

APPENDIX A: SUMMARY OF SPATIAL DATA AND SCRIPT DELIVERABLES

Script Name	**Purpose**
main.py	Primary script to run approach with calls to Loss, Pumping Threat and Aquifer Susceptibility functions
loss_funct.py	Create grid centroids representing Loss
pumping_threat_funct.py	Create grid centroids representing Pumping Threat hazard for unconsolidated and bedrock aquifers.
aquifer_susceptibility_funt.py	Create grid centroids representing unconsolidated Aquifer Susceptibility
wells.py	Parse wells by aquifer type
buffercoast.py	Create buffers from coastline for entire coastal B.C. for bedrock aquifer susceptibility

Graphical Model Name:	**Purpose:**
Flood Hazard	Generate flood hazard mapping by area
Loss	Rasterize Loss centroids
Pumping Threat	Generate Pumping Threat layers using Kernel Density function and mapped aquifers
Coastal Hazards	Generate Coastal Hazards layers

APPENDIX B: MAPPING RESULTS FOR SUSCEPTIBILITY, PUMPING THREAT, FLOOD HAZARD, COASTAL MORPHOLOGY, COASTAL HAZARDS, AND VULNERABILITY

The following maps show GIS modelling results in two primary areas: the southern Gulf Islands and corresponding southeast Coast of Vancouver Island, and Vancouver and the Fraser River Delta and surrounding areas (unconsolidated aquifers only):

- Figure B1 – Susceptibility of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B2 – Susceptibility of unconsolidated aquifers in the Vancouver area.
- Figure B3 – Susceptibility of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B4 – Pumping Threat of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B5 – Pumping Threat of unconsolidated aquifers in the Vancouver region.
- Figure B6 – Pumping Threat of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B7 – Flood Hazard, Coastal Morphology and Coastal Hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B8 – Flood Hazard, Coastal Morphology and Coastal Hazards in the Vancouver area
- Figure B9 – Vulnerability of unconsolidated aquifers to pumping along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B10 – Vulnerability of unconsolidated aquifers to pumping in the Vancouver area.
- Figure B11 – Vulnerability of bedrock aquifers to pumping along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B12 – Vulnerability of unconsolidated aquifers from coastal hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B13 – Vulnerability of unconsolidated aquifers from coastal hazards in the Vancouver area.
- Figure B14 – Vulnerability of bedrock aquifers from coastal hazards along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B15 – Total Vulnerability of unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure B16 – Total Vulnerability of unconsolidated aquifers in the Vancouver area.
- Figure B17 – Total Vulnerability of bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.

APPENDIX C: MAPPING RESULTS FOR LOSS AND OVERALL RISK

Preliminary results for Loss and Overall Risk are shown in the following maps:

- Figure C1 – Loss in unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C2– Loss in unconsolidated aquifers in the Vancouver area.
- Figure C3 – Loss in bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C4 – Overall risk from sea water intrusion in unconsolidated aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.
- Figure C5 – Overall risk from sea water intrusion in unconsolidated aquifers in the Vancouver area.
- Figure C6 – Overall risk from sea water intrusion for bedrock aquifers along the southern east coast of Vancouver Island and southern Gulf Islands.