SFU
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The Hydrogeology of Salt Spring Island

A summary of research conducted by Simon Fraser University as part of a project "Risk Assessment Framework for Coastal Bedrock Aquifers"

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1 Introduction

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

Unlike other water quality risk assessment methodologies used for source water protection that focus on chemical hazards related to contaminants that may be related to land use (agriculture, spills), the more important hazard in coastal aquifers is salinization due to landward encroachment of the freshwater-saltwater interface or inundation and overtopping of the land surface by seawater, which may adversely impact water quality and the availability of fresh water.

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

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

This report summarizes a portion of the research carried out by Isabelle Larocque towards her MSc degree in the Department of Earth Sciences at Simon Fraser University (Larocque, 2014). The report focuses on the Hydrogeology of Salt Spring Island, as a representative Gulf Island. Aspects of Ms. Larocque’s MSc thesis related to impacts of climate change on the saltwater-freshwater interface are not included, but will be addressed in a later report concerning the risk assessment. A separate report will include the results of drilling, hydraulic testing and sampling (for water chemistry and isotopes) of a monitoring well on Salt Spring Island.

The scope of work reported upon herein includes:

1. Compiling existing hydrogeological data for Salt Spring Island.
2. Developing a hydrogeological conceptual model of Salt Spring Island, including:
    a) Characterizing the main geological units;
    b) Estimating the hydraulic properties of the aquifers;
    c) Estimating recharge;
    d) Describing the groundwater flow system; and
    e) Describing the groundwater chemistry.

For each aspect of the hydrogeological conceptual model, the results are compared to previous studies of other Gulf Islands.

2 Background

2.1 The Saltwater-Freshwater Interface

In coastal and island aquifers, a salinity gradient exists where seawater and freshwater mix at the coastal margin (Figure 1). This zone is called the saltwater-freshwater interface, or the transition zone (Barlow, 2003). The stable dynamic of the interface was first explained by Kohout (1960) who identified cyclic flow using extensive observations of the Biscayne aquifer in Florida, USA. The seawater naturally intrudes inland, forming a wedge of saltwater that underlies the freshwater; the “toe” of the wedge is the most inland point (Figure 1). In island aquifers, the freshwater floats on the saltwater as a lens-shaped layer (Fetter, 2001). During cycling, mixing occurs through molecular diffusion along the transition zone (Figure 1). The density of seawater mixing with freshwater becomes less than the native seawater, and thus the seawater is carried back to the surface along the interface, which prevents the encroachment of seawater inland (Kohout, 1960).

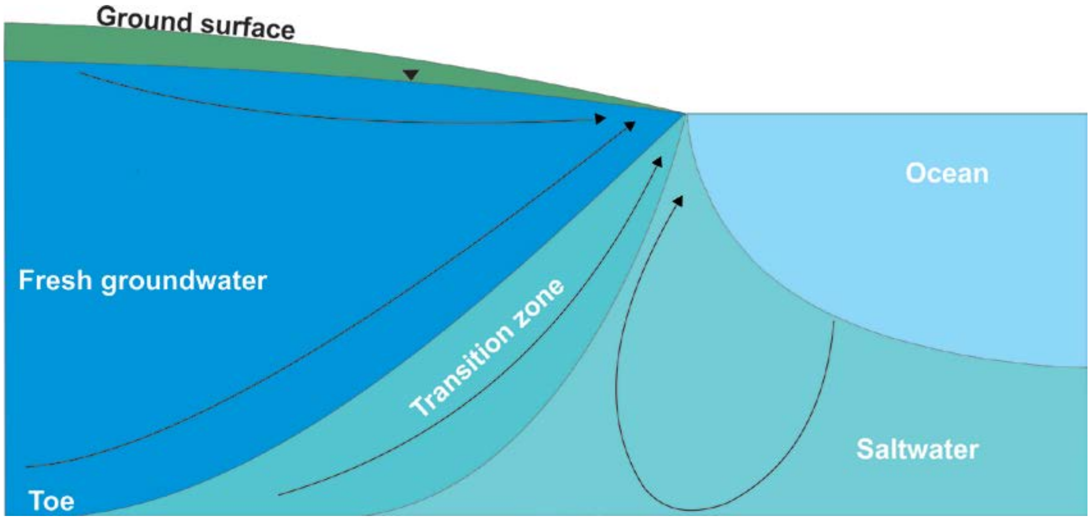


Figure 1. Saltwater-freshwater interface (transition zone) in coastal and island environments.

The nature and location of the saltwater-freshwater interface is controlled by the freshwater head, thus topography and the aquifer hydraulic properties play a significant role in defining the interface position. If freshwater recharge to the aquifer decreases, the freshwater hydraulic gradient (or water table slope) will also decrease, leading to an overall decline in the height of the water table above sea level, and a consequent reduction in the depth to the saltwater wedge (Fetter, 2001). In addition, groundwater pumping may lower the water table, reversing the hydraulic gradient near the coast and causing the saltwater interface to move landward (Barlow, 2003). This landward movement or encroachment of the saltwater wedge leads to groundwater contamination through an increase in salinity.

Some areas and wells are at higher risk of contamination. Deep wells are particularly at risk of becoming contaminated as they may be completed close to, within, or below the saltwater interface and may draw in seawater during pumping (i.e., upconing) (USGS, 2000). Wells located close to the shoreline are also at higher risk of contamination than wells located further inland (Fetter, 2001). Pumping rates exceeding the capacity of the aquifer or the total drawdown caused by multiple pumping wells can induce further movement of the saltwater interface landward. Sea level rise and storm surges through inundation represent a risk of fresh groundwater contamination from above, infiltrating the soil and reaching the water table. Low topographic areas are more prone to inundation and their low hydraulic gradient makes these areas also more prone to seawater intrusion (Ferguson and Gleeson, 2012).

3 Geography, Climate, Hydrology, Soils and Vegetation

3.1 Geography

The southern Gulf Islands comprise some 40 islands and are located in the southwest corner of British Columbia (BC), at the southeastern tip of Vancouver Island. The islands lie within the Strait of Georgia, between the mainland (Vancouver) and Vancouver Island (Figure 2).

Salt Spring Island, the study area for this research, is the largest (185.54 km^2) and most populous Gulf Island (10,234 inhabitants in 2011; Statistics Canada, 2014; it is about 26 km long and 9 km wide (Islands Trust, 1978). To the west, Salt Spring Island is bordered by Vancouver Island and to the east lie the outer Gulf Islands; Galiano, Mayne, Saturna, and Pender Islands. The maximum elevation of Salt Spring Island is Bruce Peak: 709 masl (Wikipedia, 2014). Other prominent peaks include Baynes Peak (Mount Maxwell): 593 masl (Peakbagger, 2004); Mount Tuam: 602 masl; and Mount Eskrine: 441 masl (Wikipedia, 2014). The coastlines are rocky and characterized by either steep cliffs or low relief outcrops (Mackie, 2002).

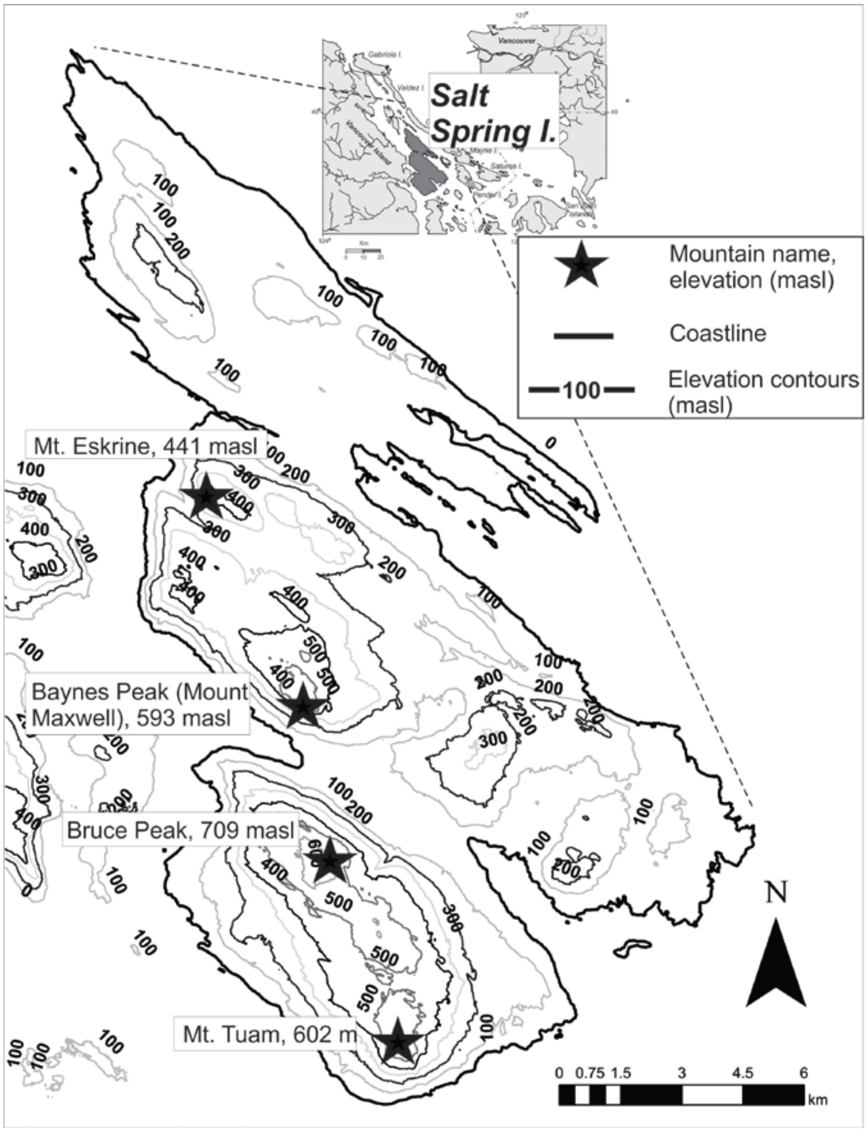


Figure 2. Location map of Salt Spring Island (BC), topography and main mountains (spatial data from DataBC (iMapBC), n.d.; Bednarski and Rogers, 2012).

3.2 Climate and Hydrology

The Gulf Islands experience cool, dry summers and humid, mild winters; the climate is referred to as Cool Mediterranean (van Vliet et al., 1987). The islands are influenced by a rain shadow resulting from the Olympic Mountains to the south and the insular Mountains to the west (van Vliet et al., 1987). For the 1971-2000 period, Environment Canada (2013) reported average daily temperatures varying between about 2.6 and 16.3°C on a yearly basis in the Cusheon Lake area (Station ID: 1016992), and between 4.0 and 18.1°C in the St. Mary Lake area (Station ID: 1016995). Mean monthly rainfall ranges from about 22.9 mm in July to 176.5 mm in November in the Cusheon Lake area, and between 24.7 mm in July to 163.3 mm in November in the St. Mary Lake area for the same period (Figure 3 and Figure 4). Most precipitation falls as rain.

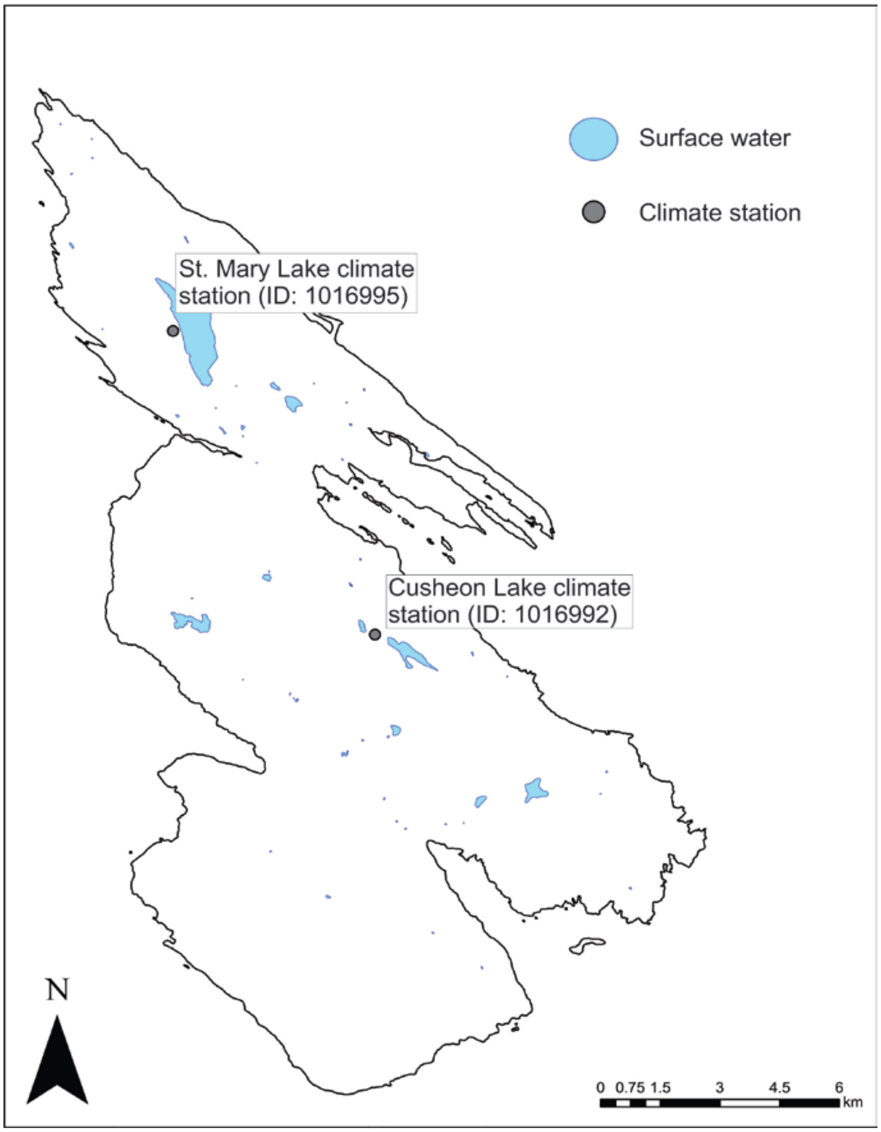


Figure 3. Location of the two Environment Canada climate stations and surface water bodies on Salt Spring Island (spatial data from DataBC (iMapBC), n.d; Environment Canada, 2013).

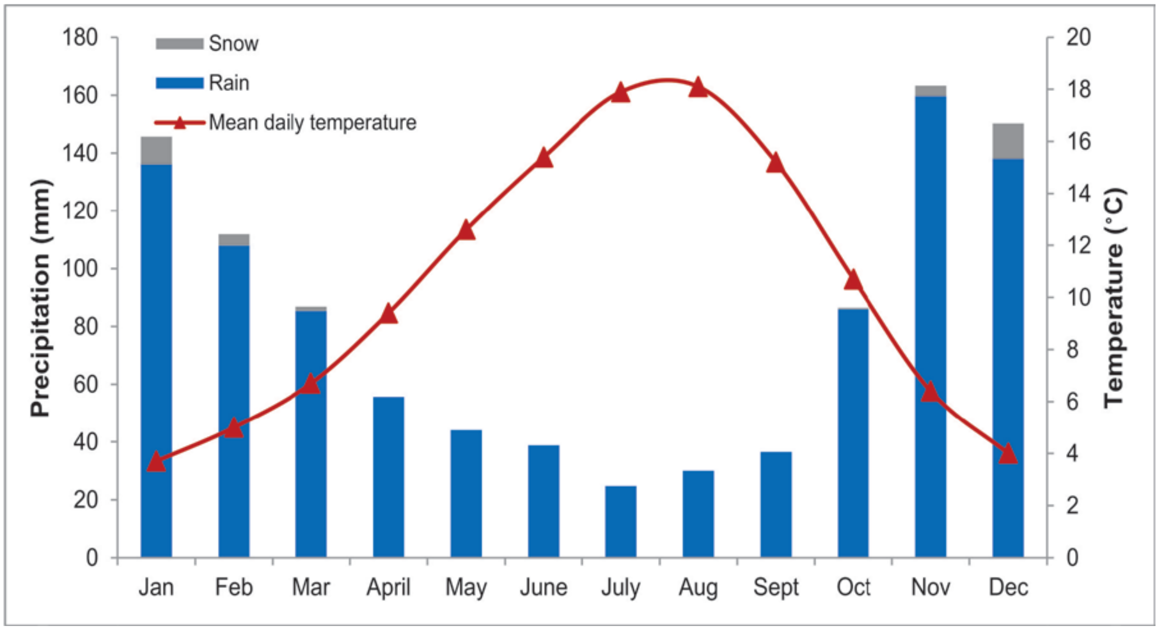


Figure 4. Monthly average temperature and precipitation at the St. Mary Lake climate station (Station ID: 1016995) for the 1971-2000 period. The blue bars represent mean monthly precipitation as rain and the grey bars, mean monthly precipitation as snow; the red curve, mean daily temperature (data from Environment Canada, 2013).

Only a small number of freshwater lakes dot the landscape of the southern Gulf Islands (Kohut et al., n.d.). Nevertheless, there are nine lakes on Salt Spring Island (Figure 5). Lake and watershed size do not necessarily correlate; smaller lakes (Blackburn, Ford and Stowell) are located in large watersheds, large lakes (Weston, Maxwell and St. Mary) in relatively smaller watersheds, and only three lakes (Roberts, Cusheon and Bullocks) have a size that is proportional to their respective watershed (Lamb et al., 2010). Lakes are an important surface water source to community water supply systems (Lamb et al., 2010). St. Mary Lake, Blackburn Lake, Cusheon Lake, Lake Maxwell, Ford Lake and Lake Weston flow into fish bearing streams (Barnett et al., 1993). Table 1 shows surface area and volume for all lakes other than Roberts Lake.

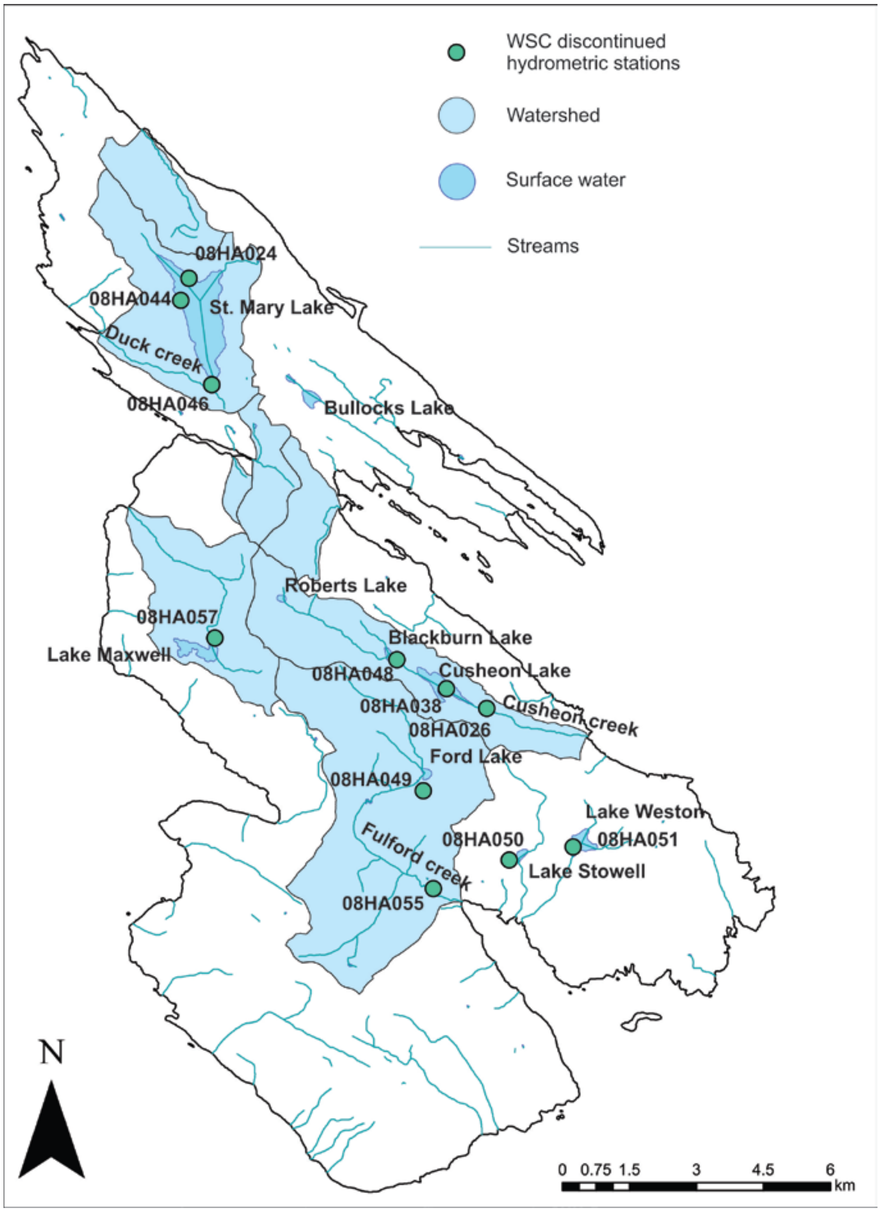


Figure 5. Lakes, stream, watersheds and location of Water Survey of Canada (WSC) discontinued hydrometric stations (spatial data from DataBC (iMapBC), n.d; Environment Canada, 2011).

Table 1. Lake surface area and volume (data from Barnett et al., 1993).

	Surface Area (km^2)	Volume (km^3)
St. Mary Lake	1.81	0.01567
Cusheon Lake	0.27	0.00116
Blackburn Lake	0.04	0.00014
Bullocks Lake	0.10	0.00051
Lake Maxwell	0.28	0.00216
Ford Lake	0.04	0.00014
Lake Weston	0.18	0.00109
Lake Stowell	0.06	0.00026

Currently, Environment Canada does not operate any active (real-time) hydrometric stations on Salt Spring Island. However, in past years, there were five Water Survey of Canada (WSC) hydrometric stations on Saltspring Island; three of which measured flow. Duck Creek at outlet of St. Mary Lake (08HA046: 1980-1998), Cusheon Creek at outlet of Cusheon Lake (08HA026: 1970-1998) and Fulford Creek (08HA055: 1983-1993). Cusheon Creek has historic records for the complete year, while Duck Creek and Fulford Creek records cover only a part of a year. The other two hydrometric stations measure water levels on St. Mary Lake (08HA024: 1969-1972) and Cusheon Lake near Ganges (08HA038: 1976-1998) (Barnett et al., 2013). Six more hydrometric stations were active in the past, mostly operated by the BC Ministry of Environment for short periods of time (2-3 years) (Environment Canada, 2011). Figure 5 illustrates the locations of the various discontinued hydrometric stations on Salt Spring Island.

Low flows are observed for all streams in the Gulf Islands between June and October (Barnett et al. 1993). Figure 6 shows the annual maximum, mean and minimum discharge over the period of record at Cusheon Creek. Cusheon Creek (08HA026) had periods of zero to no flow from June to October. Monitoring at Fulford Creek (08HA055) only took place from March to October. Contrary to Cusheon Creek, annual minimum flows recorded at Fulford Creek are always above 0 m^3/s for the 1983-1986 period (0.008, 0.025, 0.011 and 0.005 m^3/s) (Environment Canada, 2011). This suggests Fulford Creek might be a groundwater discharge zone. This observation was also made by Hodge (1995), who suggested that flow in Fulford Creek is likely sustained by groundwater.

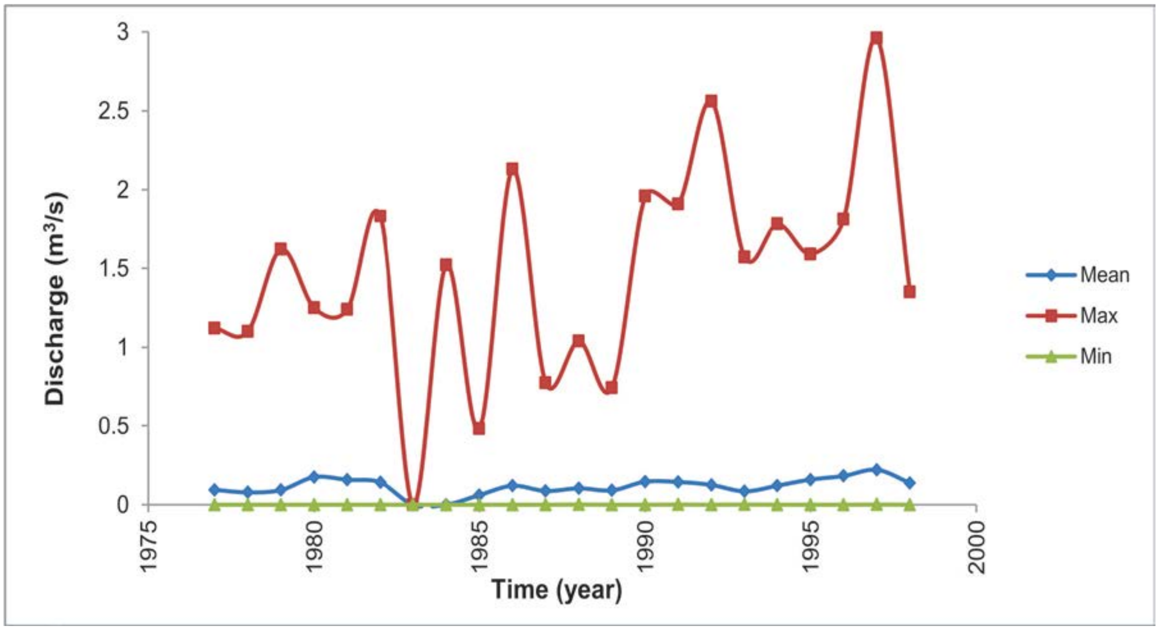


Figure 6. Annual maximum, mean and minimum discharge at Cusheon Creek between 1977 and 1998. No data are available between 1970-1977 (data from Environment Canada, 2011).

3.3 Soils and Vegetation

Nineteen soil types have been identified on Salt Spring Island (van Vliet et al., 1987). Most of parent materials are of glacial origin; very few are of fluvial origin. The soils are of variable texture and thickness (generally < 1 m thick), and are variably drained. A detailed soils map is available as a pdf (http://sis.agr.gc.ca/cansis/publications/surveys/bc/bc43-1/index.html), but is not shown here given its poor resolution.

The Gulf islands are located within the Coastal-Douglas-fir Biogeoclimatic Zone (Krajina, 1969 from van Vliet et al., 1987). Consequently, Douglas fir is very abundant in the region, and is intermixed with other coniferous tree species such as grand firs, western red cedar, shore pine, Sitka spruce and western hemlock. Red alder, broadleaf maple, northern black cottonwood, western flowering dogwood and bitter cherry are deciduous trees found on Salt Spring Island. Salal, Oregon grape and fireweed are also found in the region (van Vliet et al., 1987).

4 Geology

4.1 Surficial Geology

The surficial geology of Salt Spring Island is composed of thick layers of unconsolidated deposits from the last glaciation. In most upland areas, these deposits have been eroded away (Hodge, 1995) and bedrock is exposed at the surface. Surficial sediments are of fluvial, marine and glacial materials

(Halstead, 1967) and are thickest in valley bottoms (Mackie, 2002). A range of surficial materials have been mapped: Fine Marine/Lacustrine, Organic (land depressions and valleys), Till and Coarse Marine/Fluvial, Glaciofluvial/Marine, and Colluvium and Glacial Drift (edges of valleys up to higher elevations). These sediments form the parent materials for the soils found on Salt Spring, such as Beddis, Crofton and St. Mary as described in the previous section (van Vliet et al., 1987).

4.2 Bedrock Geology

The bedrock geology of Salt Spring Island was mapped in detail by Greenwood and Mihalynuk (2009) by studying outcrops and interpreting existing borehole stratigraphy data. Figure 7 shows there are important broad differences in geology between the northern and southern portions of Salt Spring Island. The northern portion is composed of layered sedimentary rocks (Nanaimo Group) (green tones), while “igneous” rocks characterize the southern portion (pink tones) (Greenwood and Mihalynuk, 2009). Greenwood and Mihalynik (2009) also generated two geological cross-sections (Figure 8), which are reproduced here. The geological legend for both the map and the cross-sections is shown in Figure 9. The detailed geological map is available on line (http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/2009/Pages/2009-11.aspx).

Eleven formations comprise the Upper Cretaceous Nanaimo Group (Table 2). These are recognized as successions of sandstone-conglomerate units interbedded by mudstone and fine-grained sandstone deposited in one basin (Mustard, 1994). Sandstone and conglomerates predominantly comprise the Benson, Comox, Extension, Protection, DeCourcy and Geoffrey Formations. While the Haslam, Ganges, Cedar District, Northumberland, and Spray Formations are mainly black shale (Greenwood and Mihalynuk, 2009).

The units characterizing the south-central portion of the island are the Fourth Lake (Buttle Lake Group), the McLaughlin Ridge, the Nitinat Formations and Saltspring Intrusions (Sicker Group). These units are of Carboniferous and Permian age. Finally, Mount Hall Gabbro Sills are part of the Vancouver Group from the Triassic period. Overall, the lithology of the south central portion of the island is mainly composed of calcareous siltstone, cherty tuff, breccia, pyroxene, diorite, granite, granodiorite and hornblende (Greenwood and Mihalynuk, 2009).

The structural distribution of the Upper Nanaimo Group was created by multiple ancient deformational (Mustard, 1994) and more recent glacier glacio-isostatic deformations (Clague, 1983). The bedrock throughout the southern Gulf Islands thus has been extensively folded and fractured (Journeay and Morrison, 1999).

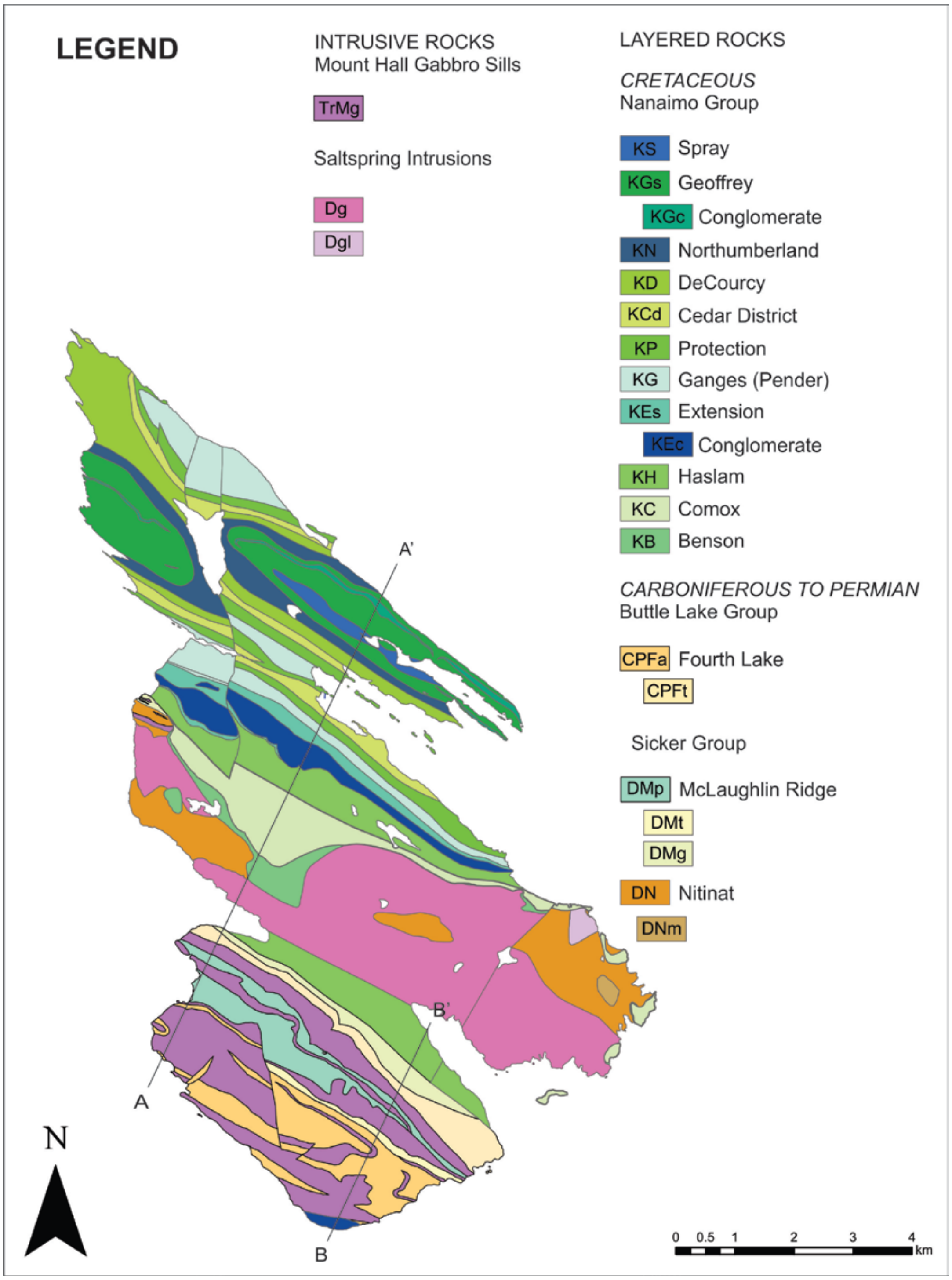


Figure 7. Salt Spring Island geology showing two lines of cross-section (geology from Greenwood and Mihalynuk, 2009). A detailed description of the various rock units is given geological legend shown in Figure 8.

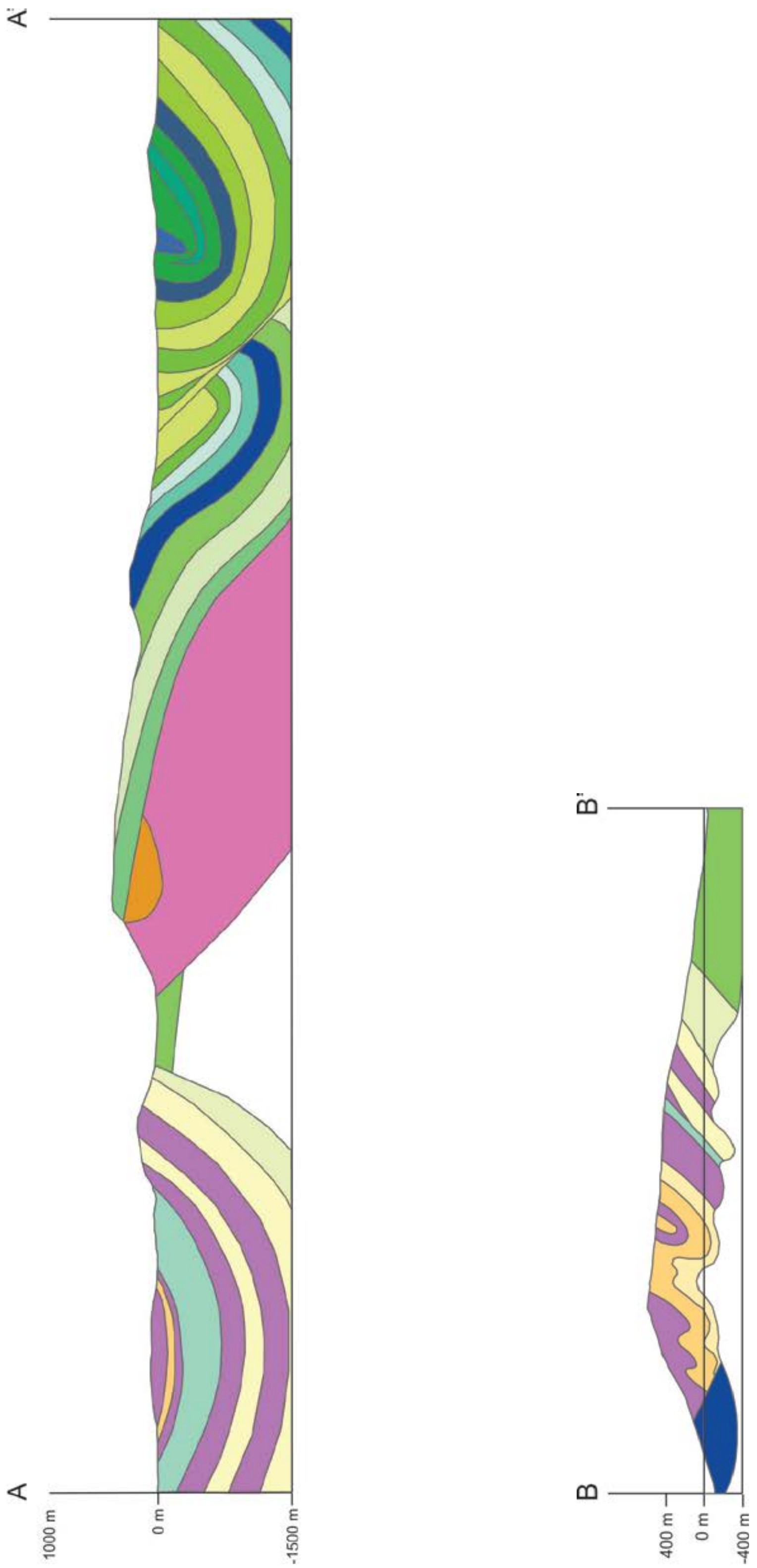
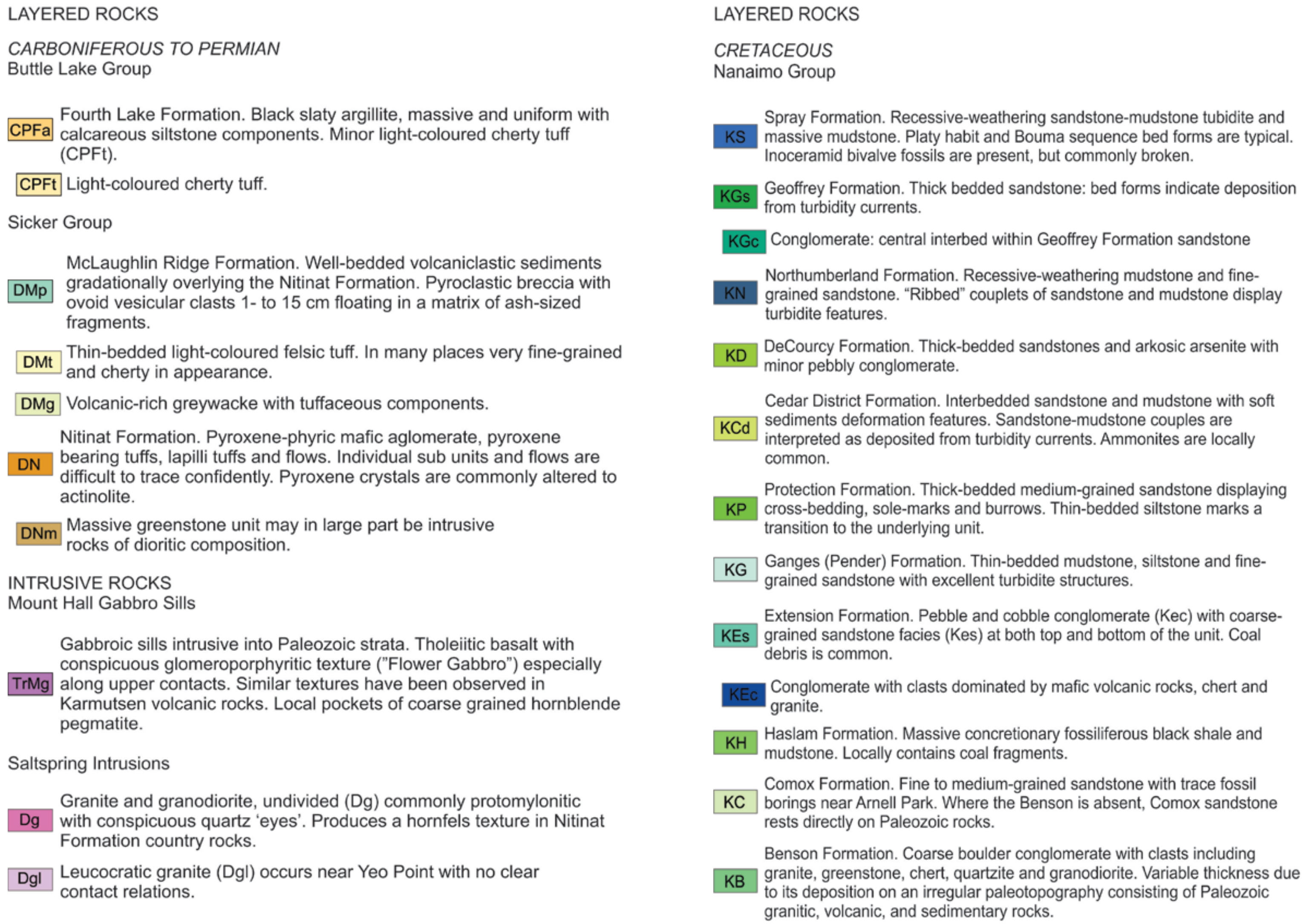


Figure 8. Cross-sections A-A’ and B-B’. Location of the cross-sections is shown on Figure 7 (modified from Greenwood and Mihalynuk, 2009).



LAYERED ROCKS

CARBONIFEROUS TO PERMIAN
Buttle Lake Group

CPFa Fourth Lake Formation. Black slaty argillite, massive and uniform with calcareous siltstone components. Minor light-coloured cherty tuff (CPFt).

CPFt Light-coloured cherty tuff.

Sicker Group

DMp McLaughlin Ridge Formation. Well-bedded volcaniclastic sediments gradationally overlying the Nitinat Formation. Pyroclastic breccia with ovoid vesicular clasts 1- to 15 cm floating in a matrix of ash-sized fragments.

DMt Thin-bedded light-coloured felsic tuff. In many places very fine-grained and cherty in appearance.

DMg Volcanic-rich greywacke with tuffaceous components.

DN Nitinat Formation. Pyroxene-phyric mafic aglomerate, pyroxene bearing tuffs, lapilli tuffs and flows. Individual sub units and flows are difficult to trace confidently. Pyroxene crystals are commonly altered to actinolite.

DNm Massive greenstone unit may in large part be intrusive rocks of dioritic composition.

INTRUSIVE ROCKS
Mount Hall Gabbro Sills

TrMg Gabbroic sills intrusive into Paleozoic strata. Tholeiitic basalt with conspicuous glomeroporphyritic texture ("Flower Gabbro") especially along upper contacts. Similar textures have been observed in Karmutsen volcanic rocks. Local pockets of coarse grained hornblende pegmatite.

Saltspring Intrusions

Dg Granite and granodiorite, undivided (Dg) commonly protomylonitic with conspicuous quartz 'eyes'. Produces a hornfels texture in Nitinat Formation country rocks.

Dgl Leucocratic granite (Dgl) occurs near Yeo Point with no clear contact relations.

LAYERED ROCKS

CRETACEOUS
Nanaimo Group

KS Spray Formation. Recessive-weathering sandstone-mudstone tubidite and massive mudstone. Platy habit and Bouma sequence bed forms are typical. Inoceramid bivalve fossils are present, but commonly broken.

KGs Geoffrey Formation. Thick bedded sandstone: bed forms indicate deposition from turbidity currents.

KGc Conglomerate: central interbed within Geoffrey Formation sandstone

KN Northumberland Formation. Recessive-weathering mudstone and fine-grained sandstone. "Ribbed" couplets of sandstone and mudstone display turbidite features.

KD DeCourcy Formation. Thick-bedded sandstones and arkosic arsenite with minor pebbly conglomerate.

KCd Cedar District Formation. Interbedded sandstone and mudstone with soft sediments deformation features. Sandstone-mudstone couples are interpreted as deposited from turbidity currents. Ammonites are locally common.

KP Protection Formation. Thick-bedded medium-grained sandstone displaying cross-bedding, sole-marks and burrows. Thin-bedded siltstone marks a transition to the underlying unit.

KG Ganges (Pender) Formation. Thin-bedded mudstone, siltstone and fine-grained sandstone with excellent turbidite structures.

KEs Extension Formation. Pebble and cobble conglomerate (Kec) with coarse-grained sandstone facies (Kes) at both top and bottom of the unit. Coal debris is common.

KEc Conglomerate with clasts dominated by mafic volcanic rocks, chert and granite.

KH Haslam Formation. Massive concretionary fossiliferous black shale and mudstone. Locally contains coal fragments.

KC Comox Formation. Fine to medium-grained sandstone with trace fossil borings near Arnell Park. Where the Benson is absent, Comox sandstone rests directly on Paleozoic rocks.

KB Benson Formation. Coarse boulder conglomerate with clasts including granite, greenstone, chert, quartzite and granodiorite. Variable thickness due to its deposition on an irregular paleotopography consisting of Paleozoic granitic, volcanic, and sedimentary rocks.

Figure 9. Geological legend for Figures 7 and 8 (modified from Greenwood and Mihalynuk, 2009).

Table 2. Lithology of Salt Spring Island.

Rock Type	Geologic Period	Group	Formation	Dominant Lithology
Sedimentary	Cretaceous	Nanaimo	Benson	Sandstone and conglomerate
			Comox	
			Extension	
			Protection	
			DeCourcy	
			Geoffrey	
			Haslam	Black shale
			Ganges	
			Cedar District	
			Northumberland	
			Spray	
Igneous	Triassic	Vancouver	Mount Hall Gabbro Sills	Basalt, hornblende
	Carboniferous to Permian	Sicker	McLaughlin Ridge	Pyroclastic breccia, rhyolite
			Nitinat	Pyroxene
			Saltspring Intrusions	Granite, granodiorite
Sedimentary		Buttle Lake	Fourth Lake	Calcareous siltstone, cherty tuff

(From Greenwood and Mihalynuk, 2009)

5 Hydraulic Properties

5.1 Hydraulic Properties and Hydrostructural Domains

Hydraulic properties describe the aquifers; they characterize the capacity of aquifers to store and transmit groundwater (Sterrett, 2007). These properties are determined through the analysis of hydraulic test data such as slug/bail test data, pumping (or aquifer) test data, and tidal response test data.

A fractured bedrock aquifer flow regime is more influenced by structure than by lithology and stratigraphy (Abbey and Allen, 2000; Allen et al., 2003). As a result, bedrock aquifers in the Gulf Islands have been divided into hydrostructural domains (Mackie, 2002); domains are identified according to their relative fracture network permeability. Mackie (2002) identified three main hydrostructural domains to classify aquifers of the Gulf Islands: ‘highly’ fractured interbedded mudstone and sandstone (IBMS-SS), ‘less’ fractured sandstone (LFSS) and fracture zone (FZ). This classification was used to characterize domains and estimate hydraulic properties based on discrete fracture modeling at the regional scale (Surrette and Allen, 2008; Surrette et al., 2008).

Several Gulf Islands studies have attempted to characterize the permeability of these hydrostructural domains using various methods, ranging from pumping test analysis (e.g. Allen et al., 2002; Scibek et al., 2013) to using measurements of discrete fractures mapped throughout the Gulf Islands and undertaking discrete fracture network modeling (Surrette et al., 2008).

A considerable pumping test dataset (data from BC Ministry of Environment) had been compiled and analyzed for the Gulf Islands (e.g., Allen et al., 2002), but few data existed for Salt Spring Island. Therefore, this study compiled existing (and available) pumping test data for Salt Spring Island. In order to complement the existing datasets, tidal response tests were performed on Salt Spring Island during June 2013. These results are summarized in Section 5.3. As well, water level data for the provincial observation wells were analyzed using tidal response analysis. Finally, to compare the hydraulic properties for Salt Spring Island to the Gulf Islands region more broadly, all pumping and tidal response tests results for the southern Gulf Islands were compiled (some were re-analyzed). The results of the broad analysis of hydraulic properties for the Gulf Islands are discussed in Larocque (2014).

This study did not consider the permeability of major faults, which are distinct hydrostructural domains. Major faults (St. Mary Lake and Gulf Islands Faults) are considered to form dominant permeable pathways (Kingerlee et al., 2010) in both the sedimentary rocks and the metamorphic igneous rocks present on Salt Spring (Allen et al., 2003).

5.2 Pumping Test Data Analysis

5.2.1 Sources of Data

A total of 32 pumping test datasets were available for Salt Spring Island (Table 3). Three pumping test reports (E. Livingston Associates, 1974, 1975; Pacific Hydrology Consultants Ltd., 1979, 1992) were provided by the BC Ministry of Environment. These pumping tests were performed during the 1970s and 1990s in order to define the long-term capacity of water supply wells. One pumping test document by Lowen Hydrology (2000) reported on four pumping tests. Two publically available pumping test documents by Gooding Hydrology (2011) and Waterline Resources Inc. (2013) reported on water quality and aquifer capacity, respectively. The documents generally include more than one pumping test, during which multiple wells were pumped and/or recovery tests were done.

Table 3. Pumping test document information.

Consultant	Purpose of Pumping Test	Year of Pumping Test	# Datasets	# Datasets Used	Well ID	Test Duration
E. Livingston Associates	Long term capacity of water supply wells	1974 & 1975	7	5	1, 2	Long and short
Pacific Hydrology Consultants Ltd.		1979	2	2	77-5	Long
		1992	11	2	1, 2	Long
Lowen Hydrology Consulting	CPCN conditions	2000	4	3	2, 3 [b]	Long
Gooding Hydrology	Potable water report	2011	2	1	WTN [c] 14175	Long
Waterline Resources Inc.	Hydrogeological impact assessment	2012 & 2013	6 [a]	6 [a]	1, 2, WTN [c] 97146	Long

[a] The raw data were not available for this study. In this case, the “# of datasets available” and “# of datasets used” represent the number of pumping tests performed; [b] Well no 2 is an observation well during pumping of well no 3; [c] WTN = BC Well Tag Number; Long duration tests: >3 hours; Short duration tests: <3 hours.

5.2.2 Pumping Test Data Analysis Approach

In BC, there are no general regulations regarding pumping test field procedures and methods of analysis for assessing aquifer properties. Recently, guidelines for conducting pumping tests have been made available ("*A Guide to Conducting Well Pumping Tests*"; BC Ministry of Environment and British Columbia Groundwater Association, no date). In addition, there are prescribed methods for conducting pumping tests in water supply wells that require a Certificate of Public Convenience and Necessity (CPCN) ("*Water utilities: Guide to applying for a CPCN*"; BC Ministry of Environment, 2007). Consequently, in BC, pumping tests historically have been carried out (and continue to be carried out in some cases) in different ways depending on the purpose of the study. For example, Pacific Hydrology Consultants Ltd. and E. Livingston Associates used a constant drawdown approach, which is suited for estimating the specific capacity of the well, but not the aquifer properties. Standard pumping methods require a constant discharge (pumping rate), and if a constant discharge is not maintained throughout the test, the data can be challenging to analyze. Also, for Salt Spring Island, various consultants did not always use the same field testing approach or a standard analytical method for estimating the aquifer properties (e.g. Cooper-Jacob method), therefore, this study employed different approaches for assessing the results.

Datasets were first classified according to the type of pumping test performed: constant discharge rate or constant drawdown. A variety of approaches were used to determine the aquifer transmissivity (T) from the test data. Only one dataset provided an estimate of Storativity (S); therefore, the focus is on T.

1. If a constant discharge was maintained during pumping, the Cooper-Jacob (Cooper and Jacob, 1946) and/or Theis recovery (Theis, 1935) methods were used. The Jacob method was used for data from the pumping part of the test, while the recovery method was used for data collected once the pump was shut off.

2. If a constant discharge rate was not maintained during pumping, a recovery analysis was done; however, it is more difficult to analyze recovery data when constant discharge is not maintained during pumping (Sterrett, 2007). As discussed below, the resulting T values were consistent with the results of the analyses of the constant discharge tests.

3. Raw data were not available from Waterline Resources so their values are simply reported here. The T values were calculated using the program AQTESOLV (Waterline Resources Inc., 2013). Waterline Resources also calculated T using standard analytical methods (e.g. Cooper-Jacob method) even if constant discharge was not maintained during the pumping test.

4. When the aim of the pumping test was to maintain a constant drawdown in the well (e.g. tests by Pacific Hydrology Consultants Ltd. and E. Livingston Associates), T values were determined by first calculating the specific capacity and then estimating T using a standard equation (see "Specific Capacity Method" section below). When specific capacity had already been calculated by the consultant, this value was used to calculate T.

With the exception of the specific capacity method for estimating T, the analytical methods used to analyze the pumping test data assume the aquifer is confined. Some of the datasets show evidence of purely radial flow, similar to what was found by Allen (1999), and therefore, analysis could be undertaken with standard methods (Theis, Cooper-Jacob, Recovery). However, some datasets show evidence of linear flow within a confined aquifer, as observed by Allen (1999) in other datasets from the Gulf Islands. Allen (1999) determined that if a radial flow period could be identified in the drawdown response of such linear response datasets (i.e. there is a linear portion of the drawdown curve over some interval), a standard method of analysis can be used to estimate the hydraulic properties of the aquifer. This requires selecting an appropriate portion of the curve for analysis (Allen, 1999). Overall, however, the drawdown responses suggest the aquifer behaves in a confined manner.

Some datasets were not usable, and thus were discarded from the analysis.

5.2.3 Aquifer Hydraulic Conductivity

Hydraulic conductivity (K) is normally calculated by a simple division of transmissivity (T) by the saturated aquifer thickness (b), assuming horizontal flow into the well. In the case of a fractured bedrock aquifer, the sum of all the fractures in the well technically represents the aquifer thickness, as the water moves only through the fractures. However, adding all the fracture apertures cannot be done accurately given the complexity of the task. As a result, the saturated thickness of the aquifer is considered based on the aquifer behaving as an equivalent porous medium (EPM). In this case, b is often calculated as the depth of the well minus the depth to water (if the water level lies below the base of the casing) or minus depth of casing (if the water level lies within the casing). Both methods were used in this study depending on the quality of information available. When well depth was not provided in the consultants' reports, a value of 250 ft (76.2 m) was used (a rough estimate of the representative depth of many wells in the Gulf Islands).

5.2.4 Results for Aquifer Properties from Pumping Tests

Transmissivity and hydraulic conductivity values are generally within two orders of magnitude regardless of the method of testing and analysis used (Table 4). Most tests (15 of 23) yield T values on the order of 10^{-5} m^2/s. Eight tests yield T values on the order of 10^{-6} m^2/s. Twenty tests yield K values on the order of 10^{-7} m/s, one on the order of 10^{-6} m/s, and one on the order of 10^{-8} m/s. Again, the high K value is excluded from further analysis. Even if recovery data were not collected following a pumping test in which the discharge was held constant, the T and K values are within the same range as the other values.

Only one pumping test provided an estimate of S (well #2; Lowen Hydrology Consulting, 2000). S was estimated as 3.4×10^{-3}, which falls within the range of S estimated for the sandstone-dominant formations in the Gulf Islands (Allen et al., 2002).

Based on these results, the lithology does not appear to be a dominant factor (Table 4). Within the sandstones (Geoffrey and Extension Formations), T values range from 6.1×10^{-6} to 1.1×10^{-4} m^2/s (K between 8.1×10^{-8} m/s to 1.5×10^{-6} m/s). Within the mudstone, the T values range from 1.0×10^{-5} to 2.6×10^{-5} m^2/s (K between 2.4×10^{-7} and 7.6×10^{-7} m/s). Despite the lack of consistency in the field methods used by the different consultants, the T and K values vary over a limited range.

This study estimated T directly from the pumping test and then used b (for each well individually) to calculate K. For the sandstones, the differences in the range of the log-transformed values of T (-5.21 – (-3.96) = 1.25) and K (-7.09 – (-5.82) = 1.27) are almost identical, indicating that the direct estimation of T and the calculated K are entirely consistent. For the mudstones, the differences for T and K are 0.41 and 0.50, respectively.

Table 4. Summary table of T and K values for all constant discharge and constant rate usable pumping tests.

Consultant	Year of Testing	Well ID	Analytical Method	Specific Capacity (m^3/s/m)	T (m^2/s)	K (m/s)	Formation	Lithology
E. Livingston Associates	1974	1	Recovery	NR	1.9E-05	2.7E-07	Geoffrey	Sandstone or Sandstone Conglomerate
			Specific capacity	2.5E-05	3.5E-05	5.1E-07		
		2	Jacob	NR	3.04E-6[c]	1.9E-7		
	1975	2	Recovery	NR	6.4E-06	8.1E-08		
			Specific capacity	1.5E-05	2.1E-05	2.6E-07		
Pacific Hydrology Consultants Ltd.	1979	77-5	Recovery	NR	4.4E-05	6.1E-07	Geoffrey	Sandstone
			Specific capacity	8.0E-05	1.1E-04	1.5E-06		
	1992	1	Specific capacity	1.4E-05	1.9E-05	2.4E-07	Haslam	Mudstone
		2	Specific capacity	1.1E-05	1.5E-05	NA		
Lowen Hydrology Consulting	2000	2	Jacob	NR	2.6E-05	4.8E-07	Ganges	Mudstone
		3	Jacob	NR	1.0E-05	4.1E-07		Mudstone
		3	Recovery	NR	1.9E-05	7.6E-07		Mudstone
Gooding Consulting	2011	WTN[a] 14138	Jacob	NR	1.4E-05	1.6E-07	Extension	Sandstone Conglomerate
Waterline Resources Inc.	2012-13	1	Recovery	NR	8.1E-06	1.3E-07	Geoffrey	Sandstone
			Cooper-Jacob	NR	2.3E-05	3.7E-07		
			Recovery	NR	7.8E-06	1.2E-07		
			Cooper-Jacob	NR	7.8E-06	1.2E-07		
		2	Recovery	NR	1.1E-05	2.6E-07		
			Cooper-Jacob	NR	1.0E-05	2.5E-07		
			Recovery	NR	6.1E-06	1.5E-07		
		Tag 97146[b]	Cooper-Jacob	NR	8.3E-06	1.8E-07		
			Recovery	NR	7.9E-06	1.8E-07		
			Cooper-Jacob	NR	2.4E-05	5.3E-07		

[a] WTN = BC Well Tag Number; [b] Referred to as John's well in the original document; [c] value excluded; NR = not relevant; NA = not available.

5.2.5 Limitations and Uncertainties in Pumping Test Results

Strict conditions are listed for the standard pumping test analysis methods used in this study, such as the aquifer has to be confined top and bottom, and there is no recharge to the aquifer (Theis, 1935). The aquifers behave as though they are confined during these relatively short duration tests (most of them last < 5 days), based on the overall radial (Theis-like) behaviour or linear flow within a confined aquifer. Longer duration tests, however, have shown evidence of unconfined behaviour (Allen, 1999). Being of short duration, the pumping tests do not show evidence of recharge or leakage from above. Other conditions such as a horizontal formation of infinite areal extent and uniform thickness, homogenous and isotropic, horizontal flow to the pumping well and fully penetrating wells (of infinitesimal diameter) (Cooper and Jacob, 1946; Fetter, 2001) are also not strictly held. The fractures are not uniformly distributed, particularly at the well scale, and the aquifer is undoubtedly heterogeneous and perhaps anisotropic. Also, not all pumping tests were conducted at a constant pumping rate. Nevertheless, as shown above, the T and K values obtained from the various analytical methods show remarkable consistency.

5.3 Tidal Response Data Analysis

5.3.1 Tidal Monitoring Program - June 2013

With the aim of complementing the existing hydraulic properties dataset for Salt Spring Island, tidal response tests were performed in June 2013 (June 21-28). Coupled with tidal heights, water levels in wells can be used to estimate the hydraulic diffusivity (D) of an aquifer at a regional scale (Jha et al., 2008). D is defined as the ratio of transmissivity to storativity (T/S) or the ratio of hydraulic conductivity to specific storage (K/Ss).

A list of 11 unused wells was provided by the Salt Spring Island Water Council. Seven wells proved unsuitable for the study; these were either shallow dug wells, flowing artesian wells, or wells that were not located near the coast and would not have a tidal signal. Ultimately, five wells were selected for tidal monitoring. These wells were either open (no pumping equipment) or contained submersible pumps; some were located in a pump house and others had no overhead protection.

The wells, TA-1 to TA-5, are all located within a few hundred metres of the coast (Table 5; Figure 10). Pressure transducers with dataloggers (HOBO U20 Water Level Data Loggers - 4 m range) were installed in each of the five wells. To account for atmospheric pressure changes, pressure transducers (barologgers) were installed in two wells to strictly measure atmospheric pressure during the monitoring period (Table 5; Figure 10). These wells (TA-1 and TA-5) are located in the north and south of the island, in Booth Bay and Fulford Harbor, respectively. All transducers were programmed to record pressure and temperature every five minutes.

Water levels recorded in provincial observation wells (Observation wells 281 and 373) located on Salt Spring Island were also considered in this analysis (Table 5; Figure 10). Water level data were extracted from the BC Observation Well Network (BC Ministry of Environment, 2013b) for June 21 to 28 (2013), which corresponds to the field monitoring period.

Three tide gauges are located around Salt Spring Island: Fulford Harbour, Ganges Harbour and Burgoyne Bay (Figure 10). Tidal heights were downloaded from WWW Tide and Current Predictor prior to the field visit (Pentcheff, 2013). Two titanium cased pressure transducers (HOBO U20 Water Level Data Loggers - 4 m range), Ocean-1 and Ocean-2, were installed in the ocean to measure actual tide elevation in areas where tide gauges data are not available (Table 5; Figure 10). The transducers were first inserted in a protective housing and then strapped to the base of pier posts. These transducers were also programmed to record pressure and temperature every five minutes.

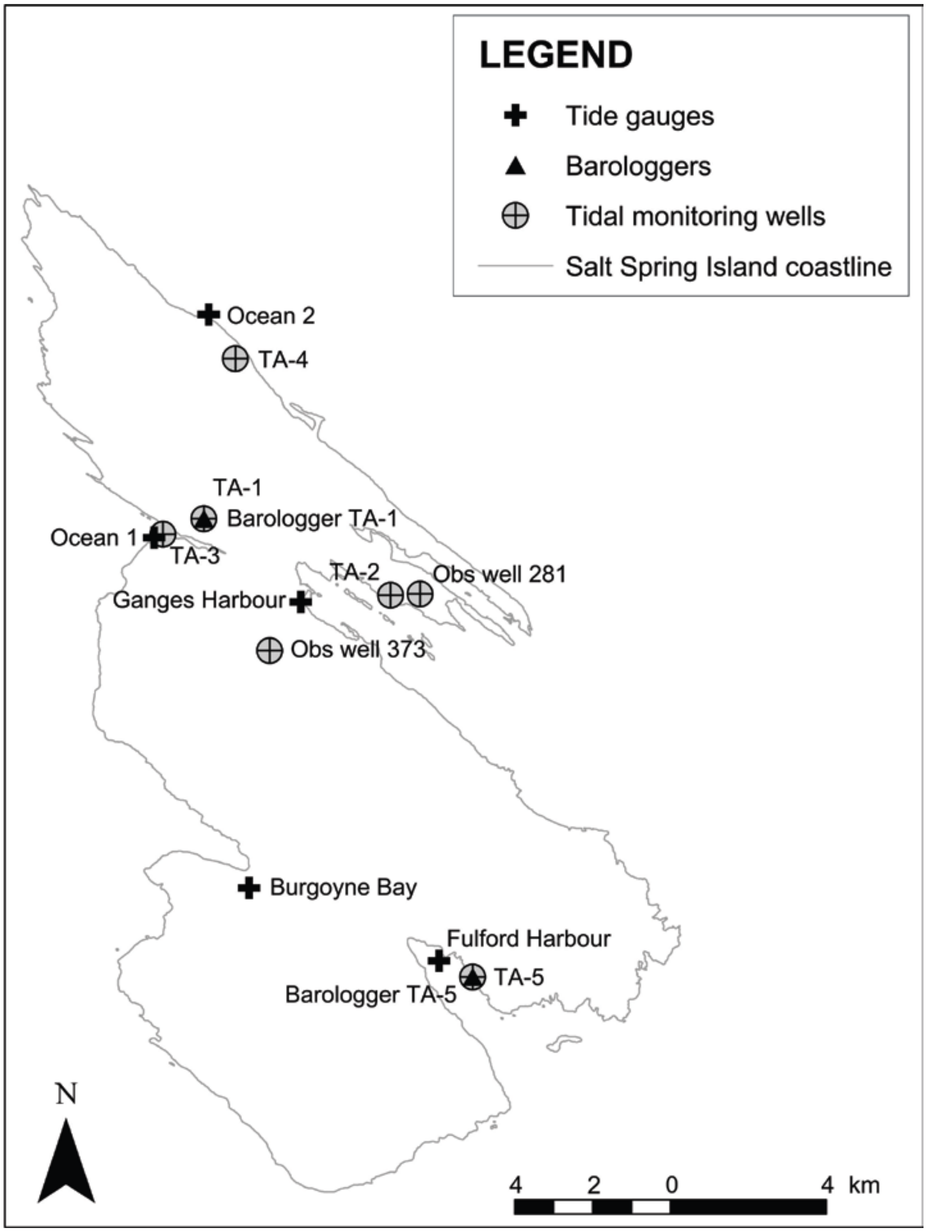


Figure 10. Locations of tidal monitoring wells, observations wells, barologgers, and tide gauges including the two additional tide height stations.

Table 5. Transducer location, well information and monitoring period.

Well ID	Location	Depth to Water (m)	Ground Elevation (m)	Well Distance to Coast (m)	Depth of Well (m)	Monitoring Period
TA-1	Baker Road	1.855	54	580	NA	June 22-26, 2013
Barologger TA-1		NR	54	580	NR	June 22-26, 2013
TA-2	Ganges Road	2.082	17	76	17	June 22-26, 2013
TA-3	Swan Point	5.4	10	83	75	June 22-27, 2013
TA-4	Hedger Road	6.05	40	305	17	June 24-26, 2013
TA-5	Reginald Hill	0.725	27	70	91	June 24-27, 2013
Barologger TA-5		NR	27	70	NR	June 24-27, 2013
Obs well 281	Long Harbour Road	NR	NA	375	107	June 21-28, 2013
Obs well 373	Mt Belcher Heights	NR	NA	1445	98	June 21-28, 2013
Ocean 1	Booth Bay	NR	NR	NR	NR	June 22-27, 2013
Ocean 2	Fernwood Point	NR	NR	NR	NR	June 22-26, 2013

NA= Not available; NR= Not relevant.

5.3.2 Tidal Data Analysis Approach

A tidal cycle is characterized daily by a 'high' high tide, a 'low' high tide, a 'high' low tide and a 'low' low tide, which is called a mixed tide. In coastal areas, tidal fluctuations influence groundwater levels dynamically. The water level in a well rises and falls with the tides (Figure 11), although the amplitude of the oscillation is damped and there is a delay (lag) in the response. The amplitude damping and lag of groundwater response to tides depends on the diffusivity (D=T/S) (Jacob, 1950). Thus, tidal response testing can be used to estimate the hydraulic properties of the aquifer at a regional scale (Rotzoll et al., 2013).

Both the Amplitude and Time-Lag methods were used to analyze the tidal response data in this study (Jacob, 1950). When a tidal oscillation was not observed, the data were not used for analysis. Local effects such as pumping can also be detected in wells. When local effects were strong enough to mask tidal signals, water level data could not be used.

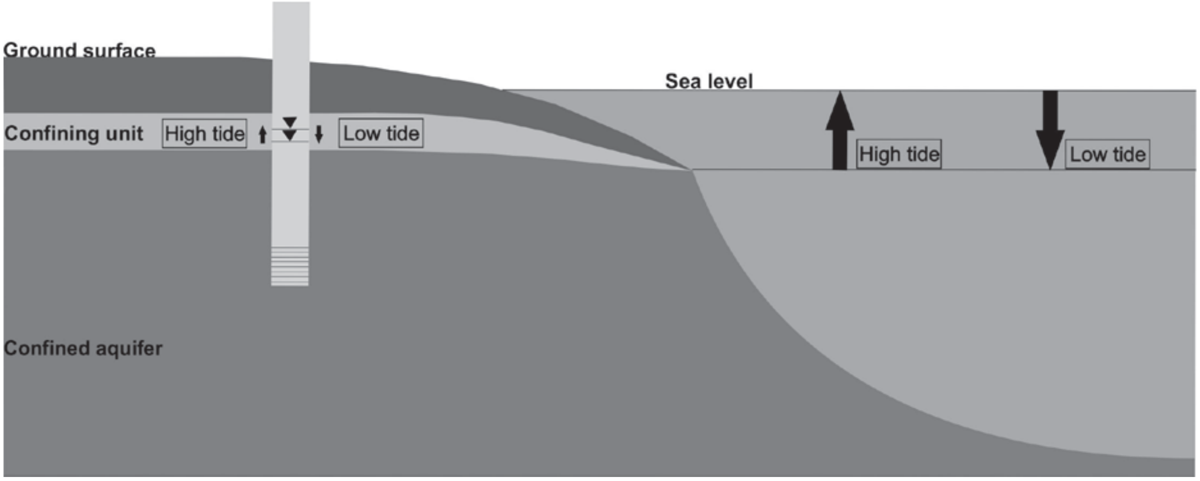


Figure 11. Tidal signal in a well responding to tidal fluctuations. The amplitude damping and time lag depend on the hydraulic properties of the aquifer.

Analysis of tidal response data was performed over one period of the water level variation in the well and the corresponding tidal period (Figure 12). Water levels in the wells and the tidal heights were first normalized such that they oscillate around the respective average levels. The tidal period (t_p) was found by measuring the time between the 'high' high and 'low' high tide. The tidal period is approximately 12 hours. The tidal period of some wells in this study was as short as 8.7 hours as opposed to 12 hours. Yet, this does not appear to have a major effect of the resulting diffusivity values (see results below). The amplitudes of the water level in the wells (H_x) and the tides (H_0), and the time lag (τ) between the tide and water level peaks were calculated using data collected by the pressure transducers (or the predicted tide level for permanent tide gauges at Booth Bay or Fernwood Point). Finally, the distance of the well from the coast (x) was determined in ArcGIS using UTM coordinates measured in the field. For the observation wells, the UTM coordinates were retrieved from the WELLS database (BC Ministry of Environment, 2013a).

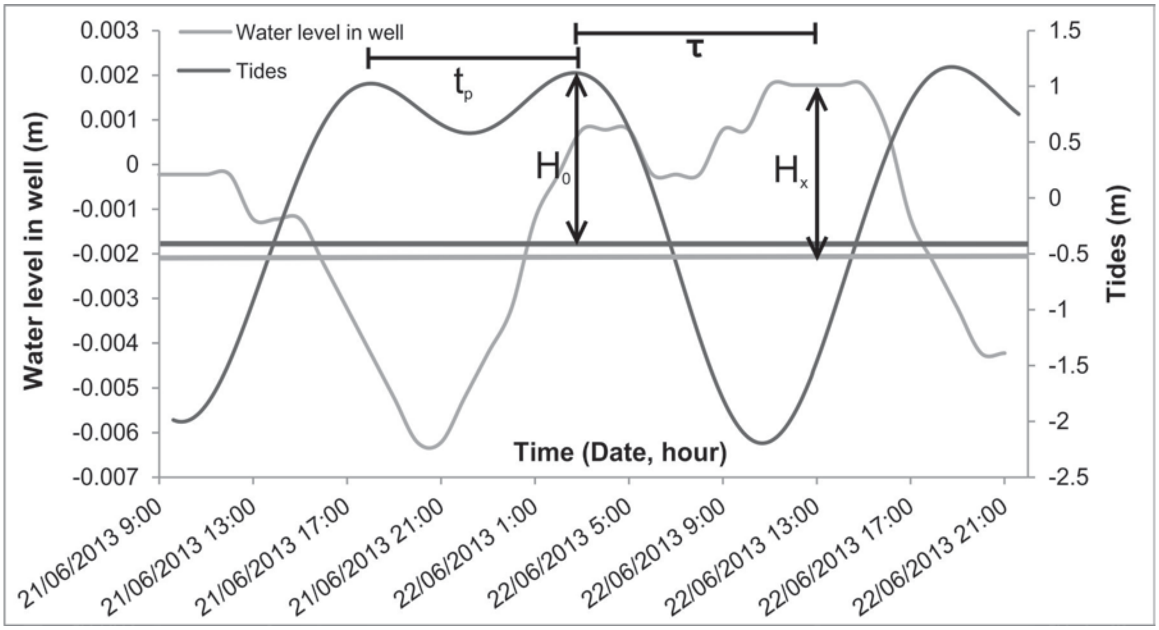


Figure 12. Illustration showing the variables used to calculate the diffusivity using the amplitude and time-lag methods. The light grey curve represents the water level in the well; the dark grey, the tide. Data from observation well 281.

5.3.3 Estimation of Transmissivity and Hydraulic Conductivity

Transmissivity (T) is calculated by multiplying diffusivity (T/S) by an independent estimate of storativity (S). Allen et al. (2002) compiled short and long duration pumping test data for the Gulf Islands. In the current study, the geometric mean of S from the compiled data was calculated for each geological formation, regardless of whether the tests were of short or long duration. The average S ($2.9\text{x}10^{-4}$) value for sandstone-dominant formations was calculated from 19 pumping tests in the Gulf Islands (Allen et al., 2002). Very few S values are estimated for mudstone-dominant formations (1) and igneous rock (4) in the Gulf Islands region and they fall within the range estimated for sandstone-dominant formations ($2.4\text{x}10^{-7}$ to $3.7\text{x}10^{-2}$). Therefore, an S value of $2.9\text{x}10^{-4}$ was also used to estimate T for the mudstone-dominant formations and the igneous rocks. No tidal tests were conducted in sandstone-dominant formations.

Hydraulic conductivity (T/b) was estimated using the saturated thickness of the aquifer as the measured length between the bottom of the well and the groundwater level (Table 5). Using this approach, it is assumed that all of the fractures and the unfractured rock matrix behave as an Equivalent Porous Media (EPM). This is necessary because detailed information on fractures is not available for each well. Therefore, the K value represents the bulk fractured material and not that of the individual fractures, which is appropriate for a regional scale assessment of the aquifer.

4.2.4 Results for Aquifer Properties from Tidal Response Tests

Tidal signals were detected in three wells (TA-3, TA-5 and observation well 281) out of the seven wells available on Salt Spring. Four other wells (TA-1, TA-2, TA-4 and observation well 373) did not show a consistent tidal signal, and local effects, such as pumping, are likely the cause of groundwater fluctuations in these wells (see Larocque, 2014).

Diffusivity values calculated using the Amplitude method range from 0.025-0.35 m^2/s, and from 0.25-2.23 m^2/s from the Time-Lag method. They vary by one order of magnitude between the two methods among the three wells (Table 6).

Table 6. Tidal analysis variables and diffusivity (T/S) from amplitude and time lag methods.

Well ID	**Amplitude of Sea Tide**	**Tidal Period**		**Time Between Tide Peak and Groundwater Level Peak**	**Amplitude at Point x**	**Approximate Distance to Coast**	**Diffusivity (m^2/s)**	
	h_o (m)	**hours**	**t_p (s)**	**τ (s)**	**H(x) (m)**	**x (m)**	**Amplitude (T/S)**	**Time Lag (T/S)**
TA-3	1.86	9.92	35700	6900	0.0135	83	0.025	0.41
TA-5	1.53	10	36000	2520	0.186	70	0.10	2.23
Obs well 281	1.66	8.67	31200	37140	0.003	375	0.35	0.25

Transmissivity varies within three orders of magnitude (Table 7) depending on the test method. Using the amplitude method T ranges from 7.2x10^{-6} to 1.0x10^{-4} m^2/s, and using the time lag method from 7.3x10^{-5} to 6.4x10^{-4} m^2/s. Hydraulic conductivity also varies within three orders of magnitude. Using the amplitude method, K ranges from 1.0x10^{-7} to 1.0x10^{-6}m/s, and using the time lag method from 7.3x10^{-7}to 7.1x10^{-6} m^2/s. The time lag method yielded higher values (for T and K) by at least one order of magnitude in two wells (TA-3 and TA-5), but very similar values in observation well 281.

Overall, T in the various rock types (mudstone-dominant and igneous) tested on Salt Spring Island appear to be mainly on the order of 10^{-5} to 10^{-4}m^2/s. Hydraulic conductivity is on the order of 10^{-7} to 10^{-6} m^2/s for these rock types using both analysis methods.

Table 7. Transmissivity and hydraulic conductivity calculated from diffusivity.

Well	Transmissivity (T=D*S)		Saturated Thickness[a]	Hydraulic Conductivity[b]		Formation	Lithology
	Amplitude T (m^2/s)	Time Lag T (m^2/s)	b (m)	Amplitude K (m/s)	Time Lag K (m/s)		
TA-3	7.2E-06	1.2E-04	70	1.0E-07	1.7E-06	Ganges	Mudstone
TA-5	3.0E-05	6.4E-04	91	3.3E-07	7.1E-06	Saltspring Intrusions	Granite
Obs Well 281	1.0E-04	7.3E-05	100	1.0E-06	7.3E-07	Northumberland	Mudstone

[a] Estimated well depth below water table; [b] Estimated b for individual wells.

5.3.4 Limitations and Uncertainties in Tidal Response Test Results

The Jacob solution for tidal response analysis was developed for simple aquifer geometry: a one-dimensional, homogeneous, isotropic, confined and semi-infinite aquifer with a sharp ocean boundary (Rotzoll et al., 2013). The one order of magnitude range of T and K between rock types is likely caused by heterogeneity. The transmissivity for the three wells, however, is also uncertain because an average S value for sandstone-dominant formations was used in the calculation.

5.3.5 Comparison of Hydraulic Properties with the Other Gulf Islands

Several studies have focused on characterizing the hydraulic properties of the bedrock aquifers in the Gulf Islands (BC) (Allen et al., 2002; Mackie, 2002; Surrette, 2001). In this section, the results from Salt Spring Island are compared with pumping (Allen et al., 2002) and tidal response test results (Scibek et al., 2013; BC Ministry of Environment, 2013b; Saturna Island wells, 1998 and 2001) collected on neighboring Gulf Islands. A comprehensive analysis is provided by Larcoque (2014). The results are summarized briefly here.

Pumping Tests

The pumping test analysis results are from a single source, a study conducted in 2002 by Simon Fraser University (Allen et al., 2002). Pumping tests were conducted on Mayne, Galiano, Denman, Pender and Saturna Islands. The tests were conducted in the Gabriola, Geoffrey, Spray, DeCourcy, Cedar District and Protection Formations. The Spray and Cedar District Formations are mudstone-dominant, while the others are sandstone-dominant. In total, test data were available from 11 long-duration and 20 short-duration tests, both including single and multiple wells tests. A consistent method of analysis (Allen, 1999) was used to determine T and S. On Salt Spring Island, pumping tests were conducted in the Geoffrey, Extension, Ganges and Haslam Formations, as discussed above. Geoffrey and Extension are sandstone-dominant formations, while the Ganges and Haslam are mainly mudstone-dominant.

The average transmissivity value from the pumping tests for sandstone is 1.4x10^{-5} m^2/s and 1.9x10^{-5} m^2/s, and 1.6x10^{-5} m^2/s for mudstone on Salt Spring and the Gulf Islands, respectively (Table 8). The average hydraulic conductivity value for sandstone is 2.4x10^{-7} m/s and 2.5x10^{-7} m/s, and 3.6x10^{-7} m/s and 4.7x10^{-7} m/s for mudstone on Salt Spring and the Gulf Islands, respectively. This comparison shows consistency among results despite the limitations and uncertainties discussed in Section 5.3.4.

Storativity values cannot be assessed as no value could be estimated from the pumping tests conducted on Salt Spring Island. Overall, the average transmissivity of the Salt Spring Island aquifers is very similar to transmissivity values calculated on the Gulf Islands by Allen et al. (2002).

Table 8 ***Average transmissivity and hydraulic conductivity estimated from pumping tests by rock type.***

	Lithology	
Location	**Sandstone**	**Mudstone**
	T (m^2/s)	
Salt Spring	1.4E-05	1.6E-05
Gulf Islands	1.9E-05	1.6E-05
	K (m/s)	
Salt Spring	2.4E-07	3.6E-07
Gulf Islands	2.5E-07	4.7E-07

Tidal Response Tests

Scibek et al. (2013) conducted an analysis of tidal response data as part of a larger project that consisted of developing hydrogeological conceptual models and water budgets for Gabriola, DeCourcy and Mudge Islands. Transmissivity was calculated assuming a storativity value of 1x10^{-4}. Hydraulic conductivity (K=T/b) was calculated assuming the water column depth below the water table as the thickness of the aquifer. In order to complement these existing tidal response datasets, observation well water level data from Saturna, Pender, Mayne and Galiano Islands, along with the tidal response data collected on Saturna Island Salt Spring Island were also analyzed. All data were analyzed using both the Amplitude and Time-lag methods (Jacob, 1950).

Transmissivity is similar between Salt Spring Island and the other Gulf Islands for mudstone-dominant formations, but also between all formation types. All transmissivity values range between 2.2x10^{-5} and 1.4x10^{-3} m^2/s (Table 9). Transmissivity calculated for igneous rock on Salt Spring is within the same range as for the other Gulf Islands. Values obtained are also similar to sandstone-dominant values on neighbouring islands, which range between 2.5x10^{-7} and 1.4x10^{-5} m/s. Again, igneous rock yields comparable values to other formation types with 3.3x10^{-7} and 7.1x10^{-6} m/s (Table 9).

Table 9 *Average transmissivity and hydraulic conductivity estimated from tidal response tests by rock type.*

	Lithology					
Location	**Sandstone**		**Mudstone**		**Igneous**	
	T (m^2/s)					
	Amplitude	**Time Lag**	**Amplitude**	**Time Lag**	**Amplitude**	**Time Lag**
Salt Spring	NA	NA	2.7E-05	9.2E-05	3.0E-05	6.4E-04
Gabriola	5.2E-05	2.7E-04	3.0E-05	1.4E-03	NA	NA
Saturna	1.3E-04	5.2E-05	NA	NA	NA	NA
Pender	NA	2.2E-05	1.6E-04	8.8E-05	NA	NA
Mayne	NA	NA	NA	NA	NA	NA
Galiano	NA	1.6E-04	NA	NA	NA	NA
	K (m/s)					
	Amplitude	**Time Lag**	**Amplitude**	**Time Lag**	**Amplitude**	**Time Lag**
Salt Spring	NA	NA	3.2E-07	1.1E-06	3.3E-07	7.1E-06
Gabriola	2.4E-06	1.4E-05	1.2E-06	7.0E-05	NA	NA
Saturna	1.6E-06	7.5E-07	NA	NA	NA	NA
Pender	NA	2.5E-07	1.8E-06	9.6E-07	NA	NA
Mayne	NA	NA	NA	NA	NA	NA
Galiano	NA	2.1E-06	NA	NA	NA	NA

NA – Not available

6 Recharge

6.1 Previous Recharge Studies in the Gulf Islands

Determining recharge in the Gulf Islands is a challenge. Recharge is believed to occur mainly through sub-vertical fractures, joints and faults located at the ground surface at regional and local topographic highs. It varies spatially due to the complexity of the fractured bedrock and connectivity of the fractures (Allen, 2012). Previous studies have attempted to estimate recharge to aquifers in the Gulf Islands at an island scale (Foweraker, 1974; Hodge, 1977 and 1995; Liteanu, 2003; Allen and Liteanu, 2006; Trapp, 2011; Scibek et al., 2013) and for the Gulf Islands more broadly (Appiah-Adjei, 2006; Denny et al., 2007). Various methods were used: hydrograph analysis, water balance modeling (using the HELP hydrologic model described below), the Water Table Fluctuation (WTF) method, and 3-D numerical groundwater modeling. The range in recharge values varies between 1 and 62.7% of mean annual precipitation, and the mean values from these studies range from 2.6 and 45% of mean annual precipitation (Table 10).

Table 10. Recharge estimates from previous studies in the Gulf Islands.

Study	Study Area	Method	Recharge Estimate (% of Precipitation)	
			Mean	Range
Foweraker (1974)	Mayne Island	nr	3	nr
Hodge (1977 and 1995)	Salt Spring Island	Hydrograph	2.6[a]	1-4.4[a]
Appiah-Adjei (2006)	Gulf Islands	HELP	45	20-60
Denny et al. (2007)	Gulf Islands	HELP	36.5[b]	12.1-62.7[b]
Liteanu (2003)	Saturna Island	3-D numerical modeling	20	10-50
Trapp (2011)	Saturna Island	HELP	56	5-56
Scibek et al. (2013)	Gabriola Island	WTF method	10[c]	1-20[c]

[a] The mean and range are estimated based on the total precipitation at St. Mary Lake weather station in 2012 and the amount of precipitation recharging the aquifer used by Hodge (1995) (e.g. (25.4 mm / 974.2 mm) * 100 = 2.6 %); [b] This estimate is from a series of models incorporating surficial sediment and bedrock within a modeled soil column; [c] Values estimated for Gabriola Island using the Water Table Fluctuation (WTF) method; nr: method not reported.

The method used by Foweraker (1974) is unknown, but the estimated 3% (25.4 mm) from that study was used in the 1977 “Groundwater Conditions on Saltspring Island” report (Hodge, 1977). Assuming a specific yield of the order of 10^{-4} and using the Water Table Fluctuation (WTF) method with water levels in observation well 281 for the period spanning 1984 to 1993, Hodge (1995) determined that between 1 and 43.2 mm of precipitation recharges groundwater in that area. This range encompasses Foweraker’s estimate and supports this value at a regional scale. Scibek et al. (2013) estimated a range of recharge of 1-20% of precipitation on Gabriola Island using the WTF method. A specific yield value range of 0.001-0.01 was used. Scibek et al. (2013) compiled estimates of recharge for the Gulf Islands more broadly, suggesting that recharge is likely between 10% and 45%, with 20% being the most likely estimate.

Appiah-Adjei (2006) and Denny et al. (2007) both used the US Environmental Protection Agency’s (US EPA) Hydrological Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994) to estimate recharge. The model uses a stochastic weather series to drive percolation through representative soil columns incorporating surficial sediments/soils and bedrock. The mean and range estimated from these two studies are similar despite the higher values estimated by Appiah-Adjei (2006).

Three-dimensional groundwater flow models have also been used to validate / test previous recharge estimates. Liteanu (2003) used a value of 20% of precipitation, and range of 10-50%. Recharge values used by Trapp (2011) used a value of 56% of precipitation to calibrate models to hydraulic head observations, seasonal water table measurements and geochemistry.

For the reported estimates, it is noted that the WTF method relies strongly on the estimated specific yield (Sy) value, and there are few estimates of this aquifer parameter from long term pumping test data. An order of magnitude difference in Sy leads to a direct order of magnitude difference in the estimated recharge. Based on fracture density and rough aperture estimates (Surrette et al., 2008), Sy values likely range from 0.001 (0.1%) to 0.10 (10%), with the most likely value at around 0.01 (1%).

Overall, there remains considerable uncertainty in these estimates and continued research is underway to try and constrain recharge estimates using a 3-D coupled land surface-hydrologic model for Gabriola Island.

6.2 Recharge Estimate for Salt Spring Island

The HELP model was used to estimate groundwater recharge on Salt Spring Island for this study the HELP model, which simulates 1-D vertical groundwater flow through the unsaturated zone. The HELP model was initially developed to evaluate the performance of different landfill layer configurations by comparing water balance components (Schroeder et al., 1994), but has been used in several recharge studies.

Climate data were derived from the Victoria weather station within the UnSat Suite weather station database. The database climate normals were adjusted using monthly means for daily mean temperature, precipitation and wind speed, and seasonal relative humidity measured at the Victoria International Airport weather station during the 1981-2010 period. The HELP module was then used to quantify the water balance in a 20-m percolation column comprised of glacial till/gravelly sand overlying bedrock (Figure 13).

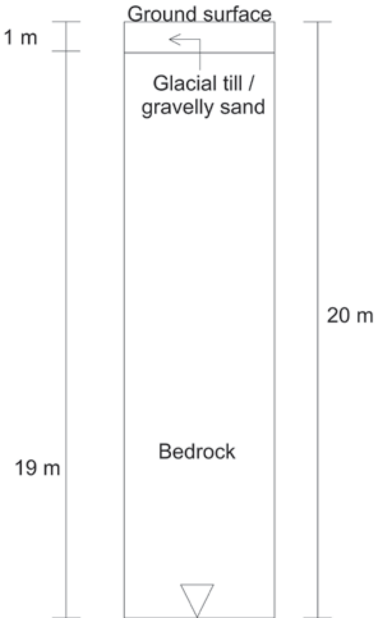


Figure 13. Vertical percolation column used in the HELP recharge simulation for Salt Spring Island.

This column depth (20 m) represents the average depth to the water table measured for all Salt Spring Island wells located more than 100 m above sea level. These measurements are a compilation from many sources: well drilling (BC Ministry of Environment 2013a), Rick Gilleland (Salt Spring Island Water

Council, personal communication) and 2013 field work. Four main soil classes (clay, topsoil, glacial till and gravelly sand) were identified by Appiah-Adjei (2006) for the Gulf Islands based on GIS soil maps and the provincial WELLS database (BC Ministry of Environment 2013a). From the soil map (Appiah-Adjei, 2006), glacial till and gravelly sand are dominant at higher elevations on Salt Spring Island. Soil properties (Table 11) were estimated based on the average soil properties for the two dominant soil types as reported by Appiah-Adjei (2006). The saturated hydraulic conductivity of the bedrock was the average of sandstone and mudstone from the pumping test analysis. The other bedrock properties (porosity, field capacity, wilting point) are highly uncertain because no studies appear to have measured these parameters in bedrock. Nevertheless, they are consistent with the values used by Appaih-Adjei (2006).

Table 11. Soil and bedrock properties assigned to the percolation column.

	Soil	Bedrock
Thickness	1 m	19 m
Porosity	0.39 vol/vol	0.1 vol/vol
Field capacity	0.069 vol/vol	0.02 vol/vol
Wilting point	0.029 vol/vol	0.002 vol/vol
Initial soil water content	0.1165 vol/vol	0.0475 vol/vol
Saturated hydraulic conductivity	0.1 cm/sec	21.96 cm/day

Parameters that influence evapotranspiration include maximum leaf area index, start and end of growing season, evaporative depth, and average wind speed (Table 12). These values are consistent with those used by Appaih-Adjei (2006). The land surface was assigned zero slope to simulate maximum recharge. The subsurface inflow (into the column) is 0 cm/day; therefore, no water is gained from the sides. The flow is vertically downward through the column and water can only exit from the base of the column.

Table 12. Evapotranspiration parameters.

Maximum leaf area index	4
Start of growing season	123 julian days
End of growing season	282 julian days
Evaporative depth	0.2 m
Average wind speed	9.11 km/h

One hundred years of climate data were generated using the embedded stochastic weather generator, and the average water balance results extracted. The water balance comprises values for precipitation, surface runoff, evapotranspiration, percolation through the soil column and water storage closure. The recharge (percolation through the soil column) was estimated at 71.86%. Water balance results are shown in Table 13.

Table 13. Water balance results from HELP modeling.

	mm	m^3	%
Precipitation	864	8635	100
Runoff	0	0	0
Evapotranspiration	247	2470	29
Percolation	621	6205	72
Change in water storage	-4	-39	-1

The recharge value estimated for Salt Spring (72% of total annual precipitation) is higher than reported in previous studies. However, it is only approximately 10% higher than the estimates reported for the other HELP modeling studies (Table 10). Appaih-Adjei (2006) obtained the lowest recharge values for columns where low permeability clay overlies the bedrock. In this study, the highest possible permeability was used (glacial till and gravelly sand). So, the estimate is likely at the upper extreme. Regardless, the values simulated using HELP appear to be very high.

The HELP model is a vertical percolation model and it works best for flat topography. Even including a surface slope does not significantly reduce the recharge and produce higher runoff (Allen, personal communication based on numerous sensitivity analyses). So, it is likely that this model is not appropriate for the steep topography of the Gulf Islands, where surface runoff and interflow on top of the bedrock surface are known to take place based on observations of water seeping along the soil-bedrock contact during rain events. A 3-D model that captures topography and can simulate saturation overland flow conditions would be more appropriate.

7 Groundwater Flow Regime

7.1 Overview

In the southern Gulf Islands, surficial sediments do not provide significant amounts of groundwater other than in areas where they are thicker (Hodge, 1995); fractured rock represents the main aquifer material. It has been interpreted that the coarse-grained formations have relatively poor intergranular permeability, and that most of the water flow within both fine- and coarse-grained formations is related to fracturing. Nevertheless, it is believed some water can be transmitted through sandstone or shale inter-grain pores (Hodge, 1995). Overall, the groundwater is transmitted through a complex system of faults, bedding planes, joints and fractures (Hodge, 1995; Kohut et al., n.d; Mackie, 2002; Surrette et al. 2008).

Recharge to the Gulf Islands aquifers (as discussed in more detail in Section 6) is dominantly by infiltration of precipitation (Allen and Suchy, 2001; Appaih-Adjei, 2006). Groundwater levels are generally higher at high topographic elevation. Recharge dominates in the highlands and the groundwater eventually discharges locally into streams (as baseflow) or lakes, while some will flow deeper as part of the regional groundwater flow system (Hodge, 1995), ultimately discharging into the ocean (Kohut, 1960). In these coastal aquifers, the transition zone is considered to be present where freshwater and seawater mix (see Figure 1).

The bedrock aquifers on Salt Spring Island are considered to be moderately to highly vulnerable based on level of development and susceptibility to contamination (Data BC (n.d.), http://maps.gov.bc.ca/ess/sv/imapbc/).

7.2 Island Scale Groundwater Flow

A representation of island-scale groundwater flow (Figure 14) was estimated using water table data from various sources.

1. The WELLS database (BC Ministry of Environment, 2013a). Depth to water is routinely measured after drilling, and these static water level measurements are often the only source of information available for regional studies. Because wells are drilled over a long time period and at different times of the year, there is some error in using them as representative of current conditions. Also, water levels may still be recovering from pumping and the water depth may be underestimated.
2. Monthly datasets for multiple years were available for eight areas across Salt Spring Island for a total of 17 wells (Rick Gilleland, Salt Spring Island Water Council, personal communication). For each well, the average depth to water was calculated using all available measurements.
3. Depth to water data for provincial observation wells (#281, #373) (BC Ministry of Environment, 2013b). Average depth to water was calculated from hourly measurements for 2012.
4. Depth to water measurements from the 2013 field season.

Measurements from Rick Gilleland, the provincial observation wells, and the 2013 field season were all made from ground surface. Measurements from the WELLS database are assumed to be from top of casing, but casing height is not reported. As a result, a well casing elevation of about 0.3048 m (1 ft) was assumed as representative of most wells on the Gulf Islands. This value was used to correct the measured values to ground level. Ground elevation at each well was calculated using LiDAR maps (Bednarski and Rogers, 2012). Depth to water was then subtracted from ground elevation to estimate water elevation above sea level. Extrapolation to the whole island was done using the natural neighbour tool in ArcGIS. Despite the various sources and their quality, the water table map produced is reasonable and follows the general topography of Salt Spring Island.

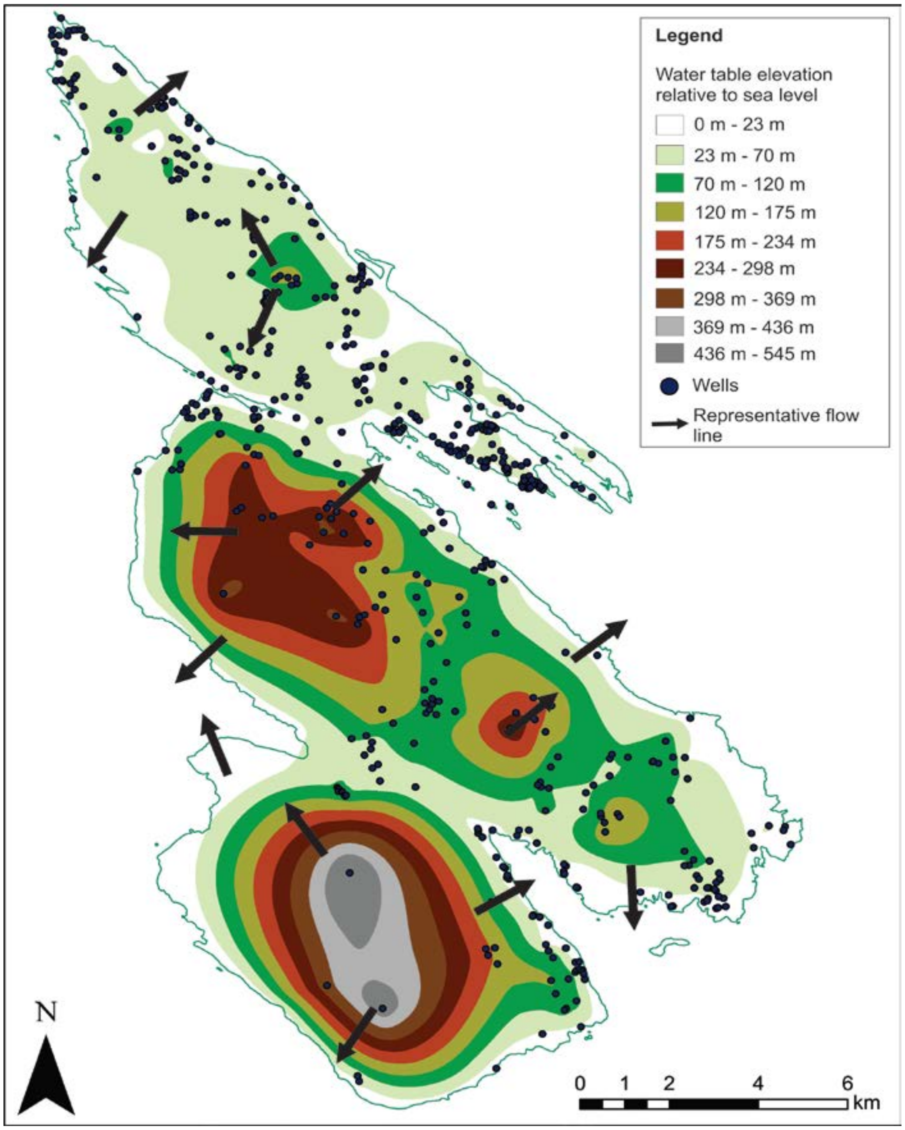


Figure 14. Water table elevation map of Salt Spring Island. The elevation is relative to sea level. A generalized representation of the groundwater flow lines is shown.

Representative groundwater flow lines are drawn simply on the basis of water table topography. As expected, groundwater flows from high elevation to low at a regional scale. Locally, however, groundwater can be expected to discharge into streams and lakes. Differences in flow line direction due to geological contrasts are not reflected in this map. Where there is an abrupt change in permeability, flow lines will deflect. Also, the flow lines do not represent the likely pathways along major faults.

7.3 Seasonal Variations of Groundwater Levels

Water level data are available for two observation wells on Salt Spring Island (#281 and #373). Both wells are drilled in sedimentary rock (#281 in shale and #373 in conglomerate and sandstone); both wells are located in the north/central part of the island (Figure 15).

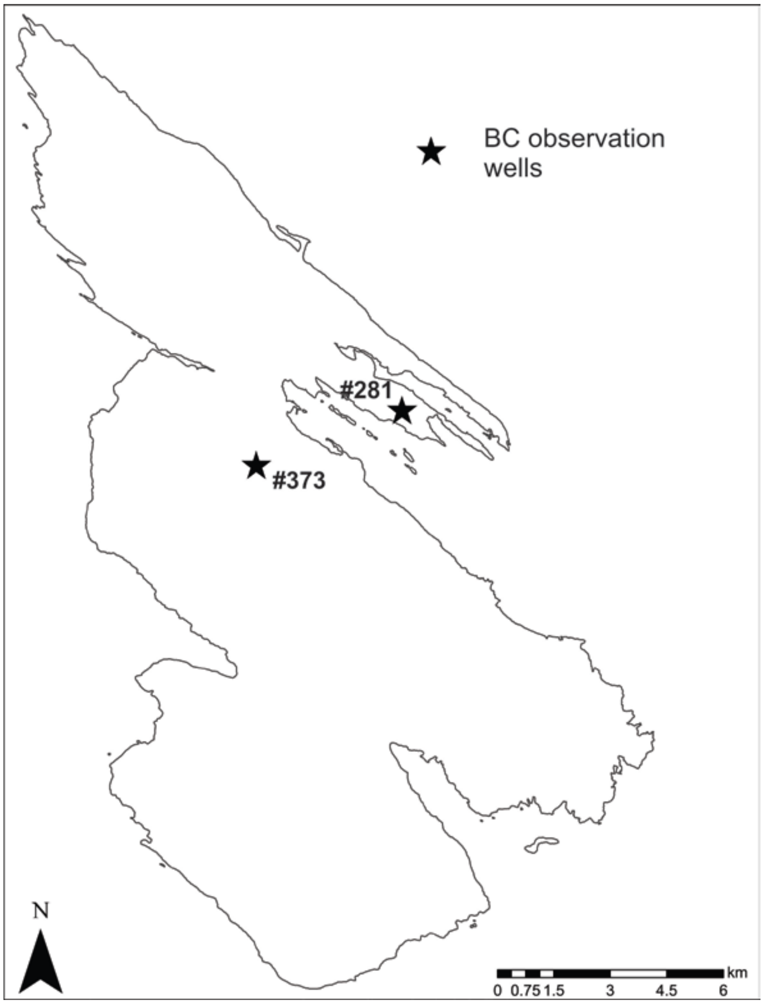


Figure 15. Location of the two BC observation wells on Salt Spring Island.

As mentioned previously, summers are cool and dry, winters are mild and wet. This climate explains low water tables in the summer and higher water tables in the fall and winter months as shown for 2012 in Figure 16. From late June to September, there is a general decline in water level, from about 1 to 0 m (relative to the deepest recorded water depth). At the end of September, the water table rises sharply and continues to rise slowly through December, reaching a peak of 2.75 m. The rapid fluctuations in water table levels observed through the year can be explained by high precipitation events followed by recessions as the water drains from the aquifer. The influence of pumping in the vicinity of the observation well is unknown. There is a well located ~15 m away from well #281. However, it is unknown as if the well was active during the observation period and/or if the two wells are hydraulically connected. All other wells in the area are located at a distance greater than 100 m from well #281.

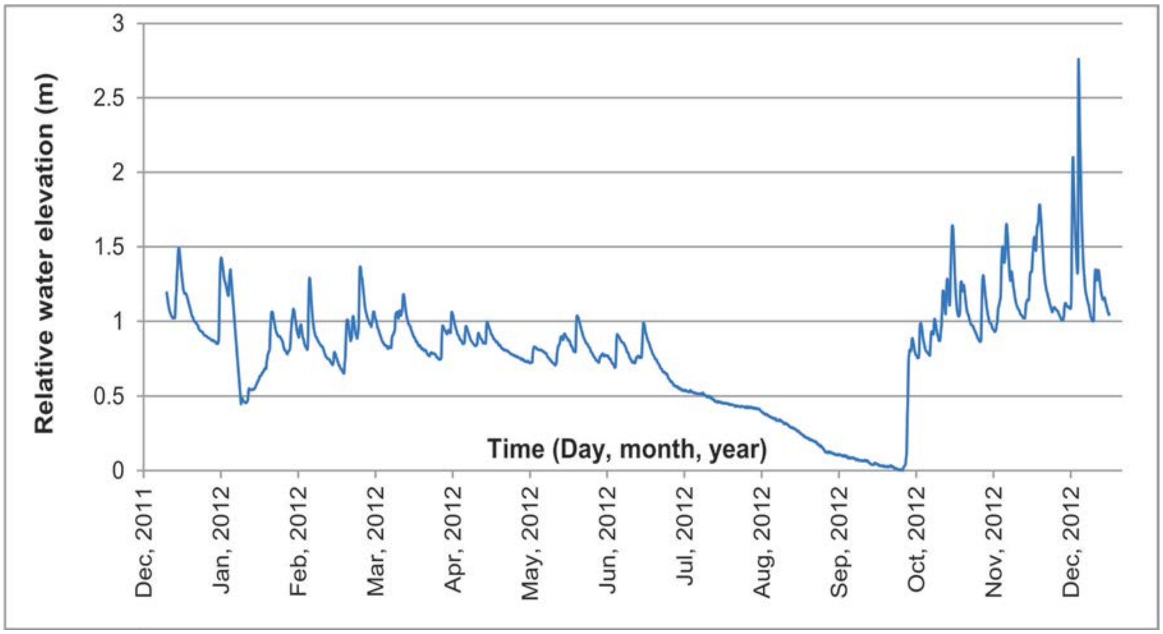


Figure 16. Groundwater level in observation well #281 in 2012. The y-axis is water elevation relative to the deepest recorded water depth. Drier periods are represented by lower depth to water values, wetter periods by higher values. Water level data are recorded hourly.

The longest period of record available is for well #281 (April 1985 – present, shown here as June 2014) (Figure 17). Water levels were not measured at a regular intervals until April 2003; they were measured either many times a month or some months were skipped (no data were collected in 1987 and 1988). From April 2003, water levels were measured three times a day. Since October 2003, water levels have been measured hourly. Despite the lack of consistency in water level measurements prior to 2003, Figure 17 shows there has not been an overall decline in water level since the observation well was established. The water elevation generally oscillates between 2 and 4 m relative to base level. Since 2003, when hourly measurements were initiated, the hydrograph appears noisier and records higher peaks. But these are simply an artefact of the more frequent measurement interval.

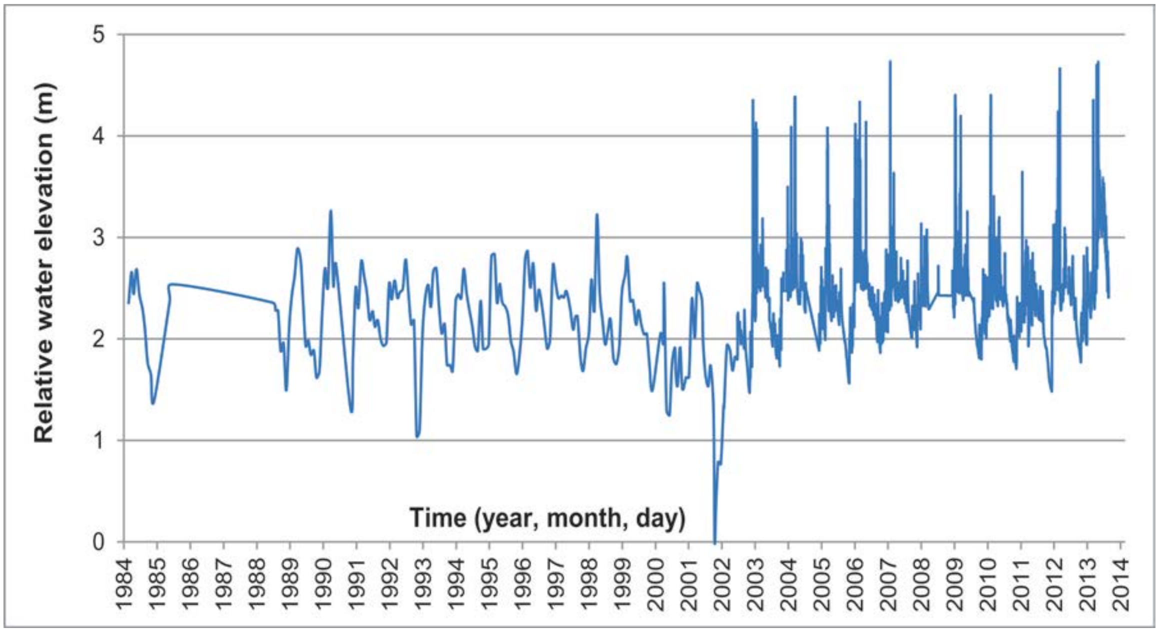


Figure 17. Groundwater level in observation well #281 from 1984 to 2014. The x-axis represents the date and time, the y-axis is water elevation relative to the deepest recorded water depth. Drier periods are represented by lower depth to water values, wetter periods by higher values. No data were collected in 1987 and 1988.

Water level measurements are available from 2006 to present for observation well #373 (Figure 18). As for well #281, there is no overall decline in water level during the period of record. Water levels generally range from 0 to 9 m. During wet periods, the water table is very close to the surface; measurements are between 7 and 9 m above base level.

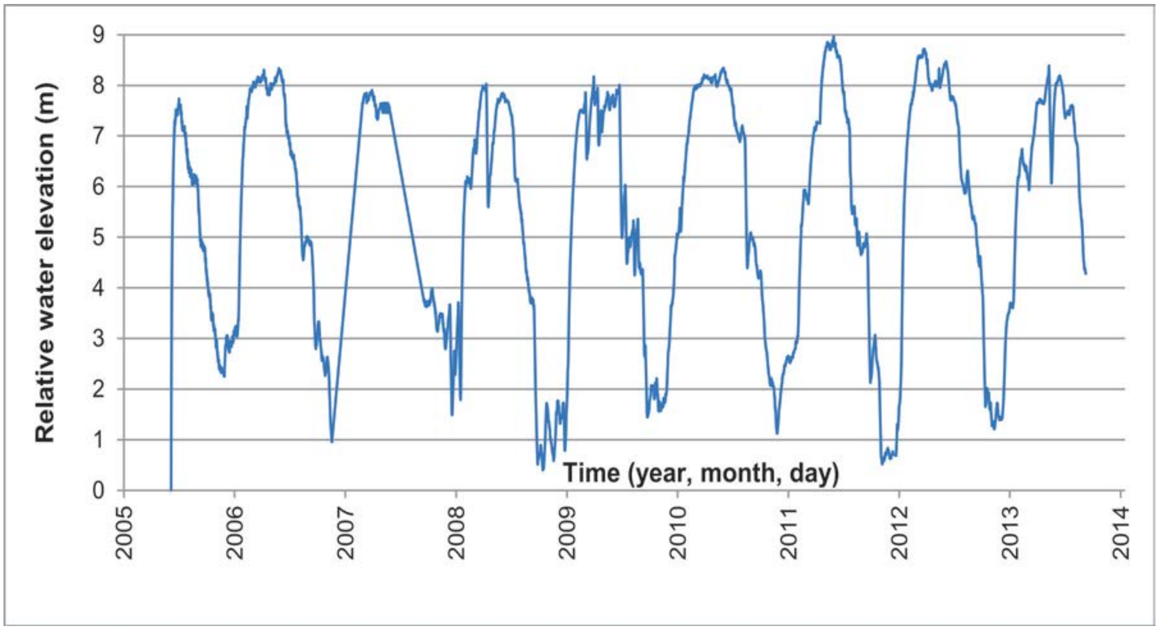


Figure 18. Groundwater level measured in observation well #373 from 2006 to 2014. The y-axis is water elevation relative to the deepest recorded water depth. Drier periods are represented by lower depth to water values, wetter periods by higher values.

Overall, the water level variations in the two observation wells show consistent seasonal variations, with water levels dropping to seasonal lows in the late summer and recovering the following fall/winter. Amplitude varies from 4 to 9 m. There appear to be no trends, although a statistically-based trend analysis was not carried out. A longer period of record would be needed to do such a trend analysis.

8 Groundwater Chemistry

8.1 Chemical Characteristics of Saltwater Intrusion

Saltwater intrusion, also referred to as salinization, is a widespread problem that results in contamination of freshwater aquifers. It is defined as the influx of saline waters into fresher waters. Freshwater in coastal aquifers is particularly vulnerable to salt contamination through many different pathways (Barlow and Reichard, 2010). Old saline waters trapped in sediments from post depositional compaction or submersion of the aquifer under seawater (Dakin et al., 1983), evaporitic salts in the aquifer skeleton (Bosch et al., 1992), sea spray, the movement of water from adjacent aquifers, current seawater intrusion, and anthropogenic sources are modes of saltwater contamination to coastal and island aquifers. Intensive water use (pumping) for agriculture, industrial and residential activities also contributes to saltwater intrusion. During saltwater intrusion, contamination often remains localized, but there are instances in which contamination has spread through whole aquifers (Barlow and Reichard, 2010). Ultimately, saltwater intrusion remains the dominant process of salinization of these coastal and island aquifers due to their proximity to the ocean.

Some areas and wells are at higher risk of contamination. Low topographic areas are more prone to inundation and their low hydraulic gradient makes these areas more prone to seawater intrusion (Ferguson and Gleeson, 2012). Deep wells are particularly at risk of becoming contaminated as they may be completed close to, within, or below the saltwater interface and may draw in seawater during pumping (see Figure 1). This problem was encountered on Lopez Island (Washington) where the United States Geological Survey (USGS) identified the depth of the deep bedrock wells as the primary reason for contamination from seawater intrusion (USGS, 2000). Wells located close to the ocean are in general more vulnerable to seawater contamination because the saltwater interface is located at shallower depth closer to the coastal margin. However, in fractured bedrock, fractures may extend inland some distance, placing wells inland more at risk of contamination. Finally, pumping rates exceeding the capacity of the aquifer or the total drawdown of multiple wells can induce further movement of the saltwater interface landward. High pumping rates have been identified as one of the main causes of seawater contamination in the Blato aquifer (Croatia) due to high pumping rates during tourism season (Terzic et al., 2008).

Saline water (TDS between 400 and 1000 mg/L) was identified on Salt Spring Island at a few locations prior to 2007 (Figure 19) (Hodge, 1995). Samples collected in 2007-08 and in 2013 (as discussed in this section) also indicate saline water (TDS>620 mg/L and/or Cl>300 mg/L[1]) at other locations (Figure 19). Some wells producing salty water are believed to be drilled below the freshwater lens, close to seashore, or near a fault zone (Greenwood, 2011). For example, a well located close to the St. Mary Lake Fault, near the St. Mary Lake shoreline, is classified as salty. Fresh groundwater flowing down surrounding hills and pushing salty water up the St. Mary Lake Fault has been proposed as an explanation for salty water sampled at that location (Greenwood, 2011). In addition, there are salt springs on Salt Spring Island. Dakin et al. (1983) referred to the Fernwood spring on Salt Spring Island and showed that this spring has a similar composition to seawater.

Approximately 20% of the water supply on Salt Spring Island is groundwater (Lamb et al., 2010). Given the importance of groundwater, it is important to have a good understanding of the spatial variation of water chemistry. This section describes the groundwater chemistry on Salt Spring Island. It defines the general characteristics of water chemistry in the context of the local geology, which differs for the northern and southern portions of the island as described in Section 3.2. The main geochemical processes controlling the water chemistry are also discussed in the context of the groundwater evolution within the Gulf Islands based on previous research. The occurrence of saltwater intrusion is also discussed.

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[1] Based on Klassen et al. (2014) samples with Cl concentration > 300 mg/L, or the TDS > 620 mg/L are considered to be impacted by salinization.

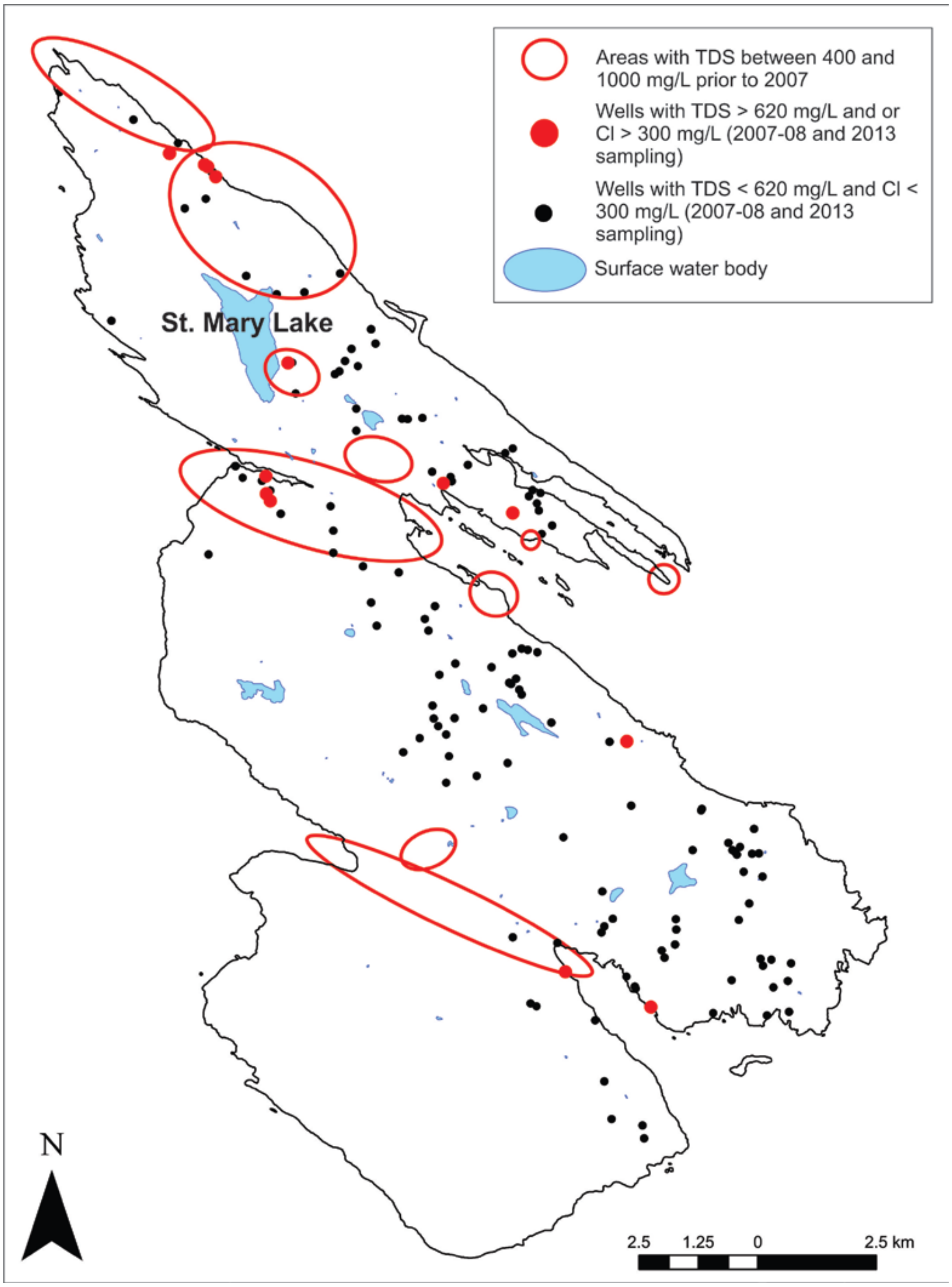

Figure 19. Locations with TDS between 400 and 1000 mg/L (Hodge, 1995 after Hodge, 1977) and with TDS > 620 mg/l and/or Cl > 300 mg/L during the 2007-08 and 2013 sampling events. The sizes of the red and orange circles are not proportional to the extent of saltwater intrusion; they only show approximate locations.

8.2 Water Chemistry Data

8.2.1 Sampling Programs

A total of 146 samples were collected from privately owned wells over a two-year period (2007-08) by the BC Ministry of Environment, and the resulting chemical database was made available for interpretation in this study. The majority of the samples were collected between June and October 2007 (125 samples). In 2008, an additional 21 samples were collected. Ten of the wells sampled in 2007 had high arsenic. As a result, five of these wells were analyzed before and after arsenic removal treatments in 2008 (Kingerlee et al., 2010). (Further information regarding the sampling procedures and laboratory analysis can be found in Kingerlee et al., 2010). The wells are open boreholes (no casing) drilled through the bedrock. One additional well located in the south of the island was sampled by Agrichem Analytical in 2008 and the results are included in this study.

In June 2013, as part of this study, an additional 13 water samples were collected. Of the 13 water samples, two are lake water samples, two are ocean samples, one is from a salt spring located on the northern coast of the island, and three were collected at different depths in the same well. Well samples are from open boreholes drilled through bedrock (6), dug (1) or artesian (1) wells. All wells were unused at the time of sampling. Samples were either "grabbed" (in the case of the dug well, lake, ocean and salt spring) or collected with a bailer (discrete depths in a well).

8.2.2 Analysis

The purpose of this study is to interpret the spatial distribution of the groundwater chemistry data in the context of the geology, rather than conducting a time series analysis due to limited time-varying data. The following summarize the criteria used to evaluate whether or not a sample was included in the analysis:

- Where multiple samples were collected from the same well at different times, a representative sample was included.
- The 2007 sample was chosen if there was a repeat sample in 2008.
- Samples only collected in 2008 were included.
- Samples collected before and after arsenic treatment removal (2008) were not included because they were included in 2007.
- All well samples collected in 2013 were included.
- Samples collected at different depths (3) are represented by the ion concentration values sampled at the deepest sampling point.
- When dissolved concentrations were missing, total concentrations were used.
- Site 58 was not included given the lack of major ion concentrations.

- Some samples had been collected after a cistern or holding tank, after a water softener, or in shallow dug wells or in unconsolidated sediments. These samples may not represent natural groundwater quality so they were excluded from the analysis.
- For most of the samples collected in 2007 and 2008, HCO_3 was not analyzed. When all other major ion concentrations were available, an electrical balance was performed to estimate the HCO_3 concentration.

Each sample site was assigned a well site number, as well as a well tag number (WTN) when possible. The well site number corresponds to the sampling site for the campaign and the WTN is the BC Ministry well identification number in the WELLS database (BC Ministry of Environment, 2013a). Only some of the wells sampled in 2007 and 2008 were assigned a WTN because a well record could not be confirmed in the WELLS database. For the remaining samples, including 2013 samples, the location of the wells was determined with a hand-held GPS and a sample site number was assigned to each sample. For reasons of confidentiality, the WTN is not reported.

Ultimately, data from 142 sites were included in the analysis: 2007, 2008, 2013 groundwater samples, one well sampled by Agrichem in 2008, and two BC observation wells (#281 and #373) (BC Ministry of Environment, 2013b), plus a representative seawater and rainwater sample. The average ocean representative sample was calculated from two ocean samples collected in June (2013) for the ion-ion plots, but both samples are included in the Piper diagram. The rainwater representative sample was obtained from NatChem (Environment Canada, 2007) for Saturna Island.

In order to interpret the spatial distribution of the water chemistry data, an ArcMap shapefile, including well location and water chemistry, was created for each groundwater sample site and overlain on the geology map created by Greenwood (2009) (Figure 20). As described in Section 3.2, the geology of the southern portion of the island differs from the geology of the northern portion. The unconformity is represented at surface by the abrupt transition from pink tones to green tones on the geology map (Figure 20). Sedimentary rocks comprising the Upper Cretaceous Nanaimo Group are exposed at surface in the northern portion of the island, while older rocks, broadly classified as “igneous rocks”, are present to the south. It is noted that while the term “igneous” is used for these rocks, they are of variable age (Paleozoic: Devonian to Triassic), spanning intrusive, volcanics, metavolcanics, metasediments (Greenwood, 2009). Also, sedimentary rocks from the Haslam Formation are represented to the south of the unconformity to a limited extent.

A Piper diagram was constructed to identify water-types and geochemical processes associated with samples located in the two major rock types. Piper diagrams show the relative concentrations (meq/L) of the major ions (Cl, SO_4, HCO_3, Na+K, Ca, Mg) and can be used to understand the chemical evolution. Several bivariate plots were made to study the relationship between specific ions: Na vs. Cl, SO_4 vs. Cl, Na vs. HCO_3, Ca/HCO_3 vs. HCO_3, and Mg vs. Ca.

Finally, median and range of total dissolved solids (TDS) were compared between samples in the two main rock types. TDS was calculated by adding the main ions (Cl, SO_4, HCO_3, Na, K, Ca, and Mg).

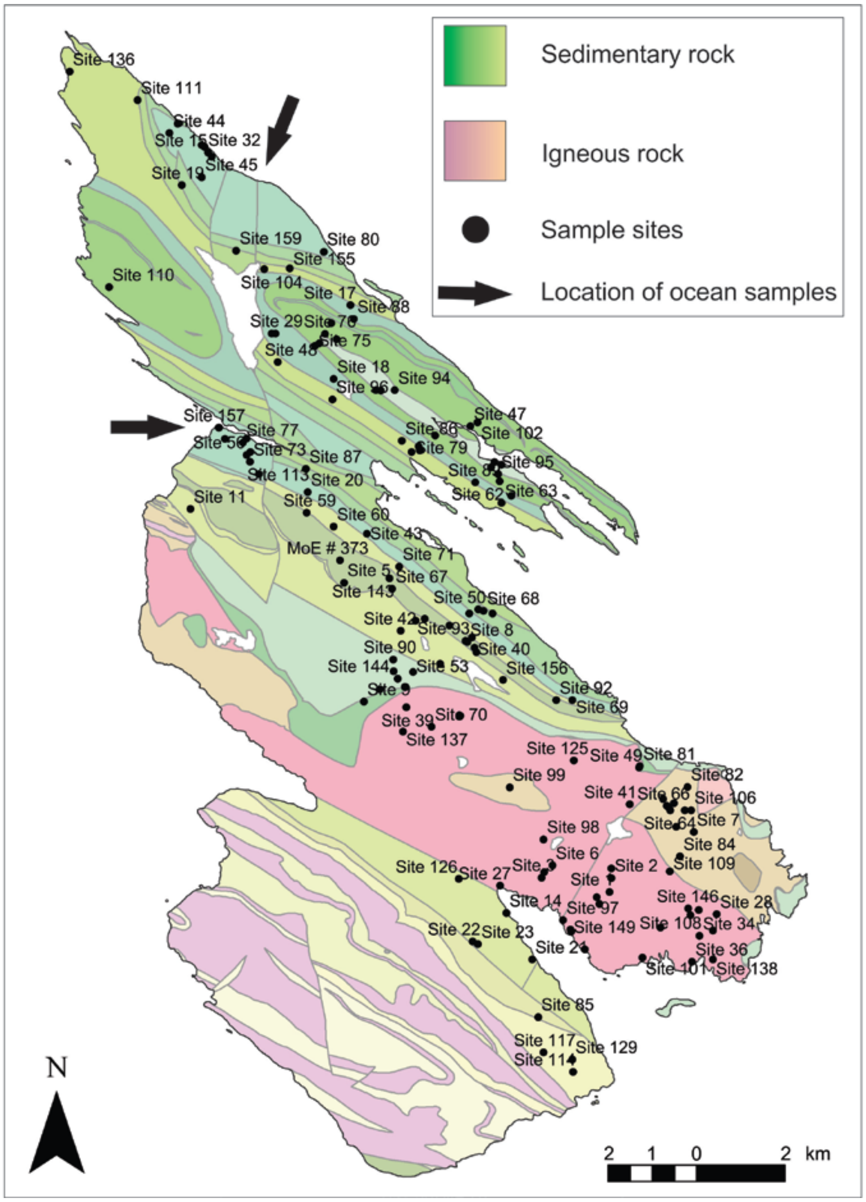

Figure 20. Location of sample sites for years 2007, 2008 and 2013, as well as the approximate locations of ocean samples. Salt Spring Island geology is by Greenwood (2009).

8.3 Results

8.3.1 Total dissolved solids (TDS)

TDS concentrations range from rainwater (5 mg/L) to seawater (24,111 mg/L). Rainwater has the same water type as ocean water due to its proximity to the ocean (see Piper diagram in Figure 21); as it falls, rain picks up particles from seaspray.

Median TDS values are quite similar between the two main rock types: sedimentary (307 mg/L) and igneous (260 mg/L). However, the ranges are different: sedimentary (10 to 4,622 mg/L) and igneous (110 to 1,113 mg/L). Overall, the range in TDS is large and non-uniform across the island.

8.3.2 Piper Diagram – Determining Water Types

Figure 21 shows the Piper diagram for Salt Spring Island. Samples are colour coded according to main rock type: sedimentary (green) and igneous (pink). The symbols are also scaled in the upper diamond according to TDS concentration. The samples collected from the sedimentary rock commonly are of Ca-HCO_3, Na-HCO_3 and Na-Ca-Mg-HCO_3 types, while samples collected in the igneous rock commonly are of Ca-HCO_3 and Na-Ca-Mg-HCO_3 types. Both the ocean water sample and the rain water sample are Na-Cl types. The salt spring has a Na-Cl type.

Overall, the water chemistry appears to be governed by carbonate mineral dissolution followed by mixing with seawater (salinization paths 1 and 2) and/or cation exchange as described by Allen and Suchy (2001):

Carbonate mineral dissolution – Carbonate dissolution can be recognized by an increase in calcium and bicarbonate ions in the water. On Salt Spring Island, it represents the change in chemical composition transformation from rainwater to fresh groundwater.

Cation exchange – On this diagram, cation exchange is characterized by an increase in sodium concentration and a small increase in TDS. Cation exchange appears to be a dominant process in the sedimentary rocks, but not the igneous rocks.

Salinization path 1 – This path is characterized by an increase in TDS and chloride concentration as waters, already rich in sodium, come into contact with seawater. Only sedimentary rock samples are located along this path.

Salinization path 2 - This path is characterized by an increase in chloride and sodium concentration, and TDS. Freshwater and seawater are the two end members on this path. Samples from igneous rock moslty plot close to the freshwater end member, while sedimentary samples are better distributed along the path and show a greater degree of mixing with seawater.

These various processes are explored further in the following section by considering the bivariate plots.

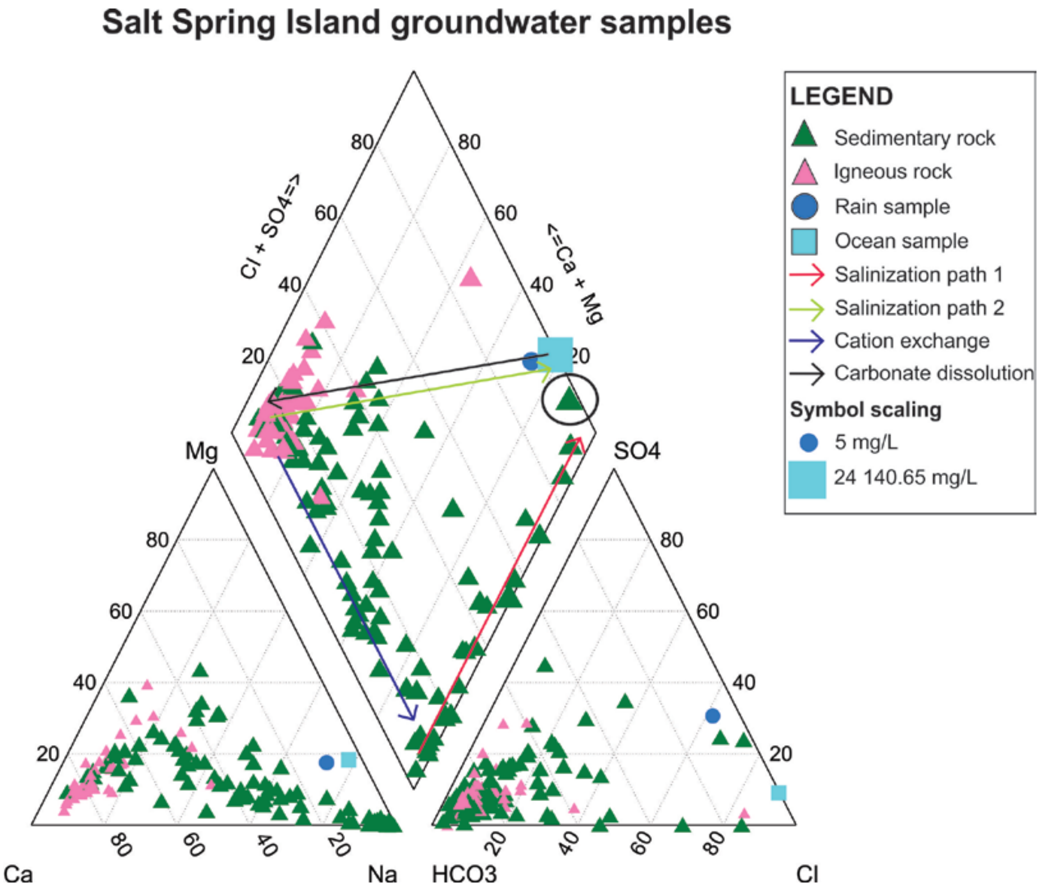

Figure 21. Piper diagram for Salt Spring Island groundwater. Water samples were collected in 2007, 2008 and 2013. The size of the symbols is scaled according to TDS values; the larger the TDS value, the larger the symbol. The salt spring sample is circled.

8.3.3 Main Geochemical Processes

Seawater Mixing

A bivariate plot with Na against Cl displaying the freshwater-seawater mixing line can be used to determine if groundwater is mixing with seawater. Figure 22 shows Na vs. Cl, employing the same colour and symbols as used for the Piper diagram, to illustrate the differences according to the main rock type. The mixing line was generated using the Na and Cl concentrations of the rain sample and an average of the two ocean samples. Samples located on the mixing line suggest water chemistry is strongly influenced by mixing with seawater (Bear et al., 1999). The salt spring sample plots close to this mixing line.

Figure 22 supports the distribution of some samples along the salinization paths (1 and 2) suggesting mixing with seawater is a dominant process. It appears that no rock type is significantly more prone to salinization than the other. On the other hand, from the Piper diagram (Figure 21), salinization appears more dominant in the sedimentary rock type. Samples located above the freshwater-seawater mixing line suggest another geochemical process is adding Na to the aquifer system (Allen and Suchy, 2001).

Most samples plot above the mixing line, but Na concentrations are higher for the sedimentary rocks than for the igneous rocks. The potential provenance of the Na ion within the sedimentary rocks is discussed in the following section.

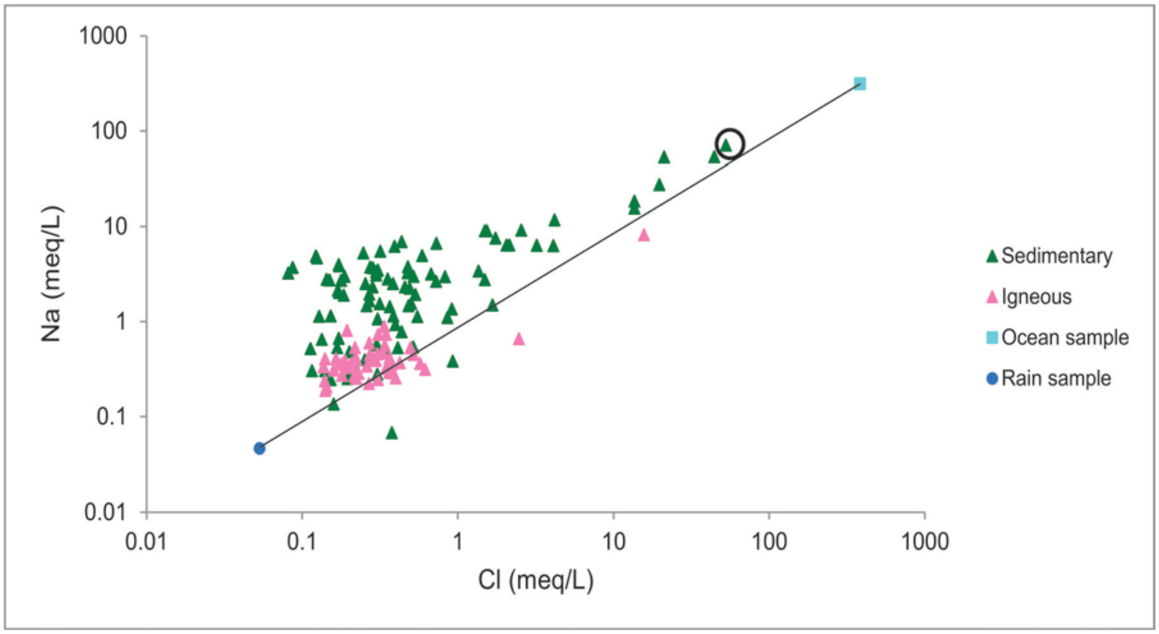

Figure 22. Bivariate plot of Na and Cl. Samples collected in the sedimentary rocks are green; samples collected in the igneous rocks are pink. The black line represents the freshwater-seawater mixing line; delineated by the Na and Cl concentration of ocean water and rainwater in the Gulf Islands (BC), light blue square and dark blue circle, respectively. The salt spring sample is circled.

A bivariate plot of SO_4 vs Cl is shown in Figure 23. This plot suggests that some SO_4 originates, to a small degree, from mixing with seawater. Some samples are located on the freshwater-seawater mixing line. Additional sources of SO_4 are uncertain, but may be from the interaction of seawater with rocks (e.g. pyrite oxidation through dissolution) prior to mixing with freshwater (Allen and Kirste, 2012). Some samples have low Cl concentrations, but still greater SO_4 concentrations than rain. This suggests some samples interact with rocks, but do not mix with seawater. Samples with very low SO_4 concentrations are likely the result of microbial driven SO_4 reduction.

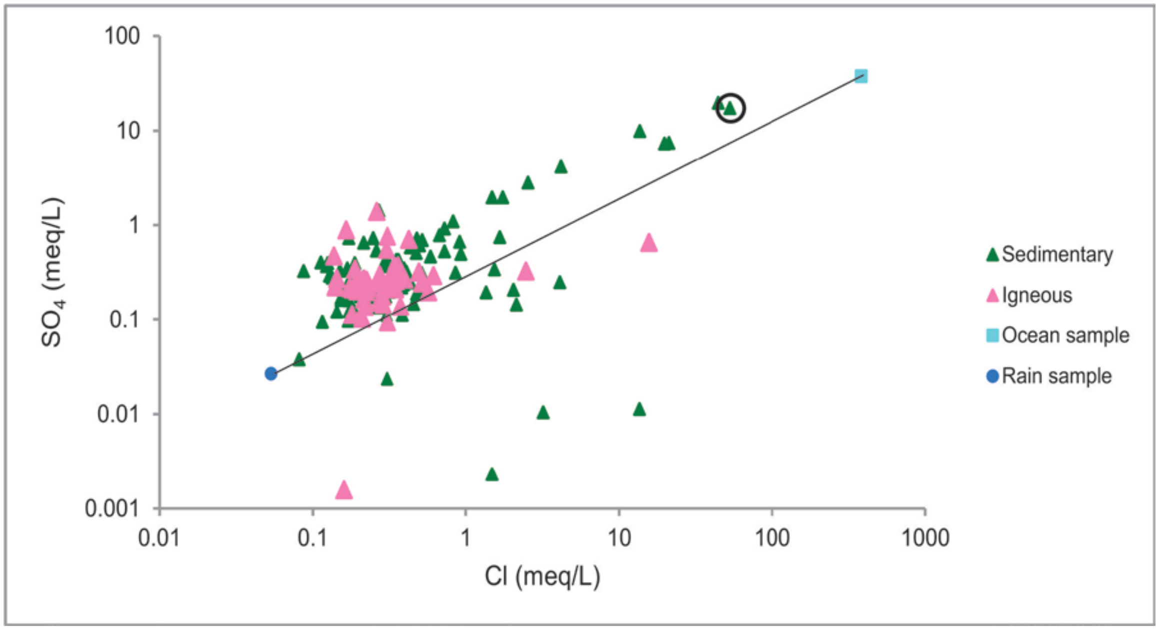

Figure 23. Bivariate plot of SO_4 and Cl. Samples collected in the sedimentary rocks are green; samples collected in the igneous rocks are pink. The black line represents the freshwater-seawater mixing line; delineated by the SO_4 and Cl concentration of ocean water and rainwater in the Gulf Islands (BC), light blue square and dark blue circle, respectively. The salt spring sample is circled.

Cation Exchange within the Sedimentary Rocks

The Piper diagram (Figure 21) suggests that cation exchange is an important geochemical process on Salt Spring Island, specifically within the sedimentary rocks. There is a shift in chemistry from Ca-Mg to Na+K. Thus, the relative concentrations of Ca and Mg decrease while the concentration of Na+K increases. Generally no increase in TDS is expected, unless it is coupled with calcite dissolution. Here, however, a small increase is observed, suggesting calcite dissolution is taking place. Both processes, calcite dissolution and cation exchange, are captured in Figure 24 for samples located on the 1:1 curve. As mentioned previously, cation exchange is not a dominant process in the igneous rocks.

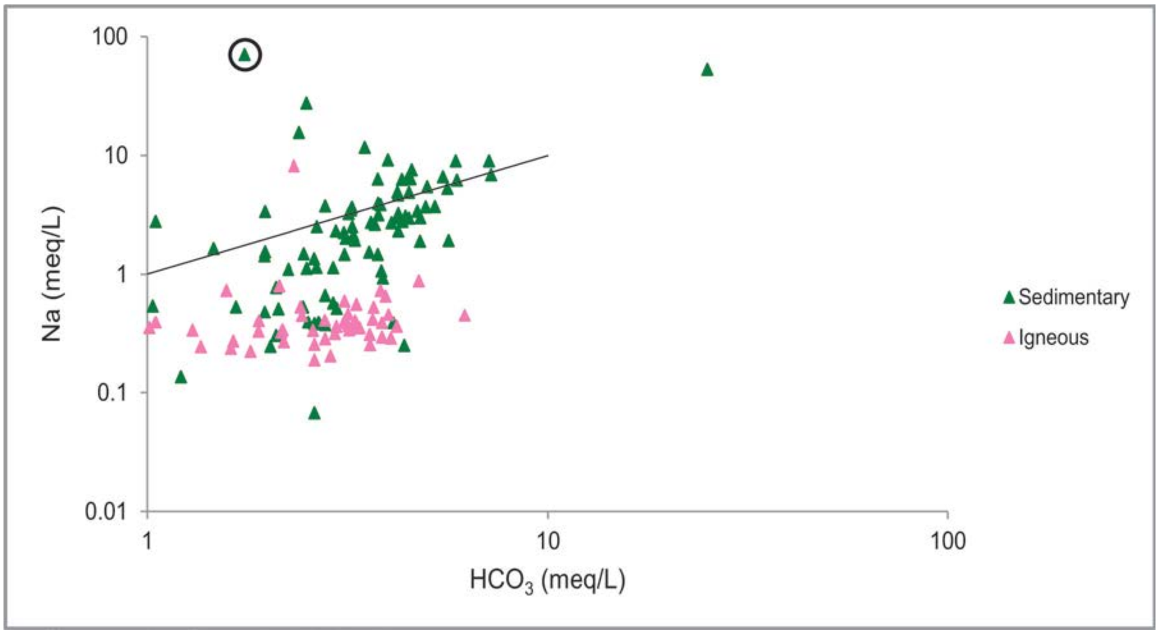

Figure 24. Bivariate plot of Na and HCO_3. Samples collected in the sedimentary rocks are green; samples collected in the igneous rocks are pink. The salt spring sample is circled.

Mineral Dissolution

Within the Nanaimo Group sedimentary rocks, the clasts are comprised primarily of quartz and plagioclase feldspar, with lesser amounts of potassic feldspar and other rock fragments (Mustard, 1994). Carbonate cements are typical, with less common silica and rare chloritic to clay cements reported (Mustard, 1994). As discussed above, the “igneous” rocks are comprised of different rock types. All samples sites in the south of the island are located within the Saltspring Intrusions (Dg), Nitinat (DN), and McLaughlin Ridge (DMt and DMg) Formations (Figure 20). Greenwood (2009) describes the Saltpring Intrusions as granitic, the Nitinat as clinopyroxene-rich mafic volcanics, and the Mclaughlin Ridge as a felsic tuff. Generally, the granitic and felsic rock types are considered to have low reactivity (Plummer and Carlson, 2008), which would result in little weathering. Both the Nanaimo Group Rocks and the older rocks were extensively fractured during the Eocene. In outcrops, Mackie (2002) observed joints with a thin coating of fine-grained calcite.

Figure 25 illustrates the relationship between the ratio Ca/HCO_3 and the HCO_3 concentration for all samples. For every mole of calcite dissolved, only one mole of Ca is created for two moles of HCO_3 (Equation 1).

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^{-} \qquad (1)$$

For almost all HCO_3 concentrations, there is less Ca than HCO_3 in water. This suggests that calcite dissolution is taking place. The high Ca concentration as opposed to Mg concentration (Figure 26) suggests the origin of HCO_3 is more closely related to calcite dissolution than to dolomite dissolution.

Nevertheless, the ratio Ca/HCO_3 is not exactly 1:1 so dolomite dissolution might account for some of the HCO_3 content.

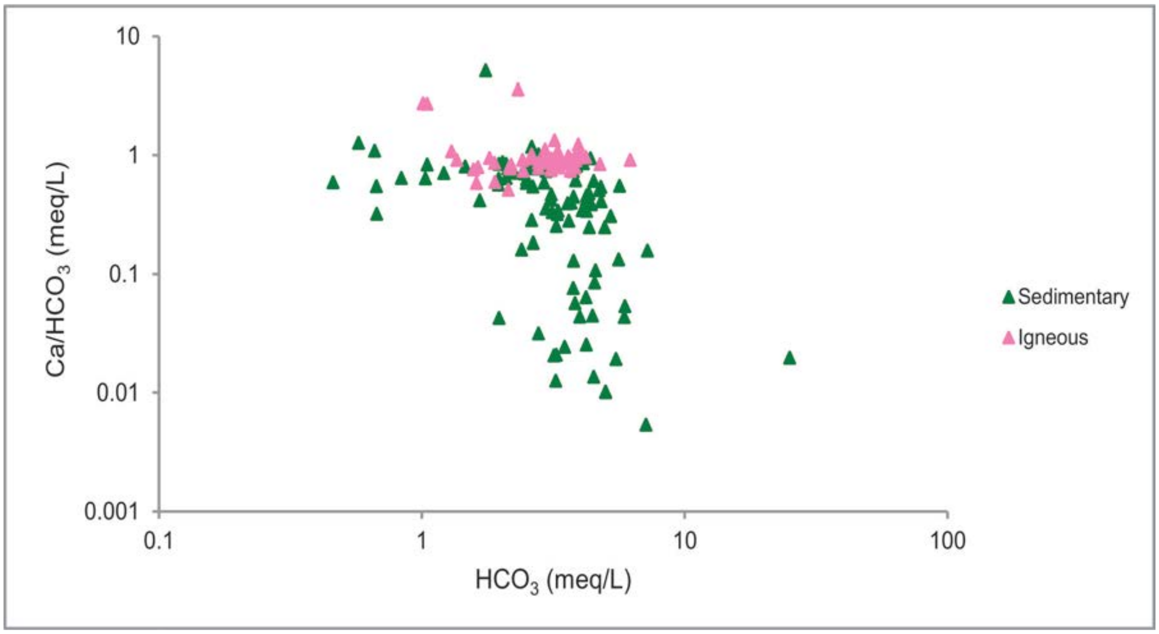

Figure 25. Ca/HCO_3 ratio against HCO_3 concentration. Samples collected in the sedimentary rocks are green; samples collected in the igneous rocks are pink.

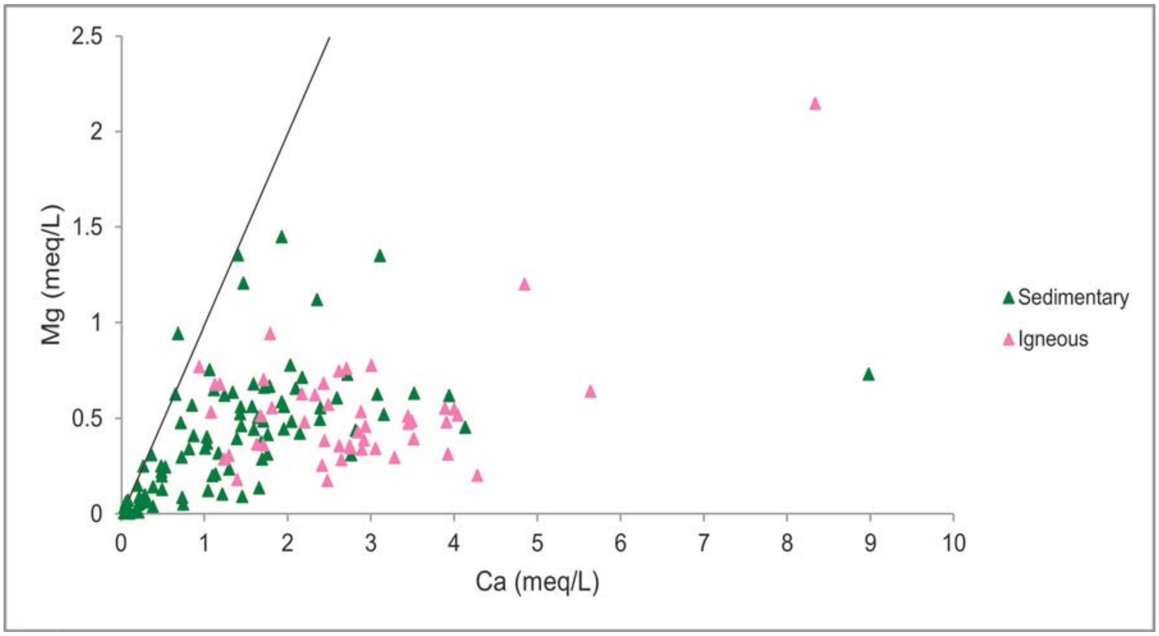

Figure 26. Mg against Ca concentration. Samples collected in the sedimentary rocks are green; samples collected in the igneous rocks are pink. The black line represents the 1:1 ratio between Ca and Mg.

It is unclear why HCO_3 and Ca are the dominant ions within the igneous rocks (Piper diagram). There are three hypotheses:

1) The dominance of HCO_3 in most samples could result from chemical weathering of calcareous argillite (Fourth Lake Formation). Even if this rock type is not dominant at the surface (Figure 20) in the vicinity of the sampling sites, it is possible that fractures connect groundwater from this formation to formations in which the wells are located. The Fourth Formation is located in the vicinity of the southern tip of the island and underlies the Mount Hall Gabbro Sills Formation.

2) Ca and Mg could originate from the dissolution of pyroxene, which is a dominant mineral in the Nitinat Formation (Equation 2):

$$(Mg_{0.7}CaAl_{0.3})(Al_{0.3}Si_{1.7})O_6 + 3.4H+ + 1.1H_2O \rightarrow 0.3Al_2Si_2O_5(OH)_4 + Ca^{2+} + 0.7Mg^{2+} + 1.1H_4SiO_4 \quad (2)$$

3) Finally, calcite in fractures may be the source, due to the fact that most of the groundwater flow in these low porosity igneous rocks is through fractures.

8.4 Discussion of Groundwater Chemistry

8.4.1 Groundwater Evolution

The groundwater evolution on Salt Spring Island is very similar to that observed for other Gulf Islands (e.g., Dakin et al., 1983; Allen and Suchy, 2001; Allen and Matsuo, 2002, Allen and Kirste, 2012), with the exception that Salt Spring Island has different rock types in the southern portion of the island compared to the northern part of the island and neighbouring Gulf Islands. The following summarizes the geochemical processes.

Rainwater has a low Ca concentration, and is a Na-Cl type (Figure 21); however, the concentrations of all ions are very low as evidenced by the low TDS (5 mg/L). The rainwater is undersaturated with respect to calcite (Appelo and Postma, 2005) so dissolution may take place if it comes into contact with sediments or rocks that contain calcite. Dissolution of calcite dominates over the dissolution of other minerals within these rocks because calcite is more soluble and has a faster reaction rate. On the Gulf Islands, the surficial sediments are generally very thin, and present only as a thin veneer over bedrock. Therefore, most geochemical processes will take place in the rocks. Given the presence of carbonate cements in the sedimentary rocks, pyroxenes in some igneous rocks, and calcite coatings on fractures, calcite dissolution is likely a dominant process. This leads to a Ca-HCO_3 water type.

As the Ca-rich water infiltrates and moves deeper in the flow system, it gains Na through cation exchange, but only in the sedimentary rocks. The Na is thought to have been emplaced on clay mineral exchange sites during the late Pleistocene (Allen and Suchy, 2001). As proposed by Allen and Liteanu (2006), during this period, the Gulf Islands were submerged to a current elevation of approximately 200 masl, and seawater entered the groundwater system, enriching the mudstone (clay) exchange sites with

Na. Following re-emergence, fresh groundwater flushed out the Cl from the rocks, but the Na remained attached to the clay exchange sites. This explains the dominant cation exchange process displayed on the Piper diagram and the Na/HCO_3 water type as well as the samples plotting above the seawater mixing line in Figure 22.

Following cation exchange, mixing with Cl-rich water becomes a dominant process. This mixing takes place along salinization path (1) on the Piper diagram, and is also evident in the Na-Cl bivariate plot. The mixing process along salinization path 1 is evident for the sedimentary rock samples, while absent for the igneous rocks. Mixing within the sedimentary rock is therefore evident from the distribution of samples along the chloride axis (Piper diagram), from low to high concentrations. Mixing is also observed on the Na-Cl bivariate plot; sedimentary samples plot slightly above the freshwater-seawater mixing line, often very close to the Na-Cl freshwater-seawater ratio.

As discussed above, a second salinization path (2) has also been described for the Gulf Islands (Allen and Suchy, 2001). This salinization path is less well represented and not as definite within both the sedimentary and igneous rocks; the samples cover a wider range along the axis, when compared with salinization path 1. Also, all samples remain closer to the freshwater end member than the seawater end member, with the sedimentary rock samples situated closer to the seawater end member.

Very few samples in the igneous rocks appear to undergo the above described groundwater evolution. This can be explained by the absence of clay exchange sites in the igneous rock. Thus, both Na and Cl would have been flushed from these rocks. As a result, if mixing were to occur within the igneous rock, it would more likely be represented by an increase in Na, Cl and TDS (salinization path 2).

8.4.2 Saltwater Intrusion

Klassen et al. (2014) examined the entire groundwater database for the Gulf Islands with the objective of identifying appropriate indicators of salinization. The preliminary results of that study suggest that if the Cl concentration > 300 mg/L, or the TDS > 620 mg/L, then the sample falls within the uppermost 5% of all Gulf Islands samples (i.e., the 95th percentile) and can be considered to be impacted by salinization. Based on these Cl and TDS values, seven sites with high Cl and 13 sites with high TDS, are affected by high salinities on Salt Spring Island. All samples, but one, are located along salinization path 1 on the Piper diagram, spanning from low to high Cl concentrations. The remaining sample is located on the Ca+Mg axis above the seawater end member.

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

The mixing process appears to occur primarily in the sedimentary rocks, but it might simply be related to the higher density of wells sampled in this region. Also, the topography is generally lower in the northern portion of the island where sedimentary rock dominates, with many flat areas located close to the coast. Prior to 2007, saltwater intrusion had been observed around Scott Point, Southey Point, Booth Bay and Eskrine Point and in the south, in Fulford harbour. More recently, saltwater intrusion has also been observed at Fernwood (St. Mary Lake Steering Committee, n.d.). Most samples from the 2007-2013 study identified as having saltwater intrusion problems are located in flat and coastal areas. Only one is located inland; a fracture connection to the sea is a plausible explanation for saltwater intrusion at that location (Figure 19).

Based on a spring sample collected by Dakin et al. (1983) and one in this study, the salt springs on Salt Spring Island appear to have a composition similar to seawater; although additional sampling is needed to confirm these results.

9 Conclusions

Existing hydrogeological data for Salt Spring Island and the Gulf Islands were gathered and field studies were completed during the 2013 summer field season to complement the existing data. A hydrogeological conceptual model of Salt Spring was developed based mostly on existing knowledge. The components of this conceptual model included: 1) a description of the main geological units and their associated hydraulic properties; 2) characterization of the groundwater flow system in this coastal setting, considering the role of fractures, recharge and seasonal water table variations; and 3) interpretation of the groundwater chemistry in the context of the geology.

Overall, the hydrogeology of Salt Spring Island is consistent with that of the other Gulf Islands. The main difference is the presence of igneous fractured rock in the south-central part of the island, whereas the north-central part of the island is comprised of the Upper Cretaceous Nanaimo Group sedimentary rocks similar to the other Gulf Islands. The igneous rock units, which are of Carboniferous to Permian age, are broadly composed of granite, rhyolite and pyroxene. Despite the difference in rock type, the general hydrogeology of the igneous rocks is consistent with that of the sedimentary rocks. Recharge is locally derived from precipitation, and groundwater generally flows from areas of high to low elevation, discharging along the coast at a regional scale, but also locally in creeks and lakes. Recharge occurs primarily through fractures, and spatial variation in recharge is expected given the heterogeneity of fracture distribution, particularly near faults and fracture zones. The amount of recharge to aquifers remains uncertain on Salt Spring Island and on the Gulf Islands more broadly, despite the wide variety of methods used in previous studies and study to estimate recharge (e.g., water level fluctuation method, water balance modeling, etc.). Most studies estimated that approximately 20% of total annual precipitation reaches aquifers, while others predicted values as low as 3% and as high as 63%. This range shows the level of uncertainty in recharge estimation. The use of 3-D land surface-hydrologic models in future work may provide more robust recharge estimates given the steep topography of the islands.

The groundwater chemistry of Salt Spring Island is generally consistent with that of the other Gulf Islands. In the sedimentary rocks, cation exchange is a dominant process that influences the chemistry. Groundwater evolves from rainwater to a Ca-HCO_3 composition as a result of calcite dissolution, through to a Na-HCO_3 composition due to cation exchange, and finally to a Na-Cl composition due to mixing with seawater. This general evolution has been described in several previous studies. However, there are unique characteristics of the Salt Spring Island water chemistry given the presence of the igneous rocks. Contrary to the sedimentary rocks, igneous rocks do not have ion exchange sites due to the absence of clay minerals. As a result, no cation exchange takes place as the groundwater flows through the system. Only mineral dissolution and seawater mixing geochemical processes are observed. Saltwater intrusion has also been identified in some wells situated along the coast.

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