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Chemical Indicators of Saltwater Intrusion for the Gulf Islands, British Columbia

J. Klassen, D.M. Allen and D. Kirste

Department of Earth Sciences, Simon Fraser University

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Introduction

About seventy percent of the world's population resides in coastal regions (Webb and Howard, 2011). According to the UN Atlas of the Oceans, eight out of the ten largest cities are located along the coast, resulting in a total of 2.2 billion people worldwide living 100 km from the coast (United Nations, 2013a, 2013b). The population density in coastal regions is about three times greater than the global average (Small and Nicholls, 2003). Thus, currently there is a high demand for freshwater in coastal aquifers, which adds stress to the natural system (Post, 2005). Population growth and warmer temperatures under future projected climate change conditions will likely increase the demand for freshwater in the future (Post, 2005). Additional stresses related to climate change (e.g., sea level rise, changes in recharge, groundwater withdrawal, and land-use change) also have the potential to impact the delicate hydrologic balance in coastal aquifers (Turner et al., 1996). These cumulative stressors can present a significant problem in coastal aquifers where freshwater is the main water resource.

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

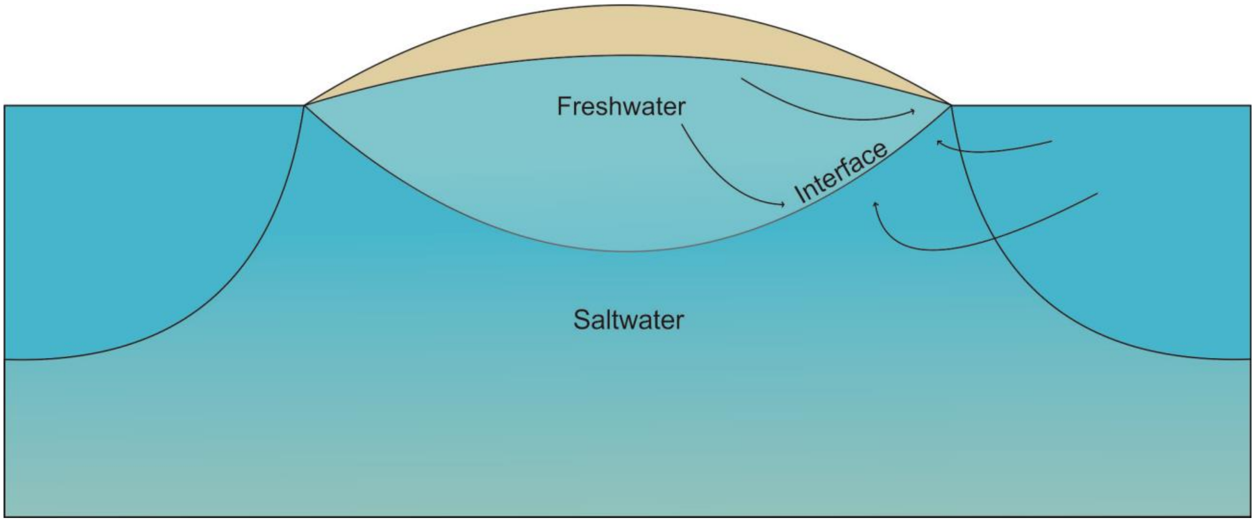

Figure 1: Illustration of the freshwater-saltwater interface. On islands, the freshwater lens is surrounded by saltwater.

Saltwater intrusion occurs when saltwater moves into a freshwater aquifer (Technically, this is seawater intrusion because “saltwater” can derive from different sources. However, for the purposes of this report the common term “saltwater intrusion” (SWI) is used.). SWI can be exacerbated by pumping freshwater at high rates or by pumping numerous wells simultaneously (high well density locations). Pumping can cause the freshwater-saltwater interface to move inland by reducing the natural gradient to the sea (Lyles, 2000). Other mechanisms leading to salinization due to pumping include upconing from depth (Reilly and Goodman, 1985; Washington State Department of Ecology, 2005) and localized intrusion by reversal of the hydraulic gradient near the well or well field (Fetter, 2001). In fractured rock, saltwater has been shown to enter wells through discrete fractures (Allen et al., 2002).

Longer period adjustments of natural discharge (unrelated to pumping) can occur from changes in land use which may reduce recharge rates, or modifications to land drainage systems (Werner et al., 2013). A lowering of the discharge can result in a shift in the position of the freshwater-saltwater interface. Groundwater recharge is expected to change under changing climate conditions (Green et al., 2011). A reduction in recharge or a change in the seasonality of recharge could lead to a landward shift in the freshwater-saltwater interface. Another potential driver of change to the position of the interface is sea level rise. Sea level is currently rising due to changes in atmospheric pressure, thermal expansion of oceans, and melting of ice caps and glaciers. Sea level is predicted to rise up to 0.6 metres by 2100 (Nicholls and Wong, 2007). A rise in sea level can lead to a reduction in the hydraulic gradient, particularly in coastal aquifers that are constrained by topography (Michael et al., 2013).

SWI typically is considered an active process, driven by changes to the hydrologic system. However, saltwater or brackish water can be encountered during drilling if the well is drilled too deep and breaches the transition zone between freshwater and saltwater. In such cases, these wells are referred to as being impacted by SWI despite the fact that they were simply drilled too deep to begin with.

Several water quality indicators have been proposed in the literature to identify groundwater that has been impacted by SWI (Panno et al., 2006; Kennedy, 2012; Allen and Liteanu, 2008; Bear, 1999; Washington State Department of Ecology, 2005). However, in some regions the natural chemical evolution of the groundwater system can make it challenging to apply these indicators, for example, due to cation exchange processes that raise the relative concentration of sodium compared to calcium (Allen and Suchy, 2001; Fetter, 2001).

This report briefly reviews some of the indicators that have been used for identifying salinization associated with SWI in coastal aquifers. These indicators, as well as a statistical approach, are then used to evaluate a comprehensive water chemistry database for the Gulf Islands, British Columbia, Canada. The objective of the assessment is to determine robust and defensible-indicators that can be used to identify wells that are impacted by salinity in a coastal setting. The salinity may be related to SWI, or progressing towards a state whereby SWI is likely.

Common Indicators of SWI

The World Health Organization states that mixing of only 2% saltwater (250 ppm) in a freshwater aquifer exceeds aesthetic objectives for the upper limit of chloride (Cl) (water begins to taste salty)(Custodio, 2005; Nova Scotia Environment, 2008). If mixing exceeds 4%, then the water becomes unusable for many uses, and if mixing exceeds 6% water becomes unusable except for cooling and flushing purposes (Custodio, 2005; Darnault and Godinez, 2008)

Water quality indicators of SWI are an important tool for water management because they enable monitoring of coastal aquifers. Monitoring typically involves the measurement of baseline water quality parameters (such as electrical conductivity, total dissolved solids, and major ions) (Barlow and Reichard, 2010). Monitoring groundwater quality can bring awareness to the early signs of migration of the freshwater-saltwater interface and provide information on saltwater encroachment (Barlow and Reichard, 2010). However, even on a short term basis, indicators of SWI can be valuable during the drilling process to identify if saltwater is being encountered while the borehole progresses. In this case, a relatively inexpensive and readily-measured indicator is needed so as not to require full chemical analysis for samples collected at discrete depths during drilling.

Multiple approaches have been proposed for determining indicators of SWI. Approaches vary from basic (e.g., elevated values of chloride are used to represent saltwater intrusion; Lyles, 2000; Kennedy, 2012; Scheidleder, 2003; Snow et al., 1990), to complex (e.g., model based indicators; Webb and Howard, 2011). This review focuses on the basic and quantitative /graphical approaches.

Basic Approaches

Saltwater contains roughly 35,000 mg/L of dissolved solids; of which 19,000 mg/L is chloride (Lyles, 2000). Consequently, Scheidleder (2003) stated that the main cause of high chloride (Cl) in coastal aquifers is most likely attributed to SWI.

Several studies have used basic approaches for identifying wells affected by SWI. For example, Lyles (2000) undertook a statistical analysis of 187 groundwater samples collected from Lopez Island, Washington, USA, and suggested that chloride concentrations over 100 mg/L are indicative of SWI. However, the study concluded that further investigation is needed to characterize other sources of salinity, not seawater, that contribute to the high levels of chloride. Kennedy (2012) developed a GIS based approach for the assessment of relative SWI in Nova Scotia; chloride concentrations greater than 50 mg/L were considered to represent elevated levels above background.

The use of single chemical parameters as indicators of SWI, however, can be problematic. According to Snow et al. (1990), high values of Cl, Na, Br and SO_4 generally correspond with SWI intrusion or connate water, and Ca, Mg, K and Sr are not useful when distinguishing between different types of saline water.

Quantitative and Graphical Approaches

Bear et al. (1999) outlined several indicators that can be used to distinguish SWI from other sources of salinity. These, as well as a few other indicators, are described below.

1. An elevated chloride concentration.
2. The ratio between Cl and Br can be used as a tracer because both chloride and bromide act conservatively when there is an absence of high amounts of organic matter. They may not act conservatively in the presence of high amounts of organic matter because they may react with the aquifer matrix. The ratio of Cl/Br in seawater is 297 and this ratio can be used to distinguish hypersaline brines (< 297) from evaporate-dissolution products (> 1000) and anthropogenic sources like sewage effluents (< 800) or agriculture-return flows (low).
3. Na/Cl ratios are typically lower in wells intruded by seawater than in ocean water; as a result, Na/Cl ratios less than 0.86 may represent wells impacted by SWI. Na/Cl ratios greater than 1 are typical of groundwater contaminated by anthropogenic sources.
4. An enrichment of Ca can be used as an indicator. High Ca/Mg and Ca/(HCO_3 and SO_4) ratios (greater than 1) may indicate the onset of SWI.
5. The Simpson Ratio, first described by Todd (1959), is the ratio of Cl/(HCO_3 + CO_3). Five classes were created to evaluate the level of contamination; good quality (<0.5), slightly contaminated (0.5-1.3), moderately contaminated (1.3-2.8), injuriously contaminated (2.8-6.6), and highly contaminated (6.6-15.5) (Todd, 1959; El Moujabber et al., 2006; Korfali and Jurdi, 2010).
6. Base exchange indices (BEX) can also be used to distinguish if an aquifer is undergoing salinization or freshening; according to Stuyfzand (2008), the best index (for a dolomite free aquifer system) is BEX = Na + K+ Mg – 1.0716Cl (meq/L) (Stuyfzand, 1986). A positive BEX represents freshening, a negative BEX represents salinization and a BEX with a value of zero represents no base exchange.

A graphical approach was developed by Panno et al. (2006), which involves plotting the ratios of different water quality parameters (Figure 2). Panno et al. (2006) suggest that a plot of

Cl/Br vs. Cl best reflects the evolution of water and trends of mixing. Mixing occurs between one end-member, representing pristine groundwater with natural background concentrations, to other end-members such as road salt and septic effluent, basin brines and animal waste, seawater, and landfill leachate. As shown in Figure 2, a water sample with a Cl/B ratio between approximately 250-400 and with a Cl concentration that exceeds 400 mg/L represents a composition that resembles saltwater, and therefore may be indicative of SWI.

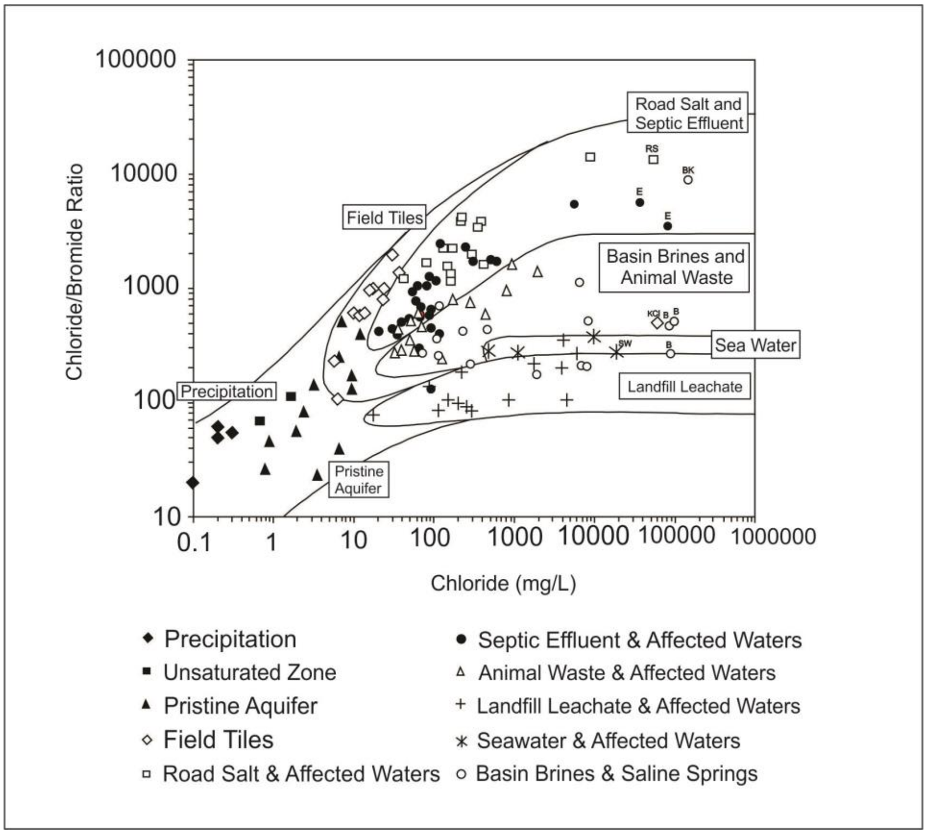

Figure 2: The evolution and mixing of pristine water to saline water (from: Panno et al., 2006).

An alternative graphical approach is to plot Cl vs. electrical conductivity (EC) (Washington State Department of Ecology, 2005). Figure 3 shows three zones on a plot of Cl vs. EC: normal, mixed and SWI. EC can be directly converted to the concentration of total dissolved solids (TDS) if the chemical composition is known or estimated based on a simple conversion factor (e.g., Eutech Instruments, 1997). Figure 3 shows that groundwater samples with Cl exceeding 200 mg/L and EC exceeding ~1000 µs/cm are most likely influenced SWI.

Groundwater samples that are characterized by Cl between 100-200 mg/L and EC between 600-2000 μs/cm represent a mixing between freshwater and saltwater.

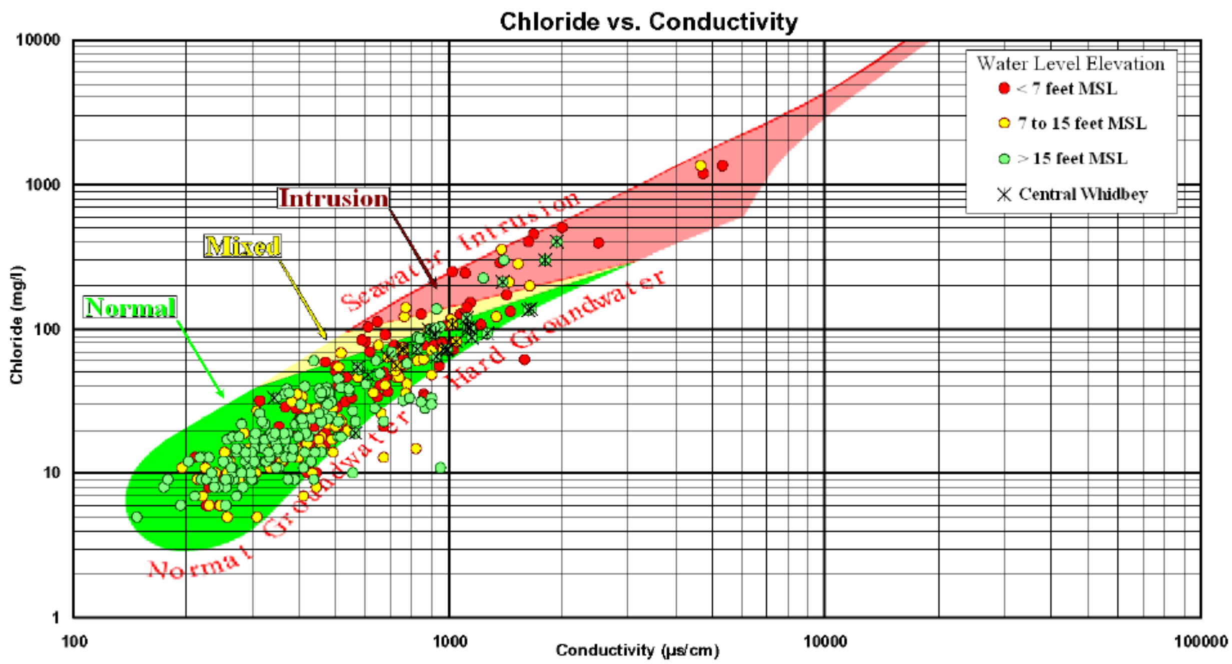

Figure 3: A plot of chloride vs. electrical conductivity showing normal groundwater conditions, saltwater intrusion, and mixing between the two (from: Washington State Department of Ecology, 2005)

Traditional Piper plots (Steinich et al., 1998; Appelo and Postma, 2005) can be used to plot the relative concentrations of the major ions on ternary diagrams. Samples representing seawater and young groundwater are often plotted as end-members with the other samples showing how the groundwater chemistry evolves (Figure 4). Symbols can also be scaled according to EC, for example.

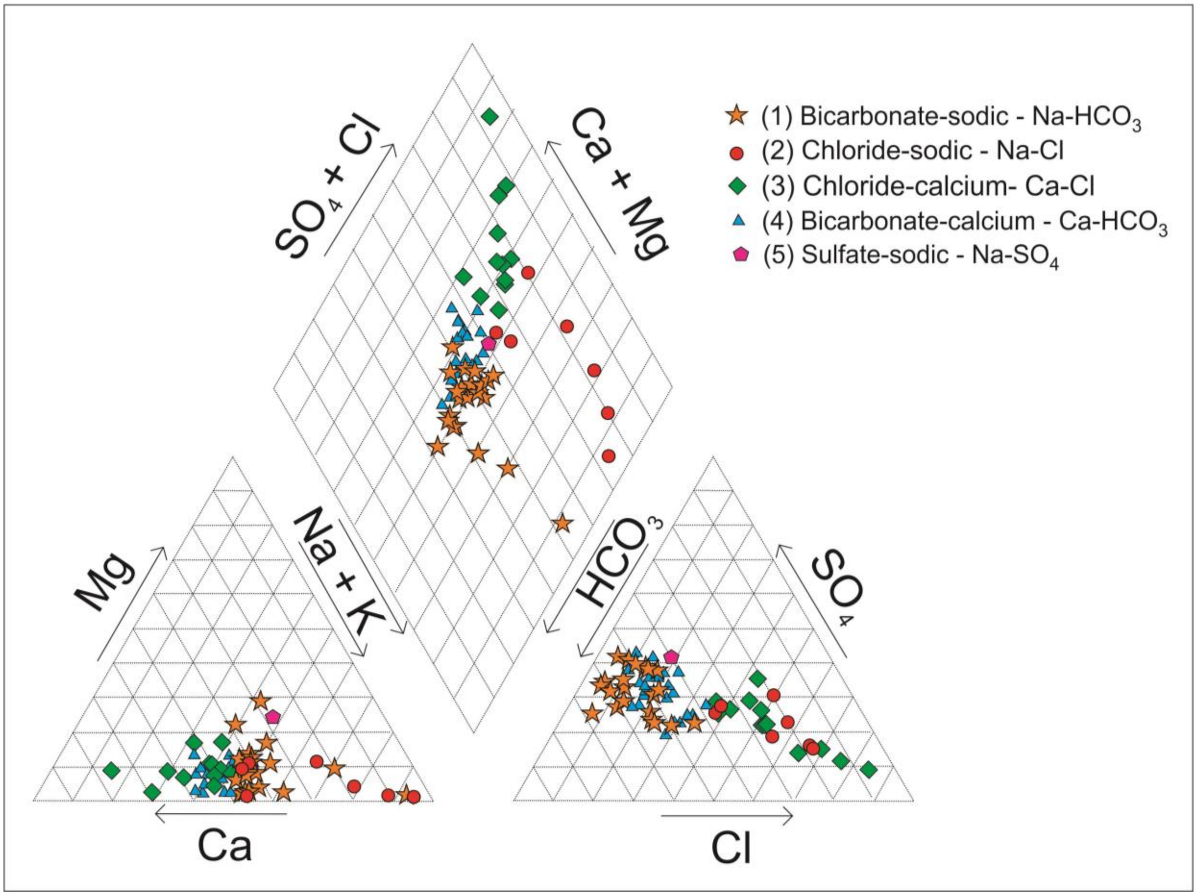

Figure 4: A Piper plot showing five water families; (1) Na-HCO_3 (2) Na-Cl (3) Ca-Cl (4) Ca-HCO_3 and (5) Na-SO_4 (Modified from: Steinich et al., 1998).

Finally, site-specific approaches can be used. For example, an approach specific to the situation where cation exchange (Ca to Na) dominates the chemical evolution involves plotting depth relative to sea level verses TDS, classified according to water type (represented as zones) (Allen and Liteanu, 2006; Figure 5). Zone 1 is characterized by waters that have a high TDS concentration due to direct salinization (mixing between fresh groundwater Ca-HCO_3 and sea water Na-Cl). Zone 2 is characterized by waters with TDS values that do not increase with depth, or that just slightly increase. These waters reflect a cation exchange process (Ca to Na) whereby no increase in salinity is observed. The water types in Zone 2 vary from Ca-HCO_3 to Na-HCO_3, with Na rich waters generally found at greater depths. Finally, Zone 3 represents waters that are mixed (between Zone 2 waters and a saline end member). These waters show variable cation composition (Ca or Na), but with increasing Cl concentration (Allen and Liteanu, 2008).

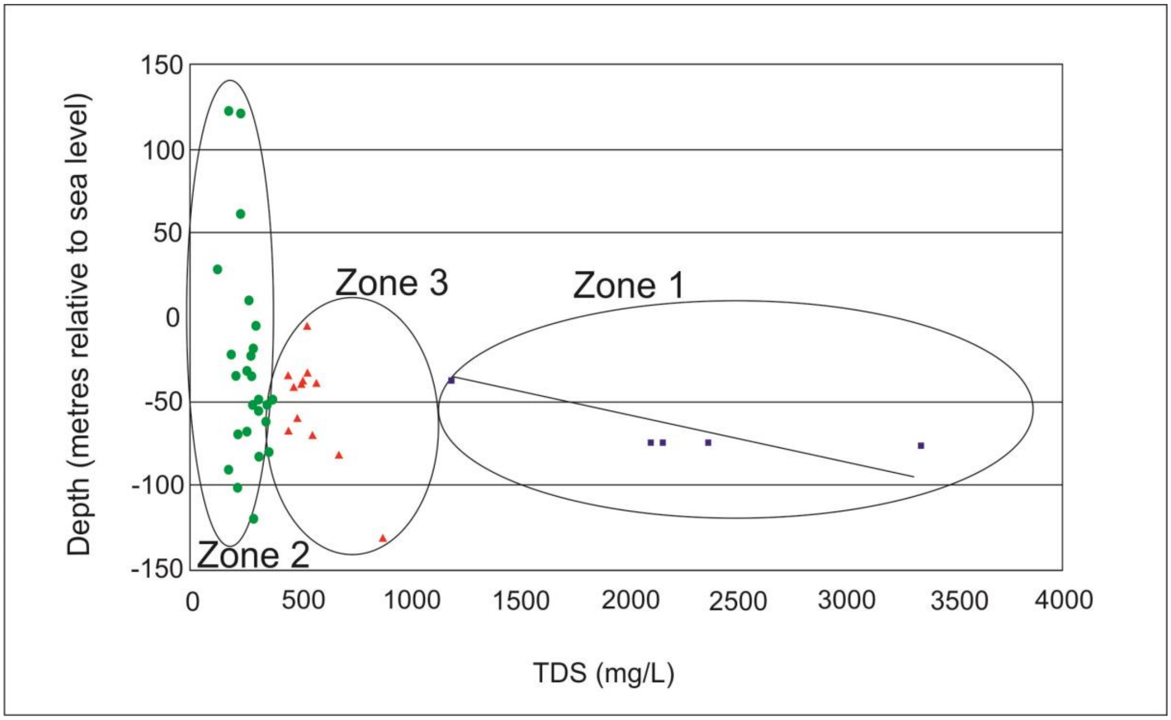

Figure 5: TDS variation with depth relative to sea level for water samples on Saturna Island, British Columbia (From: Allen and Liteanu, 2008)

The Study Area: The Gulf Islands, BC

Regional Geological Setting

The Gulf Islands are located in the Strait of Georgia, between Vancouver Island and the mainland of British Columbia (Figure 6). The islands trend NW-SE and tend to be elongate with linear ridges and valleys. Elevations generally range between 100 and 200 masl, with a maximum elevation of 350 masl on Saltspring Island. The islands are also characterized by rocky coastlines that slope shallowly into the ocean or sharp cliffs and narrow beaches. Locally, there are few natural lakes on the islands, and some support domestic and agricultural use. But the majority of residents use groundwater from the fractured bedrock aquifers as their primary source of freshwater (Denny et al., 2007). The quality of groundwater on the Gulf Islands has been impacted locally by several sources; improper disposal of agricultural waste, failed septic systems, pesticides and saltwater intrusion (Denny et al., 2007). During the summer months, when precipitation is low, the groundwater levels decline and the quality of the water can deteriorate (Allen and Suchy, 2001).

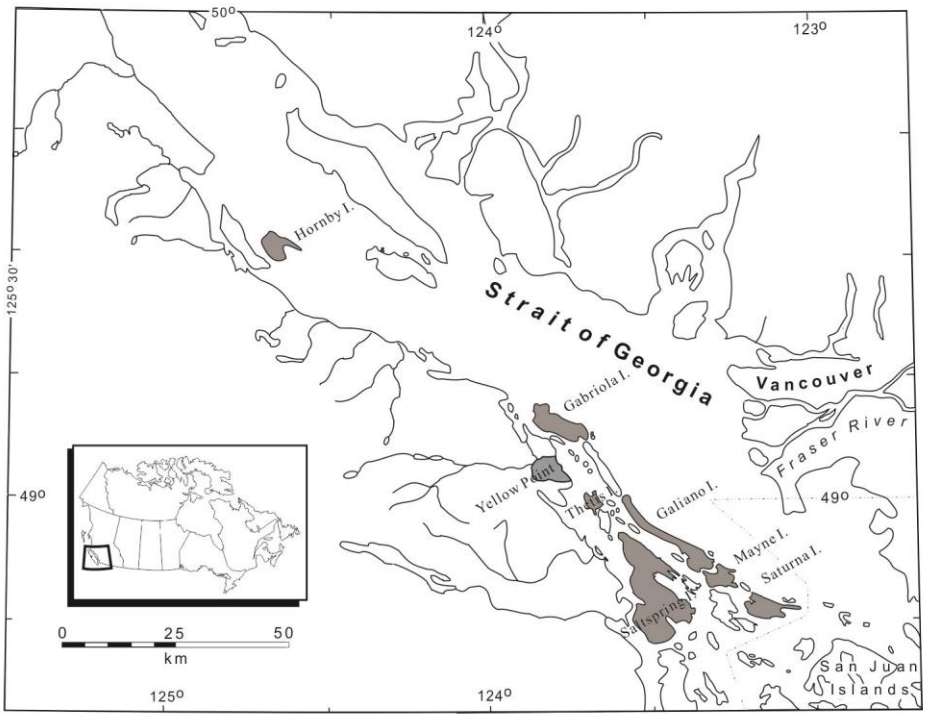

Figure 6: Location of the Gulf Islands in British Columbia, Canada. Water chemistry data for the shaded islands/areas are considered in this study.

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

During the Pleistocene, the Gulf Islands underwent regional depression due to the weight of the overlying glaciers. The land surface was depressed by as much as 300 m below present sea level (Clague, 1983). During the period of submersion below sea level (approximately 500-1000 years), there was likely sufficient time for seawater to intrude into the bedrock aquifers (Allen and Liteanu, 2008). Following rebound of the islands, fresh groundwater has gradually displaced the conservative and mobile Cl (Allen and Liteanu, 2008), but Na has been left behind on the clay exchange sites within the mudstone units; these mudstones exist both as massive mudstone, but also as mudstone interbeds within the coarser-grained sandstone. Fresh (or immature) groundwater has a $Ca\text{-}HCO_3$ composition reflecting evapotranspiration and carbonate mineral dissolution during recharge (Figure 7; Allen and Suchy, 2001). However, because Na continues to be released through cation exchange with Ca, the groundwater evolves naturally to an intermediate $Na\text{-}HCO_3$ composition (Cation shift arrow on Figure 7). Mixing between both water types and a more mature water type, Na-Cl, is also observed (Allen and Suchy, 2001). Most commonly, $Na\text{-}HCO_3$ waters mix with Na-Cl waters (Salinization Path 1 in Figure 7); however, in some wells, mixing between groundwater with a $Ca\text{-}HCO_3$ composition and a Na-Cl composition is observed (Salinization Path 2). Salinization Path 1 represents mixing with Cl-rich end member that may be remnant saltwater from when the islands were submerged, saline water present in the natural saltwater wedge underlying the island, or perhaps (although unlikely) connate water. Most of the wells characterized by this mixed water type are deep or are located near the coast. Salinization Path 2, reflects wells that have been impacted by SWI (Ca enrichment as suggested by Bear et al., 1999).

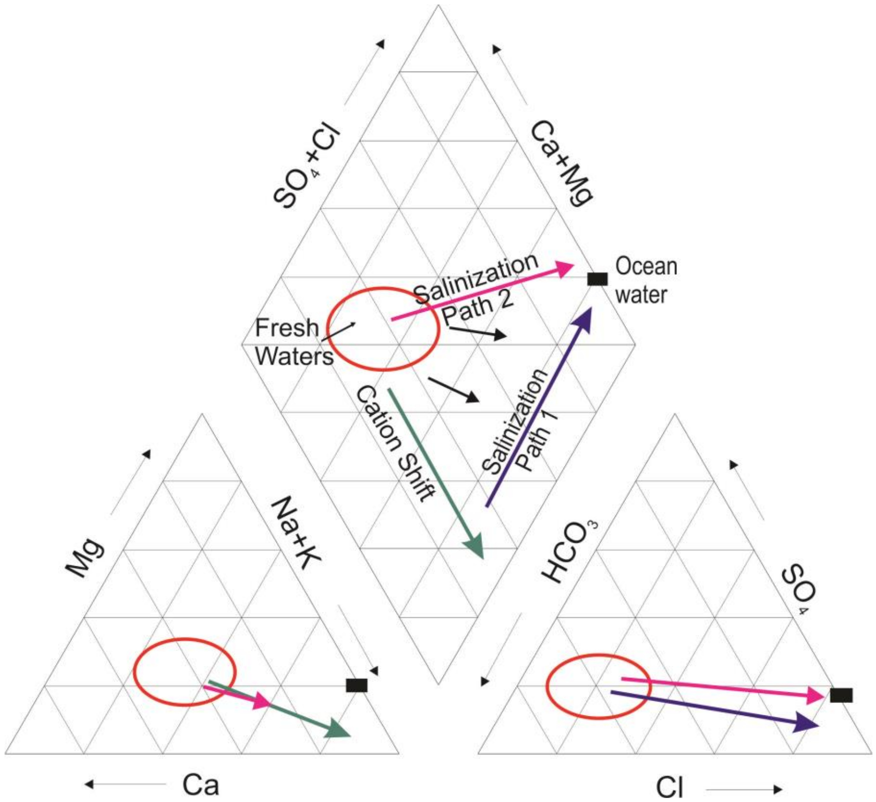

Figure 7: Groundwater chemistry evolution on the Gulf Islands (based on Allen and Suchy, 2001)

The geological history of the Gulf Islands has resulted in groundwater compositions that vary spatially. The water chemistry has evolved naturally, resulting in Na enrichment, making it challenging to use Na as an indicator of SWI. In addition, Cl is also present at high concentrations due to presence of remnant seawater, deep wells intersecting the wedge, or connate water, making the use of Cl as an indicator of SWI problematic. Furthermore, recent studies (Allen and Kirste, 2012) have shown that SO_4 concentrations can also be high in some wells due to mixing with seawater end-member that is enriched in SO_4. For these reasons, identifying indicators of SWI is not straightforward and requires consideration of various approaches.

Methodology

Groundwater Chemistry Database

Over the years 1963 to 2012, several synoptic groundwater sampling studies were undertaken in the Gulf Islands, and a substantial water chemistry database has been assembled. The islands for which groundwater chemistry data are available include Gabriola, Galiano, Hornby, Mayne, Saltspring, Saturna, Thetis and Yellow Point, near Nanaimo on Vancouver Island (Figure 6). In total, groundwater chemistry data for 992 wells are available. When a well had multiple entries, the most recent or complete record was used as a representative sample. Field and laboratory blanks, rainwater samples, ocean samples, and wells not suitable for statistical analysis (collected after being in a cistern, holding tank or after water softener was used) were removed.

The chemical parameters used for analysis included; bicarbonate (HCO_3), bromide (Br), calcium (Ca), chloride (Cl), electrical conductivity (EC), fluoride (F), magnesium (Mg), nitrate (NO_3), potassium (K), sodium (Na), sulfate (SO_4) and total dissolved solids (TDS). The commonly measured parameters were Ca, Cl, EC, F, Mg, K, Na and SO_4 and the parameters that were not measured consistently were Br and NO_3 and HCO_3 (these were calculated for Yellow Point, Gabriola, Saturna). For consistency, the sum of all the major ions was calculated to determine TDS for all the samples. With the exception of Galiano (a limited dataset), all parameters were consistently measured. As the water chemistry database was created from multiple datasets, the analytical precision varied. The detection limits for each island are stated in Table 1.

Table 1: Detection limits for chemical analyses conducted on the Gulf Islands. Where multiple detection limits are noted, different analytical techniques/laboratories were used.

Island	EC	pH	TDS	HCO_3	Br	Ca	Cl	F	Mg	NO_3	K	Na	SO_4
Units	µS/cm		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Gabriola	1	0.01	1	1	n/a	0.05	0.01	0.01	0.05	n/a	0.1	0.1	1
Galiano	No detection limits reported												
Hornby	1	0.1	1	0.5	n/a	0.05	1	0.1	0.05	n/a	1	0.05	1
Mayne	1	0.01	1	1	0.1	0.05	0.1	0.004	0.05	0.05	0.05	0.001	0.1
Salt Spring	1	0.1	10	0.5	0.1/ 0.02	0.05/ 0.02	0.5/ 0.01	0.01/ 0.004	0.05/ 0.002	0.002/ 0.02	1/ 0.01	0.05/ 0.01	0.5/ 0.05
Saturna	1	.1	1	0.5	n/a	0.05/ 0.01	0.2	0.05/ 0.2	0.05	0.05	0.01	0.1	0.5
Thetis	1	0.01	10	0.5	0.1	0.05	0.5	0.01	0.05	0.002	0.05	0.05	0.5
Yellow Point	1	0.01	1	1	n/a	0.05	0.01	0.01	0.05	n/a	0.1	0.1	1

n/a not analyzed.

Assessment of Common Indicators

A variety of common indicators used in previous studies were applied to the Gulf Islands data in order to determine which wells may be affected by SWI. To do this, several analyses were undertaken:

1. Calculating the enrichment of Ca based on the ratio of Ca/Mg and Ca/(HCO_3 + SO_4) (in mg/L) based on Bear et al. (1999).
2. Calculating the ratio of Cl/(HCO_3 + CO_3) based on Todd (1959), El Moujabber et al. (2006) and Korfali and Jurdi (2010).
3. Calculating the BEX for each island based on Stuyfzand (1986, 2008).
4. Calculating and plotting the Cl/Br ratio for each island based on Bear et al. (1999) and Panno et al. (2006).
5. Plotting Na vs. Cl (mol/L) for each island.
6. Plotting Cl (mg/L) vs. EC (µS/cm) for each island following the approach by Kelly (2005).
7. Plotting Piper plots to view whether the groundwater chemical evolution is consistent from island to island, and to identify common pathways for salinization.

8. Plotting Depth (m) vs. TDS (mg/L) for each island following the approach by Allen and Liteanu (2008).

Statistical Approach

A simple statistical approach was used in combination with bivariate plots to identify potential indicators of SWI. The first step in the statistical analysis involved determining a representative composition of seawater. While the composition of seawater varies depending on a variety of factors (Encylopeaedia Britannica, 2014), the average global seawater composition was used (Ocean samples were only available for Hornby and Saturna. For HCO_3, Br, Ca, Cl, Mg, K, Na and TDS, the global seawater composition was similar to the Hornby and Saturna ocean samples. Although the two ocean samples for EC, F and NO_3 were not similar to the global seawater composition, to be consistent overall, the global seawater composition was used) (Anthoni, J.F. 2006; Heyda, 2008; Holmes-Farley, 2003; Water Quality Association, 1999; Table 2).

Table 2: Seawater composition for Hornby and Saturna samples and average global seawater composition (sources: Anthoni, 2006; Heyda, 2008; Holmes-Farley, 2003; Water Quality Association, 1999).

	Global	Hornby	Saturna	Global	Hornby	Saturna
Parameter	**HCO_3**			**Br**		
mg/L	144.8	87.7	248.1	67.2	63	-
µS/cm	-	-	-	-	-	-
mol/L	2.4E-03	1.4E-03	4.1E-03	8.4E-04	7.9E-04	-
Parameter	**Ca**			**Cl**		
mg/L	410.5	265	385	19400	16000	18400
µS/cm	-	-	-	-	-	-
mol/L	1.0E-02	7.9E-03	9.6E-03	5.5E-01	4.5E-01	5.2E-01
Parameter	**EC**			**F**		
mg/L		-	-	13	0.7	0.05
uS/cm	56000	34300	32800	-	-	-
mol/L	-	-	-	6.8E-04	3.8E-05	2.6E-06
Parameter	**Mg**			**NO_3**		
mg/L	1288.5	866	996	0.5-2.5	-	9.7
µS/cm	-	-	-	-	-	-
mol/L	5.3E-02	3.6E-02	4.1E-02	8.1E-06 to 4.0E-05	-	1.6E-04
Parameter	**K**			**Na**		
mg/L	391.6	300	362	10787.7	8940	8530
µS/cm	-	-	-	-	-	-
mol/L	1.0E-02	7.7E-03	9.3E-03	4.7E-01	3.9E-01	3.7E-01
Parameter	**SO_4**			**TDS**		
mg/L	2697.9	2320	2150	29967.7 to 39954.4	28779.46	31071.15
µS/cm	-	-	-	-	-	-
mol/L	2.8E-02	2.4E-02	2.2E-02	-	-	-

The statistical approach initially considered the chemistry data for each island individually, and then for all islands together. For each island, a series of bivariate plots was generated to show each of HCO_3, Br, Ca, Cl, EC, F, Mg, NO_3, K, Na, SO_4 and TDS against Cl, along with the Global Seawater Mixing Line (GSML). The GSML was determined for each parameter. This was done by calculating the ratio for each parameter with Cl; that value was then used as the slope in a linear equation (y=mx+b). Wells that plot along the GSML (within the 95th confidence interval) are considered as being potentially affected by SWI.

The next step involved combining all the data for the Gulf Islands. Three parameters were considered: Cl, EC and TDS. Not all wells were sampled for all three parameters; therefore, for completeness, only the wells that had measured values of all three were used, resulting in 795 samples. For this reason, the dataset is considered a Partial Dataset. The results of the statistical analysis were later compared to the results when the Full Dataset was used (i.e. the statistical analysis includes all the wells regardless of whether one or more parameters (Cl, EC or TDS) is missing from the dataset).

For the statistical analysis, each parameter was ordered from largest to smallest, and the samples in the top 5% and 10% for each parameter were further examined (the 95th and 90th percentiles for each parameter). Each well sample that appeared to be affected by SWI (determined from the bivariate plots) was flagged. This allowed parameters that potentially correlate with SWI to be identified.

The final step was to compare the well samples that the common indicator approaches suggest are affected by SWI with the results of the statistical approach to determine which indicator method or combination of indicators is likely the most useful.

Results

Common Indicators

The results of using a variety of plots and other common indicators of SWI are reported in this section. These results are discussed further in relation to the statistical approach in the next section.

Ion Ratios

Enrichment of Ca can indicate SWI (Bear et al., 1999). Enrichment is reflected in Ca/Mg > 1 and Ca/(HCO_3 and SO_4) > 1. A total of 646 samples were used to calculate the Ca/Mg ratio, and 512 samples for the Ca/(HCO_3 and SO_4) ratio. All of the wells, except one, had Ca/Mg > 1; six samples had Ca/(HCO_3 and SO_4) >1.

The ratio of Cl/(HCO_3 + CO_3) can be used to identify contamination by seawater. A total of 785 samples were used; 31 samples were slightly contaminated, 15 samples were moderately contaminated, 5 samples were injuriously contaminated, and 17 samples were highly contaminated.

BEX indicates if an aquifer is experiencing salinization or freshening. A total of 544 samples were used, 34 samples were indicative of salinization, 79 were near zero and 431 samples indicated freshening.

Cl/Br vs. Cl

Figure 8 shows a plot of Cl/Br versus Cl, based on the method of Bear et al. (1999) and Panno et al. (2006). Br was only analyzed for Hornby, Mayne, Salt Spring and Thetis (361 samples). Many samples fell below the detection limit and were removed; therefore, only 117 samples were plotted. Well samples that fall in or near the Sea Water zone (shaded blue in Figure 8) are considered to be influenced by SWI.

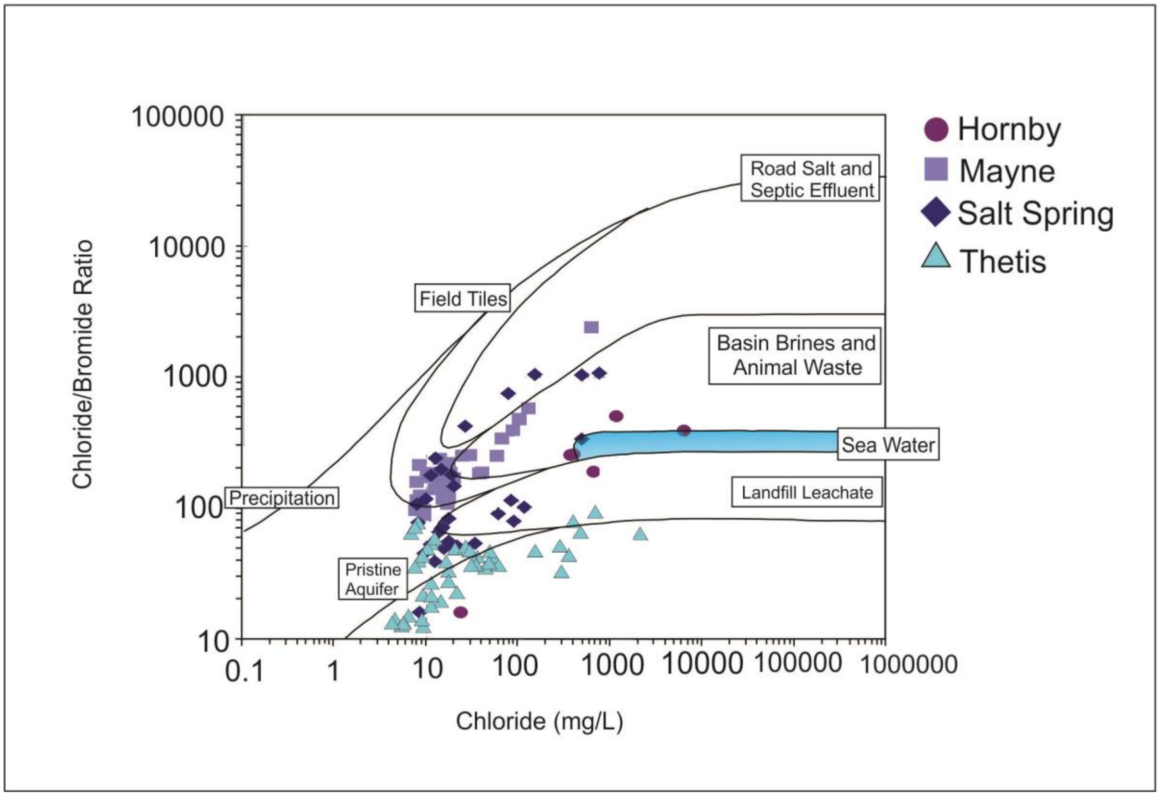

Figure 8: Chloride/Bromide vs. Chloride (based on the approach by Bear et al. 1999 and Panno et al. 2006).

Na vs. Cl

Figure 9 shows Na versus Cl for all of the Gulf Islands samples. The global seawater mixing line has a slope of 0.858. A Na/Cl ratio of 0.86 is thought to indicate SWI (Bear et al., 1999). All of the wells generally fall along this mixing line, therefore limiting the usefulness of this indicator on its own.

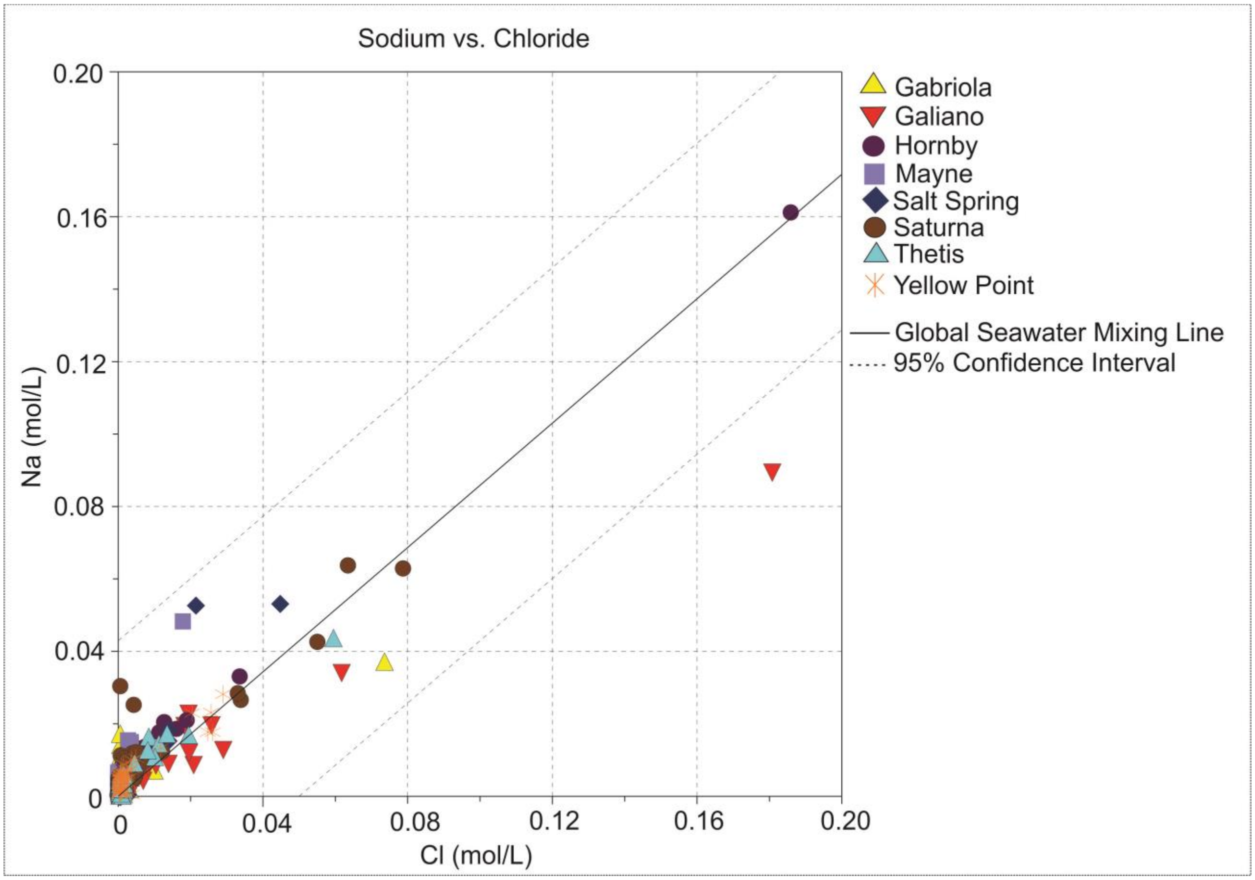

Figure 9: Sodium vs chloride for the Gulf Islands.

Cl vs. EC

A total of 795 well samples had both Cl and EC measurements (Figure 10; as per the approach by Kelly, 2005). The well samples that fall within the Seawater Intrusion zone are considered to be influenced by SWI.

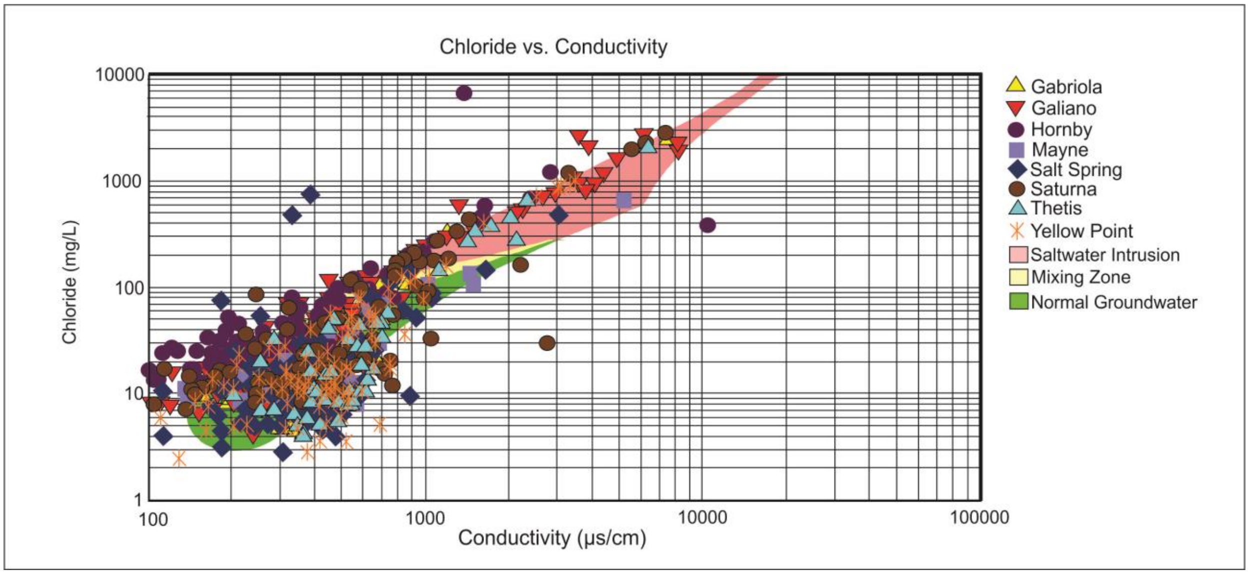

Figure 10: Chloride vs. Conductivity (based on approach outlined by Kelly, 2005)

Piper Plot

Figure 11 shows a Piper plot of all of samples for the Gulf Islands. The different groundwater chemical evolution paths and the Fresh Water composition field (shown in Figure 7) were transposed onto the Piper plot. The chemical evolution is fairly consistent from island to island. Samples considered fresh (Ca-HCO_3 type) plot near the Fresh Water field (oval in Figure 11). Cation exchange is a dominant process on all the islands. Salinization Path 1 is characterized by an increase in Cl and usually follows cation exchange. Salinization Path 2 reflects an increase in Cl but without significant cation exchange. All of the islands follow Salinization Path 1, while only Gabriola, Hornby, Saturna and Yellow Point have well samples that fall along Salinization Path 2. Salt Spring and Galiano had incomplete datasets; as a result, they are not fully represented on the Piper plot.

This Piper plot confirms that the groundwater chemistry evolution is consistent within the Gulf Islands, and that the same geochemical processes are taking place throughout the region. No one island stands out as being any different than the others.

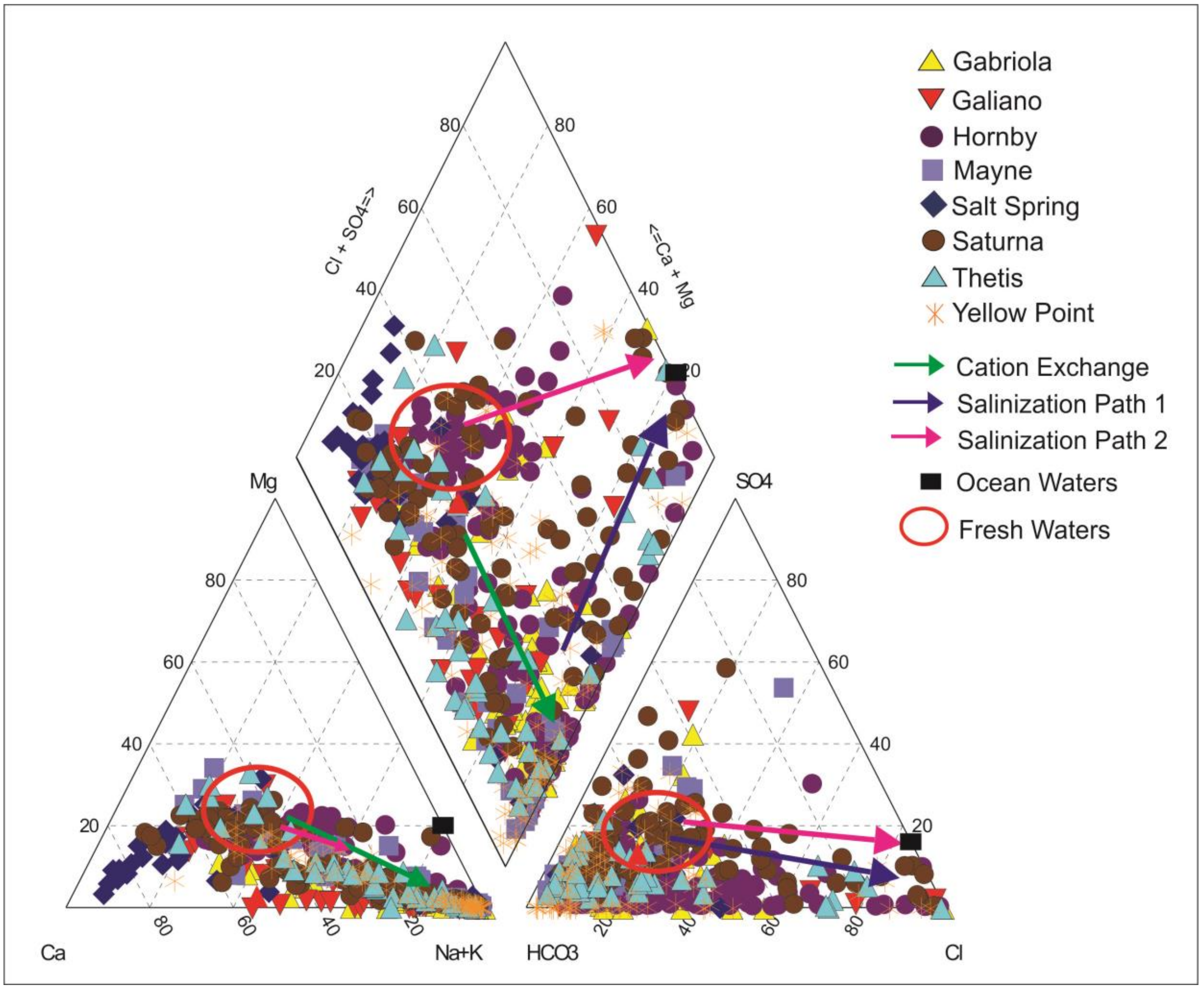

Figure 11: Piper plot for the Gulf Islands showing the groundwater chemistry evolution.

Figure 12a shows a plot of Depth vs. TDS by island using the same zone categories as Allen and Liteanu (2008). To obtain the depth relative to sea level (y-axis), the surface elevation of each well was determined using a 25-m digital elevation model (DEM). The depth of each was well then subtracted from the surface elevation to obtain "Depth relative to sea level". Some of the wells lacked information on well depth or TDS, therefore this approach was applied to 340 well samples (Galiano and Saltspring were not included because they did not have well depth information). Identification of the zones was based on the Piper plot (Figure 11). Well samples that are in Zone 1 plot near seawater along Salinization Path 1 and 2 and reflect wells that are impacted by SWI. Samples plotting in Zone 3 reflect mixing between Zone 2 waters (influenced by cation exchange) and Zone 1 (Figure 12b).

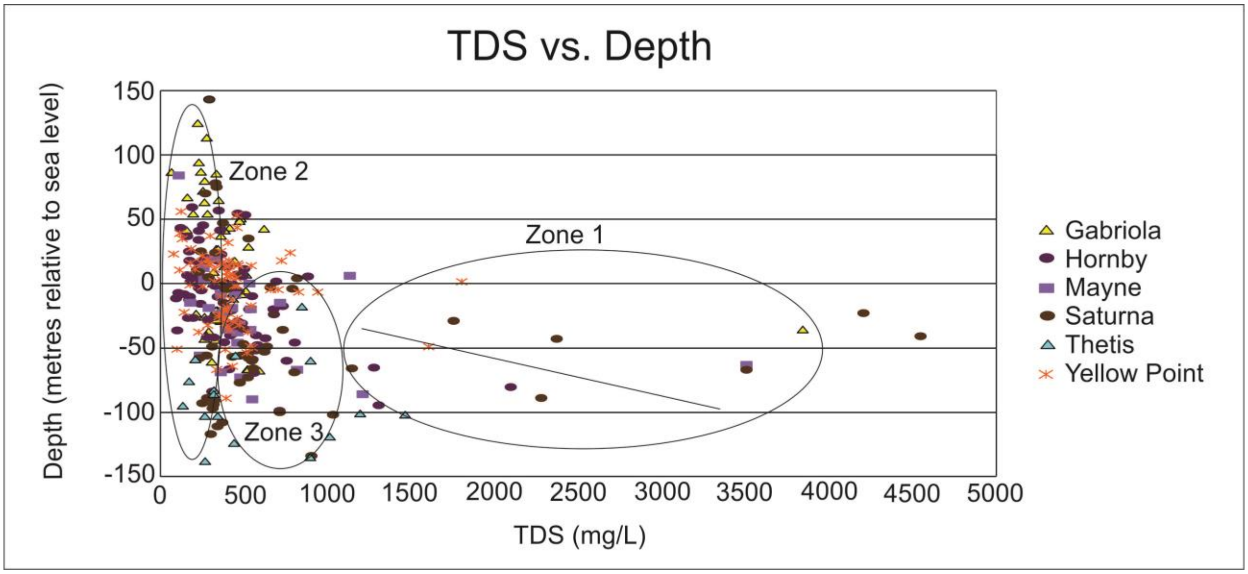

Figure 12a: TDS versus Depth for all samples.

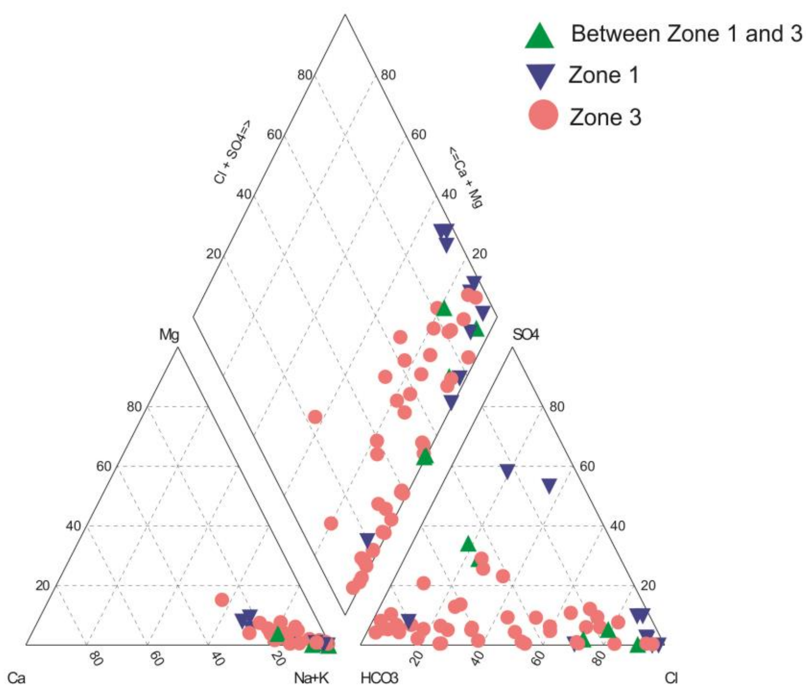

Figure 12b: Location of Zone 1 and Zone 3 waters on the Piper Plot (approximated).

Statistical Approach

Histograms for Cl, EC and TDS were created to determine the 90th and 95th percentile for the Partial Dataset (Figure 13). Samples with Cl >460 mg/L, EC >1626 μs/cm, and TDS >1044 mg/L represent the 95th percentile. Samples with Cl >129 mg/L, EC >866 μs/cm, and TDS >660 mg/L represent the 90th percentile (Figure 13).

Appendix 1 includes a table that identifies the well samples that fall in the 90th and 95th percentile; a colour scheme is employed to reflect the likelihood that a well sample is affected by SWI. If all three parameters for a sample fall within the 95th (or 90th) percentile, that well sample is considered to have a "very high likelihood of being affected by SWI". If only two parameters are within the 95th (or 90th) percentile, the well is assigned a "high likelihood of being affected by SWI". If only one parameter is in the 95th (or 90th) percentile, a "moderate likelihood of being affected by SWI" is assigned.

In Appendix 1, Column 1 flags whether the sample also had characteristics of SWI based whether the sample plotted along the Global Seawater Mixing Line (GSML) on various bivariate plots. One hundred percent (100%) of the samples in the top 95th percentile for Cl, show evidence of SWI. Eighty-seven percent (87.5%) of the samples in the 90th percentile for Cl show evidence of SWI. For EC, 100% of the samples appear to be affected by SWI in the top 95th and 90th percentiles. For TDS, 100% and 85% of wells appear to be affected by SWI for the 95th and 90th percentiles, respectively.

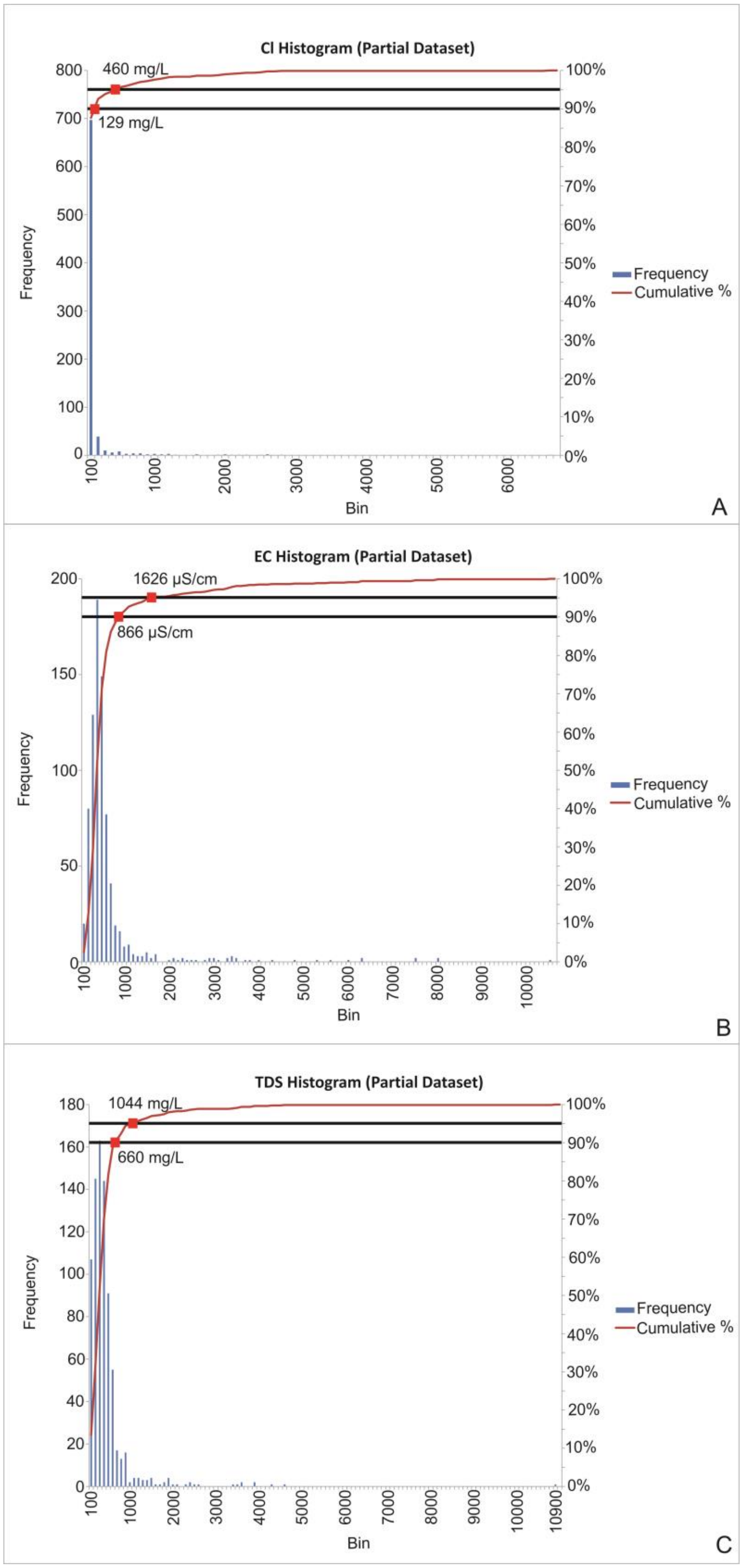

Figure 13: Histograms for Cl, EC and TDS for the Partial Dataset. The black lines mark the 95th and 90th percentiles.

A summary of the well samples that may be affected by SWI based on the combination of common indicators and the statistical approach is shown in Appendix 2. A rating was given to each well sampled based on the table Appendix 1. If a well sample was assigned a "very high likelihood of being affected by SWI" it was labelled as 95 VH or 90 VH, according to whether it fell within the 95th or 90th percentile, respectively. If it was assigned as having a "high likelihood of being affected by SWI" it was labelled as 95 H or 90 H for the 95th and 90th percentiles, respectively. Finally, if a well was assigned as having a "moderate likelihood of being affected by SWI" it was labelled as 95 M or 90 M for the 95th and 90th percentiles, respectively.

In Appendix 2, boxes that are coloured gray represent wells that were not sampled for the particular parameter required for that indicator approach, or if a value fell below the detection limit. Of the well samples that appear to be affected by SWI:

- 45% of well samples were not sampled for Ca, HCO_3 and/or SO_4 for the $Ca/(HCO_3 + SO_4)$ indicator approach.
- 19% of wells samples were not sampled for Cl, HCO_3 and/or CO_3 for the $Cl/(HCO_3 + CO_3)$ indicator approach.
- 34% of wells samples were not sampled for Na, K, Mg or Cl for the BEX indicator approach.
- 80% of well samples were not sampled for Cl and/or Br for the Cl/Br vs. Cl indicator approach.
- 8% of well samples were not sampled for Cl or EC for the Cl. vs EC indicator approach.
- 56% of well samples did not have measurements of well depth or TDS for the Depth vs. TDS approach.
- 8% were not sampled for Cl, EC and/or TDS and, therefore, were not included in the statistical approach.

Discussion

Evaluation of Indicators

The enrichment of Ca does not appear to be a good indicator for the Gulf Islands data. The first test (Ca/Mg) indicates that all wells (except for one) may be affected by SWI, as the ratio was greater than one for all of the well samples. The second test ($Ca/(HCO_3 + SO_4)$) identifies six wells that may be affected by SWI. Calcium enrichment is not a useful indicator because of the cation exchange process that takes place on the Gulf Islands as part of the natural groundwater chemistry evolution. Ca is lost from the groundwater in exchange for Na during cation exchange, which is a dominant process. As a result, this method is not consistent enough to be used as an indicator for SWI.

The ratio of $Cl/(HCO_3 + CO_3)$ appears to be a useful indicator; 100% of well samples that had a rating of 95 VH (statistical approach) and 69% of well samples with a rating of 90 VH were also identified by this approach. Zero percent of well samples that had a rating of 95 H were identified by this approach, but there were only four well samples and three of them were not included because they lacked data. For well samples with a rating of 90 H and 90 M, 18% and 30%, respectively, were identified by this approach. This indicator had the best results (100%) with wells that had a rating of 95 VH, suggesting that this indicator should not be used alone but rather in combination with other indicators.

BEX could potentially be a useful indicator; 70% and 20% of well samples with a rating of 95 VH and 90 VH were also identified with this approach. No well samples with a rating of 95 H and 90 H were identified using this approach, and 17% of well samples with a rating of 90 M were identified with this approach. Similar to the $Cl/(HCO_3 + CO_3)$ indicator approach, this indicator had the best results with wells that had a rating of 95 VH, therefore it would be useful if used in combination with other indicators.

Based on the results shown in Appendix 2, Cl/Br ratio does not appear to be an effective indicator of SWI for the Gulf Islands for the following reasons: (1) only Hornby, Mayne, Salt Spring and Thetis were sampled for Br (4 out of 8 islands); (2) the detection limit for Br on Hornby and Salt Spring was not suitable for capturing data (detection limit was assumed to be 1 for Hornby and was 0.1 or 0.02 for Salt Spring, depending on the well sample); therefore, few samples were available; (3) 80% of the well samples that appear to be affected by SWI were not sampled for Br or Cl.

Cl vs. EC does appear to be a useful indicator. All of the well samples that were identified using the Cl vs. EC indicator method were also identified using the statistical approach. This is not surprising because the same parameters are considered in both methods.

TDS vs. depth could be a useful indicator as 100% of the well samples that were identified as being affected by SWI by this approach were also identified with the statistical approach. A limitation to this approach is that 46% of the well samples that were identified as being affected by SWI by the statistical approach did not have a well depth measurement and, therefore, were not included in this approach.

The most reliable indicators were found to be Cl/(HCO_3 + CO_3), BEX, Cl vs EC, and Depth vs TDS (common indicators, when used in conjunction) and the statistical approach (90^{th} and 95^{th} percentiles); this results in 138 well samples (out of 795 samples or 17%) that appear to be impacted by SWI.

Comparison of Results for the Partial Dataset with the Full Dataset

As discussed previously, the statistical analysis had only included those wells where all three parameters (Cl, EC and TDS) were available. A final comparison considers the Full Dataset for the Gulf Islands (992 samples in total; 853 Cl samples, 922 EC samples and 947 TDS samples). Again, only Cl, EC and TDS were used, but no well samples were removed. That is, if any of Cl, EC or TDS was not available for a sample, the well was not discarded. Similar to the statistical approach used for the Partial Dataset, histograms were created for Cl, EC and TDS and the 95th and 90th percentile were determined (Figure 14).

Table 6 illustrates that the 95th and 90th percentiles for these parameters are similar regardless of whether the Full Dataset it used or not. This lends support to the use of partial information on a well sample.

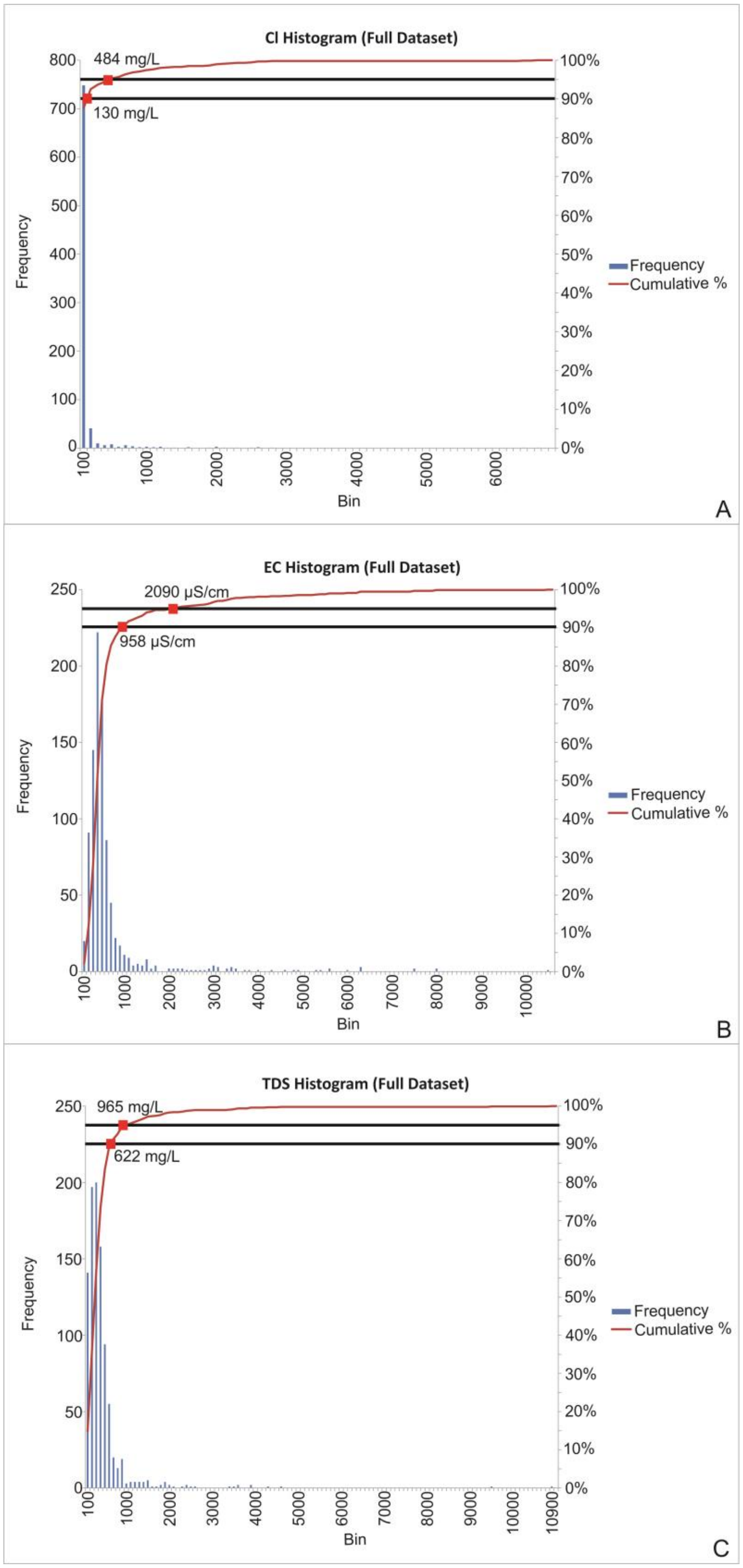

Figure 14: Histograms for Cl, EC and TDS for the Full Dataset. The black lines mark the 95th and 90th percentiles.

Table 6: Summary of 95th and 90th percentile for the partial and full dataset.

Indicator	Cl (mg/L)		EC (µS/cm)		TDS (mg/L)	
	Partial Dataset	Full Dataset	Partial Dataset	Full Dataset	Partial Dataset	Full Dataset
95th Percentile	460	484	1626	2090	1044	965
90th Percentile	129	130	869	958	660	621
# samples	795	853	795	922	795	947

Threshold Values

The threshold values for Cl, EC and TDS based on the 95th and 90th percentiles are reported in Table 7. These threshold values derive from using the Full Dataset. These are the recommended values that can be used with 95% confidence or 90% confidence that a well sample is affected by SWI. The values do not distinguish between whether SWI is caused by active salinization due to pumping or other factors, whether old seawater or connate water are present, or whether the well has simply been drilled too deep and intersects the freshwater-saltwater interface. The values simply reflect, statistically, if the measured parameter falls within these upper percentiles of all previous chemistry data for the region.

Table 7: Recommended thresholds for each of Cl, EC and TDS. Based on the 95th and 90th percentiles in the Full Dataset

Indicator	Cl (mg/L)	EC (µS/cm)	TDS (mg/L)
95th percentile	484	2090	965
90th percentile	130	958	621

Both EC and TDS are readily measured in the field using portable, inexpensive meters. Portable test kits are also available for Cl, but on site measurement is not considered to be critical. During drilling, or for simple monitoring purposes, either EC or TDS could be measured to give an indication of whether SWI is present. Conservatively, the 90th percentile values should be used to flag a likelihood of SWI. If any parameter is exceeded at the 90th percentile level, then the drilling should be halted (or during monitoring notice taken) and a water sample collected for chemical analysis.

Following the chemical analysis, several other indicators could be assessed to verify the results. Ideally, a full chemical analysis would include Br, as this is a common and important indicator for SWI. Its use currently on the Gulf Islands is limited because it is measured infrequently. Similarly, well depth should be recorded for any sampled wells.

Conclusions

The purpose of this study was to test different indicators of saltwater intrusion that have been used in other studies, as well as to use a simple statistical approach informed by bivariate plots to identify wells that are likely affected by saltwater intrusion. In the study, no distinction is made between whether the wells are currently impacted by active saltwater intrusion, or whether the source of salinity is older seawater or simply saline water beneath the freshwater interface.

Based on the analysis, chloride (Cl), electrical conductivity (EC) and total dissolved solids (TDS) are the best indicators of saltwater intrusion. Using a Partial Dataset (795 samples) comprising only those wells where all three parameters (Cl, EC and TDS) were measured, the 95th percentiles are 460 mg/L, 1626 µS/cm and 1044 mg/L, respectively. Bivariate plots were then used to identify samples that fall along the Global Seawater Mixing Line and these samples were flagged, showing that 100% of the samples in the 95th percentile for Cl, EC and TDS are likely to be affected by saltwater intrusion. The 90th percentiles for Cl, EC and TDS are 129 mg/L, 869µS/cm and 660 mg/L, respectively, with 87.5%, 100% and 85% of the water samples in the 90th percentile likely being affected by saltwater intrusion.

Using the Full Dataset (853 Cl samples, 922 EC samples and 947 TDS samples), which had one or two missing parameters (Cl, EC and TDS), the 95th and 90th percentiles were found not to vary significantly for Cl and TDS compared to the higher quality Partial Dataset, but vary significantly for EC. The 95th and 90th percentiles for Cl are 483 mg/L and 130 mg/L, 2,090 µS/cm and 958 µS/cm for EC, and 965 mg/L and 621 mg/L for TDS, respectively. These values identify robust and defensible indicators that can be used to identify wells that are impacted by salinity in the Gulf Islands.

Acknowledgements

The authors gratefully acknowledge the BC Ministry of Environment and BC Ministry of Forests, Lands and Natural Resource Operations for providing water chemistry data for Salt Spring and Thetis Islands, Steve Earle (Vancouver Island University) for providing data for Gabriola Island and Yellow Point, near Nanaimo. Data for Galiano are historical and obtained from the BC WELLS database. Data for Saturna, Hornby and Mayne Islands are from previous Simon Fraser University studies. The authors thank Sylvia Barroso (BC Ministry of Forests, Lands and Natural Resource Operations) for providing comments on an earlier draft of this report.

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Appendix 1

Chloride (Cl), Electrical Conductivity (EC) and Total Dissolved Solids (TDS) listed by decreasing value. Column 1 indicates if the well sample also plotted along the Global Seawater Mixing Line in bivariate plots, suggesting it is affected by SWI. Shown are samples that fall in the 95th percentile (above the first white row) and the 90th percentile (above the second white row). Samples are colour coded to reflect the likelihood that the well is affected by SWI.

Affected by SWI	Location	Site/WTN	Cl (mg/L)
*	Hornby	SP-13	6600
*	Saturna	MD-2	2800
*	Gabriola	511	2600
*	Galiano	20796	2593
*	Galiano	37402	2500
*	Saturna	NB-3	2260
*	Galiano	21042	2180
*	Thetis	Site 44	2100
*	Galiano	19954	2000
*	Saturna	EP-6	1960
*	Galiano	25890	1818
*	Salt Spring	Site 32	1579
*	Galiano	43157	1545
*	Saturna	EP-27A	1210
*	Hornby	WB-3	1200
*	Saturna	EP-29C	1180
*	Galiano	17919	1121
*	Galiano	653	1020
*	Yellow Point	139	1018
*	Yellow Point	145	916
*	Galiano	26014	905
*	Yellow Point	106	900
*	Galiano	16351	900
*	Yellow Point	144	870
*	Galiano	42180	776
*	Salt Spring	Site 16	752
*	Galiano	17122	730
*	Yellow Point	125	715
*	Galiano	19775	680
*	Hornby	WB-10	680
*	Thetis	Site 4	680
*	Mayne	M-HB-30	643
*	Hornby	TR-2	580
*	Galiano	22770	560
*	Galiano	35004	515
*	Salt Spring	Site 29	485
*	Galiano	21618	484
*	Salt Spring	Site 14	484
*	Thetis	Site 25	470
*	Hornby	SP-1	460
95th Percentile		Percent	100
*	Saturna	EP-28B	439
*	Hornby	PP-15	410
*	Yellow Point	177	408
*	Thetis	Site 13	390
*	Hornby	WB-9	380
*	Galiano	60517	360
*	Thetis	Site 14	350
*	Gabriola	517	346
*	Saturna	EP-2	332
*	Thetis	Site 11	290
*	Galiano	62675	284
*	Galiano	13558	283
*	Thetis	Site 24	280
*	Saturna	EP-20	272
*	Hornby	PP-7	270
*	Galiano	25732	236
*	Galiano	48235	212
*	Hornby	SP-10	210
*	Saturna	EP-3	209
*	Hornby	BT-9	200
*	Galiano	17119	189
*	Saturna	WC-7	185
*	Saturna	EP-18	180
*	Saturna	SB-HP	177
*	Saturna	OPF-1	172
*	Saturna	EP-21	168
*	Galiano	37557	167
*	Galiano	43024	167
*	Yellow Point	154	164
*	Saturna	EP-5	161
*	Saturna	LC-2	161
	Hornby	SP-12	150
*	Thetis	Site 18	150
*	Salt Spring	Site 31	149
*	Salt Spring	MoE # 281	146
	Saturna	EP-4	141
	Galiano	20655	135
*	Mayne	M-HB-29	132
	Hornby	TR-8	130
	Gabriola	516	129
90th Percentile		Percent	87.5

Affected by SWI	Location	Site/WTN	EC (µS/cm)
*	Hornby	WB-9	10450
*	Galiano	21042	8000
*	Galiano	25890	8000
*	Gabriola	511	7420
*	Saturna	MD-2	7410
*	Thetis	Site 44	6300
*	Saturna	NB-3	6280
*	Galiano	20796	6000
*	Saturna	EP-6	5590
*	Mayne	M-HB-30	5230
*	Galiano	43157	4800
*	Galiano	17919	4300
*	Galiano	16351	4000
*	Galiano	19954	3800
*	Galiano	42180	3700
*	Galiano	26014	3500
*	Galiano	37402	3500
*	Yellow Point	139	3390
*	Galiano	653	3350
*	Saturna	EP-29C	3310
*	Saturna	EP-27A	3300
*	Yellow Point	145	3250
*	Yellow Point	106	3010
*	Salt Spring	Site 29	2985
*	Yellow Point	144	2950
*	Galiano	17122	2880
*	Hornby	WB-3	2830
*	Saturna	WC-BP *	2760
*	Galiano	19775	2600
*	Yellow Point	125	2460
*	Hornby	WB-10	2400
*	Thetis	Site 4	2300
*	Saturna	LC-2	2220
*	Galiano	35004	2200
*	Thetis	Site 11	2100
*	Galiano	21618	2090
*	Thetis	Site 25	2000
*	Thetis	Site 13	1700
*	Hornby	TR-2	1642
*	Salt Spring	Site 31	1626
95th Percentile		Percent	100
*	Hornby	SP-1	1605
*	Yellow Point	177	1590
*	Hornby	PP-15	1568
*	Thetis	Site 14	1500
*	Mayne	M-HB-21	1498
*	Mayne	M-HB-29	1455
*	Galiano	60517	1440
*	Saturna	EP-28B	1440
*	Thetis	Site 24	1400
*	Hornby	SP-13	1382
*	Saturna	EP-2	1307
*	Galiano	13558	1300
*	Galiano	22770	1300
*	Saturna	WC-7	1220
*	Gabriola	517	1180
*	Galiano	62675	1170
*	Yellow Point	154	1170
*	Saturna	EP-20	1110
*	Thetis	Site 18	1100
*	Hornby	PP-7	1080
*	Saturna	SB-HP	1080
*	Saturna	LC-8	1054
*	Salt Spring	Site 79	1040
*	Salt Spring	Site 113	1035
*	Mayne	M-BB-20	1026
*	Saturna	WC-6	1024
*	Yellow Point	113	1010
*	Saturna	WC-P	994
*	Galiano	25732	987
*	Hornby	SP-10	985
*	Yellow Point	153	965
*	Saturna	OPF-1	958
*	Saturna	LC-4	941
*	Saturna	EP-3	916
*	Salt Spring	Site 56	912
*	Galiano	48235	900
*	Yellow Point	130	899
*	Galiano	37557	890
*	Hornby	BT-9	869
*	Salt Spring	MoE # 281	866
90th Percentile		Percent	100

Affected by SWI	Location	Site/WTN	TDS (mg/L)
*	Hornby	SP-13	10871
*	Saturna	MD-2	4548
*	Saturna	NB-3	4207
*	Salt Spring	Site 32	3849
*	Gabriola	511	3843
*	Saturna	EP-6	3506
*	Mayne	M-HB-30	3506
*	Thetis	Site 44	3442
*	Galiano	21042	3398
*	Galiano	20796	2593
*	Galiano	37402	2500
*	Saturna	EP-29C	2371
*	Salt Spring	Site 16	2344
*	Saturna	EP-27A	2279
*	Hornby	WB-3	2096
*	Galiano	19954	2000
*	Yellow Point	144	1880
*	Yellow Point	145	1878
*	Galiano	25890	1818
*	Yellow Point	139	1803
*	Saturna	LC-2	1754
*	Galiano	653	1711
*	Yellow Point	106	1606
*	Galiano	43157	1545
*	Galiano	19775	1474
*	Thetis	Site 4	1465
*	Yellow Point	125	1457
*	Galiano	26014	1426
*	Salt Spring	Site 29	1393
*	Hornby	PP-15	1309
*	Hornby	WB-10	1306
*	Hornby	SP-1	1277
*	Mayne	M-HB-21	1210
*	Hornby	TR-2	1207
*	Thetis	Site 25	1195
*	Saturna	WC-BP *	1145
*	Mayne	M-HB-29	1133
*	Galiano	17919	1121
*	Galiano	17122	1067
*	Galiano	42180	1044
95th Percentile		Percent	100
*	Saturna	WC-7	1032
*	Thetis	Site 13	1013
*	Yellow Point	177	941
*	Saturna	EP-28B	903
*	Galiano	16351	900
*	Thetis	Site 14	898
*	Thetis	Site 11	897
*	Hornby	PP-7	889
*	Hornby	SP-10	883
*	Salt Spring	Site 14	853
*	Thetis	Site 24	847
*	Galiano	21618	844
*	Saturna	WC-6	839
*	Yellow Point	154	827
*	Saturna	SB-HP	825
*	Saturna	LC-8	818
*	Mayne	M-BB-20	817
*	Galiano	60517	814
*	Hornby	WB-9	804
*	Saturna	EP-2	802
*	Saturna	WC-P	793
	Saturna	WC-4	789
*	Yellow Point	153	777
*	Galiano	62675	764
*	Thetis	Site 18	759
*	Hornby	GA-4	755
*	Saturna	LC-4	732
*	Hornby	BT-9	731
*	Yellow Point	113	725
	Mayne	M-HB-28	715
*	Saturna	OPF-1	714
*	Saturna	EP-20	713
*	Yellow Point	119	705
*	Galiano	13558	693
	Hornby	SS-1	692
*	Galiano	22770	690
	Saturna	WC-13	679
	Hornby	SP-9	677
*	Galiano	25732	670
	Yellow Point	120	660
90th Percentile		Percent	85

	Very High Likelihood	High Likelihood	Moderate Likelihood
Present in 95th Percentile			
Present in 90th Percentile			

Appendix 2

Summary of results for the combination of common SWI indicators and statistical approach for the Gulf Islands water chemistry data. 138 well samples are identified as being impacted by SWI.

Location	Site/WTN	SWI Flag	Rating	Ca/ (HCO3 + SO4)	Cl/ (HCO3+CO3)	Cl/Br	BEX	Cl vs. EC	Depth vs. TDS
Gabriola	511	*	95 VH		Highly Contaminated		Salinized	*	Zone 1
Gabriola	516		90 M		Slightly Contaminated			*	
Gabriola	517	*	90 H		Highly Contaminated			*	
Gabriola	528	*							
Gabriola	577						Salinized		
Galiano	653	*	95 VH		Highly Contaminated		Salinized	*	
Galiano	6955	*							
Galiano	7072	*							
Galiano	7162	*			Moderately Contaminated				
Galiano	12995				Slightly Contaminated				
Galiano	13558	*	90 VH		Slightly Contaminated			*	
Galiano	14562	*							
Galiano	16351	*	90 VH					*	
Galiano	17119	*	90 M					*	
Galiano	17122	*	95 VH		Injuriously Contaminated			*	
Galiano	17123	*			Highly Contaminated				
Galiano	17919	*	95 VH					*	
Galiano	19775	*	95 VH		Moderately Contaminated			*	
Galiano	19954	*	95 VH						
Galiano	20438	*							
Galiano	20655		90 M		Slightly Contaminated		Salinized	*	
Galiano	20796	*	95 VH					*	
Galiano	21042	*	95 VH		Highly Contaminated			*	
Galiano	21618	*	90 VH		Moderately Contaminated			*	
Galiano	22770	*	90 VH					*	
Galiano	23497	*			Moderately Contaminated		Salinized		
Galiano	25732	*	90 VH		Slightly Contaminated		Salinized	*	
Galiano	25890	*	95 VH					*	
Galiano	26014	*	95 VH		Highly Contaminated			*	
Galiano	35004	*	95 H					*	
Galiano	37402	*	95 VH						
Galiano	37557	*	90 H					*	
Galiano	42180	*	95 VH		Moderately Contaminated			*	
Galiano	43024		90 M					*	
Galiano	43044	*							
Galiano	43157	*	95 VH					*	
Galiano	48235	*	90 H					*	
Galiano	60517	*	90 VH		Moderately Contaminated		Salinized	*	
Galiano	60596				Slightly Contaminated				
Galiano	62675	*	90 VH		Slightly Contaminated			*	
Hornby	SP-1	*	95 VH		Slightly Contaminated			*	Zone 1
Hornby	SP-9		90 M						Zone 3
Hornby	SP-10	*	90 VH					*	Btw Zone 1 and 3
Hornby	SP-12		90 M						
Hornby	SP-13	*	90 VH		Highly Contaminated		Salinized		Zone 1
Hornby	TR-2	*	95 VH		Moderately Contaminated			*	
Hornby	TR-8		90 M					*	
Hornby	BT-9	*	90 VH					*	Zone 3
Hornby	BT-15				Slightly Contaminated		Salinized		
Hornby	CL-2				Slightly Contaminated				
Hornby	CL-3				Slightly Contaminated				
Hornby	CL-4				Slightly Contaminated				
Hornby	GA-4	*	90 M						Zone 3
Hornby	GA-9				Slightly Contaminated				
Hornby	WB-2				Slightly Contaminated				
Hornby	WB-3	*	95 VH		Highly Contaminated		Salinized		Zone 1
Hornby	WB-9	*	90 VH		Moderately Contaminated	*			Zone 3
Hornby	WB-10	*	95 VH		Injuriously Contaminated			*	Btw Zone 1 and 3
Hornby	SV-2				Slightly Contaminated				
Hornby	SS-1		90 M						Zone 3
Hornby	PP-7	*	90 VH		Slightly Contaminated			*	
Hornby	PP-15	*	90 VH		Slightly Contaminated	*		*	
Mayne	M-BB-20	*	90 H						Zone 3
Mayne	M-HB-21	*	90 H						Btw Zone 1 and 3
Mayne	M-HB-28		90 M						Zone 3
Mayne	M-HB-29	*	90 VH						Btw Zone 1 and 3
Mayne	M-HB-30	*	95 VH		Slightly Contaminated			*	Zone 1
Salt Spring	MoE # 281	*	90 H					*	
Salt Spring	Site 13	*	90 M						

Location	Site/WTN	SWI Flag	Rating	Ca/ (HCO3 + SO4)	Cl/ (HCO3+CO3)	Cl/Br	BEX	Cl vs. EC	Depth vs. TDS
Salt Spring	Site 14	*	90 H			*			
Salt Spring	Site 16	*	95 H						
Salt Spring	Site 29	*	95 VH					*	
Salt Spring	Site 31		90 H						
Salt Spring	Site 32	*	95 H						
Salt Spring	Site 34						Salinized		
Salt Spring	Site 56	*	90 M						
Salt Spring	Site 65						Salinized		
Salt Spring	Site 69	*							
Salt Spring	Site 79	*	90 M						
Salt Spring	Site 113	*	90 M						
Salt Spring	Site 131						Salinized		
Salt Spring	Site 132						Salinized		
Saturna	EP-2	*	90 VH		Moderately Contaminated			*	Zone 3
Saturna	EP-3	*	90 H		Moderately Contaminated			*	
Saturna	EP-4		90 M		Slightly Contaminated			*	
Saturna	EP-5	*	90 M		Slightly Contaminated			*	
Saturna	EP-6	*	95 VH	*	Highly Contaminated		Salinized	*	Zone 1
Saturna	EP-14						Salinized		
Saturna	EP-18	*	90 M		Slightly Contaminated			*	
Saturna	EP-20	*	90 VH		Slightly Contaminated			*	Zone 3
Saturna	EP-21	*	90 M		Slightly Contaminated		Salinized	*	
Saturna	EP-27A	*	95 VH		Highly Contaminated		Salinized		Zone 1
Saturna	EP-28B	*	90 VH		Injuriously Contaminated		Salinized	*	Zone 3
Saturna	EP-29C	*	95 VH		Highly Contaminated		Salinized		Zone 1
Saturna	EP-32				Slightly Contaminated				
Saturna	EP-S				Slightly Contaminated				
Saturna	LC-2	*	90 VH						Zone 1
Saturna	LC-4	*	90 H						Zone 3
Saturna	LC-8	*	90 H						Zone 3
Saturna	MD-2	*	95 VH	*	Highly Contaminated		Salinized	*	Zone 1
Saturna	NB-3	*	95 VH		Highly Contaminated		Salinized	*	Zone 1
Saturna	OPF-1	*	90 VH		Slightly Contaminated			*	Zone 3
Saturna	SB-1	*							
Saturna	SB-2	*							
Saturna	SB-7						Salinized		
Saturna	SB-HP	*	90 VH					*	
Saturna	WC-3	*							
Saturna	WC-4	*	90 M						Zone 3
Saturna	WC-6	*	90 H						
Saturna	WC-7	*	90 VH					*	Zone 3
Saturna	WC-13		90 M						Zone 3
Saturna	WC-HP		90 M						Zone 3
Saturna	WC-BP	*	95 H						Zone 1
Saturna	WC-P	*	90 H						
Thetis	Site 3	*							
Thetis	Site 4	*	95 VH		Moderately Contaminated		Salinized	*	Zone 1
Thetis	Site 11	*	90 VH		Slightly Contaminated			*	Zone 3
Thetis	Site 13	*	90 VH		Slightly Contaminated			*	Zone 3
Thetis	Site 14	*	90 VH		Slightly Contaminated			*	Zone 3
Thetis	Site 18	*	90 VH						
Thetis	Site 24	*	90 VH		Slightly Contaminated			*	Zone 3
Thetis	Site 25	*	95 VH		Moderately Contaminated			*	Btw Zone 1 and 3
Thetis	Site 32						Salinized		
Thetis	Site 44	*	95 VH		Highly Contaminated		Salinized	*	
Yellow Point	106	*	95 VH		Injuriously Contaminated		Salinized	*	Zone 1
Yellow Point	107	*	90 M						
Yellow Point	113	*	90 H						Zone 3
Yellow Point	117	*							
Yellow Point	119	*	90 M						Zone 3
Yellow Point	120		90 M						Zone 3
Yellow Point	125	*	95 VH		Moderately Contaminated			*	
Yellow Point	130	*	90 M				Salinized		
Yellow Point	139	*	95 VH		Highly Contaminated		Salinized	*	Zone 1
Yellow Point	144	*	95 VH		Moderately Contaminated		Salinized	*	
Yellow Point	145	*	95 VH		Injuriously Contaminated		Salinized	*	
Yellow Point	153	*	90 H						Zone 3
Yellow Point	154	*	90 VH					*	Zone 3
Yellow Point	177	*	90 VH		Moderately Contaminated			*	Zone 3