A Multidisciplinary Approach to Studying the Nature and Occurrence of Saline Groundwater in the Gulf Islands, British Columbia, Canada

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ABSTRACT

A multidisciplinary study involving hydrogeochemical sampling and borehole geophysics was undertaken to study the nature and occurrence of saline groundwater on two islands in British Columbia, Canada. Saturna and Hornby Islands are located at the south and north ends, respectively, of the Canadian Gulf Islands situated off the lower mainland of British Columbia. Two large-scale geochemical sampling programs were undertaken to investigate the spatial distribution of saline groundwater and to describe the geochemical evolution of groundwater in the fractured aquifer systems. Major ion chemistry indicates that cation exchange between calcium-rich waters and sodium-rich sites complicates a simple mixing trend, and saline waters appear to represent mixing either between fresh type (calcium bicarbonate) groundwater and seawater (recent saltwater intrusion) or sodium-rich groundwater and seawater (resident saline waters). Sodium-rich exchange sites are speculated to be a remnant of ocean water intrusion during the Pleistocene when the islands were submerged. As a result of its high mobility and conservative nature, chloride has been flushed from the shallow bedrock during a process of natural desalinization, but may remain trapped in the pores and fractures at depth, giving rise to a transitional saltwater wedge. Modern saltwater intrusion, brought about by increased development on the islands, is now competing with natural desalinization along the coast, and has left many drinking water supplies contaminated. Borehole geophysical logs from coastal wells confirm that saline groundwater is present at depth, and that its occurrence is related to fracture locations.

INTRODUCTION

The Gulf Islands, British Columbia are situated off the eastern coast of Vancouver Island, British Columbia, Canada (Fig. 1). The islands lie to the north of the international (Canadian-United States) border, and adjacent to the U.S. San Juan Islands. Saturna Island (31 km² in area) and Hornby Island (32 km² in area) are located at the south and north ends, respectively, of the chain of islands. Land use is typically residential or undeveloped (Crown Land), but some areas support agriculture activities. The bulk of development occurs along the shorelines, and while the total population of the islands remains relatively small (315 residents for Saturna and 1200 for Hornby), the population inflates significantly during the summer as part-time residents and visitors arrive.
The Gulf Islands derive their potable water primarily from groundwater extracted from bedrock wells. Some shallow dug wells are found in areas of relatively thick overburden. Groundwater quality on the Canadian Gulf Islands and the San Juan Islands to the south is extremely variable and is affected locally by high salinity. In addition, water levels are reduced substantially (as indicated by the occurrence of dry wells) in some areas during the summer months when precipitation is low. Further, the quality of water during the summer has also been reported to deteriorate (increased salinity, higher total suspended solids, bad smells, etc.). The high number of reported cases of groundwater deterioration, particularly to the south in the San Juan Islands, suggests that salinization may be occurring in many areas.

![Figure 1: Regional setting of the Gulf Islands showing exposure of the Nanaimo Group (Geology from Mustard, 1994a)](image)

In this paper, we describe the nature and occurrence of saline groundwater on two islands, Saturna and Hornby Islands, for which geochemical data and borehole geophysical data (on Saturna only) have been collected. The geochemical evolution of groundwater is discussed in order to provide insight on hydrogeological and hydrochemical controls for salinization in the fractured sedimentary bedrock aquifers. Borehole geophysical methods are used to describe the relation between fracturing and the occurrence of salinity. The complex geology of the area (structural, sedimentological, and glacial) in combination with topography and groundwater use patterns are expected to have a significant influence on both the spatial distribution of saline waters and the mechanisms of salinization.

**GEOLOGY AND HYDROGEOLOGY**

**Bedrock Geology**

The bedrock geology of the Gulf Islands is composed solely of sedimentary rocks belonging to the Late Cretaceous (~91 to 66 Ma) Nanaimo Group, which are exposed on Vancouver Island, the Gulf Islands, and small portions of the San Juan Islands of Washington State (Fig. 1 geology after Mustard, 1994). The strata are generally divided into ten formations, and consist mainly of alternating interbeds of sandstone, shale, and some conglomerate. The formations have indistinct boundaries
because of the transitional compositions. Lithofacies descriptions are summarized by Mustard (1994). The conglomerates, sandstones, and siltstones are more commonly exposed because the shale tends to weather rapidly.

The Nanaimo Group sequence was deformed by compression into a fold and thrust belt during the middle Eocene (England and Hiscott, 1991), and was uplifted and eroded during the Neogene (Mustard, 1994). Outcrop patterns for the different formations reflect folding of the sedimentary rocks. Therefore, strata dip and the relative orientation of the beds with respect to recharge areas, can be expected to influence groundwater flow patterns and possibly groundwater geochemistry on the Gulf Islands (Fig. 2). In addition, major faults may represent regional barriers and/or preferred pathways for circulating groundwater, and thus, may also influence groundwater geochemistry on a regional scale.

![Image](image.jpg)

Figure 2: Northeast-Southwest geological cross-section of Saturna Island showing representative groundwater flow system. Location of cross-section shown in Fig. 6.

The porosity of the Nanaimo Group rocks is, in general, extremely low (<5%), and permeability is likely derived from fractures. Fracture intensity appears to be an essential factor controlling the availability of groundwater. Often found in conjunction with shale beds, these fractured intervals produce the highest quantities of groundwater for domestic use. According to drilling logs, principal water-bearing aquifers are fractured shale beds and geological contacts. In addition, dominant fracture sets and fault zones may also provide the permeability necessary to support high yielding wells.

**Climate and Hydrogeology**

Mean annual precipitation on the Gulf Islands is similar to Victoria (811 mm/yr.), and approximately 75% of the precipitation falls from October to March. The surface water drainage on the Gulf Islands is limited, and typically consists of small creeks and several small ephemeral streams. Swamps are situated throughout the islands, both at high and low elevations. Topographically high terrains can be expected to act as recharge areas for much of the islands (Fig. 2). The hydraulic potential developed at these high elevations can be expected to generate a sufficient hydraulic gradient to direct infiltrating groundwater towards valley bottoms and the
coast; however, the nature of the flow paths and the rate of groundwater flow is largely unknown. In discharge zones, the hydraulic head is close to the surface (or above), whereas in recharge zones the water table, as seen in wells, is far deeper.

Areas of dense forest floor coverage on northern slopes of both islands likely result in minimal surface runoff during short periods of precipitation, and can be expected to act as primary groundwater recharge areas. In fact, groundwater discharge along the base of the northern slopes is significant as evidenced by flowing wells and an abundance of small seeps. On the dry southern slopes of Saturna Island where there is little forest floor vegetation, there is greater susceptibility for overland flow, and thus, lower amounts of infiltration. Similarly, rugged terrain associated with the steep cliffs of Mount Geoffrey (Hornby Island) also does not permit much infiltration.

Much of the development on the Gulf Islands has occurred along the coast, therefore, water wells are often drilled in close proximity to the shoreline. Only a few properties are situated in the recharge areas at high elevation. On East Point peninsula (Saturna Island), at least 5 wells have been abandoned due to high salinity. Similarly, many wells in the Boot Cove and Lyall Harbour areas (Saturna Island) have been abandoned due to high salinity; residential properties are now serviced by water from a man-made lake. On Hornby Island, development has taken place largely in subdivisions, thereby adding to demand for groundwater in concentrated areas. Continuing development on both islands (as with most of the other Gulf Islands) is occurring primarily along the coastlines. Low summer precipitation and a larger population base during the summer months can be anticipated to exacerbate groundwater-related problems.

GEOCHEMICAL STUDY

Sampling Program

A total of 233 water samples were collected from wells, swamps, ponds, and springs on Saturna Island (106) and Hornby Island (127) during the summers of 1997/98 and 2000, respectively. Most well waters were sampled directly from outdoor taps (ensuring that these bypassed any water softening devices). Water was allowed to run for approximately 10 minutes to purge several well volumes. Some wells (those without pumps) were sampled using a bailer or portable pump and were purged by removing 2 to 3 well volumes. Swamp and pond waters were collected using a grab sampler and springs were sampled at the source, where possible. Most springs occurred as seeps at the base of cliffs or issued from depressions in valleys. The locations of all samples are shown in Figs. 4 and 6. Spring and surface water geochemistry is not discussed in detail in this paper. The reader is referred to Allen and Suchy (accepted) for a detailed discussion of the evolution of all waters on Saturna Island.

Samples sent for laboratory analysis were collected in each of a one-litre bottle for anion analysis and a 500-ml bottle for metal analysis. Samples for dissolved metals and total alkalinity were first filtered (0.45 µm nylon membrane) and then acidified. Field sampling containers, filter chambers and probes were rinsed with distilled water between samples. Duplicate samples and field blanks were used to verify the sampling protocol. Ocean water samples (CS-2 for Saturna, and C-1 and C-2 for Hornby), and 2 rainwater samples were also collected.
Field parameters (total alkalinity, pH, electrical conductivity [EC], and temperature) were measured during, or immediately following, sample collection in order to acquire representative values of ambient aquifer conditions. All instruments were calibrated daily. Field total alkalinity was measured by acid titration to a pH 4.5, which corresponds approximately with the equivalence point for the conversion of bicarbonate ion to carbonic acid.

**Data Analysis**

Samples were sent for chemical analysis to CanTest® where metals were measured using an ICP-MS. Total alkalinity (as CaCO₃) was measured by potentiometric titration with sulphuric acid to a final pH of 4.5. The average deviation between laboratory and field determination of total alkalinity is 18.6%. Chloride, fluoride, nitrate and sulphate were measured by ion chromatography. Raw chemical data were processed using SOLMINEQ® (Alberta Research Council, 1988), a solution and mineral equilibria software program that, among other things, calculates charge balance error, speciation, and mineral saturation indices. The software was also used to adjust for field-determined pH and to calculate carbonate speciation. 158 samples had charge balance errors < 5%, and 215 samples had charge balance errors < 15%. Charge balance errors tended to favour the anions (more negative than positive errors were calculated), which perhaps may be explained by the presence of dissolved silica (SiO₂) that is not accounted for in the charge balance. 16 samples had charge balance errors in excess of 15% and were discarded. Of the 233 samples collected, 215 samples were considered for investigation.

**Groundwater Evolution**

*General Trends*

Two main hydrochemical processes act to modify groundwater composition from shallow to deeper regimes on both islands. These two processes are best illustrated on a Piper plot (Fig. 3).

The first process is a Ca²⁺/Mg²⁺ to Na⁺ shift, which could be explained by cation exchange processes (discussed later). This shift is clearly evident in the cation triangle. The second is salinization, associated with an increase in Cl⁻ concentration, which is evident in the anion triangle. Two paths are indicated. On the diamond, path 1 is from left-center to the bottom left corner, and then to the right corner ending near the ocean water point. Path 2 bypasses the cation shift with direct salinization.

![Figure 3: Geochemical evolution of groundwater.](image)
Geochemical Characteristics of Groundwater

Groundwater on Saturna and Hornby Islands has both a wide variation in composition and a wide range of salinity, reflecting the variable composition of recharge and discharge waters in the flow system. To facilitate the descriptions of the evolutionary trend of groundwater, the islands were roughly subdivided into flow regions (Figs. 4 and 6).

Figure 4: Geological setting of Hornby Island showing sample locations. Geology from Katnick et al. (2000).

Figure 5 shows bicarbonate versus pH for water samples differentiated on the basis of flow region for Hornby Island. This figure illustrates typical open and closed system paths for the dissolution of carbonate minerals in initially ion-free water (Freeze and Cherry, 1979). Most surface and spring waters plot relatively close together at a pH of slightly less than 7.0 and at a HCO₃⁻ concentration of about 10⁻³ mol/l, and represent the initial composition of recharge. Young groundwater has a P_CO₂ in the range of 10⁻¹.₅ to 10⁻₂.₅ atm, perhaps as a result of CO₂ equilibration in the soil zone and subsequent dissolution of carbonate minerals under “open” system conditions.

Figure 5: pH versus bicarbonate for waters on Hornby Island.
The initial water enters the intermediate and deep groundwater system and dissolves more carbonate minerals under “closed” system conditions, and simultaneously exchanges Ca$^{2+}$ and Mg$^{2+}$ with Na$^+$, such that the water remains at or slightly above saturation with respect to the carbonate mineral (cation exchange). All groundwaters with high cation molar ratios, defined as Na/(Ca+Mg)>3, plot above the saturation lines in Fig. 5. Allen and Suchy (accepted) showed that there is not a strong relation between the cation molar ratio and EC on Saturna Island, which suggests that cation exchange is likely independent of salinity increases in most samples. It was further demonstrated that cation exchange is occurring, while likely dissolving calcite and dolomite under closed system conditions (i.e., at the expense of CO$_2$). Similar trends are observed for Hornby Island.

**Evidence of Salinization**

A dominant hydrochemical process on Gulf Islands is salinization accompanied by an increase in EC. Salinization is typically associated with an increase in Cl$^-$, although in some areas salinization has occurred as a result of increased SO$_4^{2-}$. Two distinct pathways were identified in Fig. 3, which are related to salinization. Path 1 is characterized by an increase in Cl$^-$, which typically follows cation exchange. Path 2 is characterized by an increase in Cl$^-$, but without significant cation exchange. In previous discussion, it was noted that salinization is not directly correlated with cation exchange. The two processes can act independently from the perspective that 1) cation exchange does not require salinization, and 2) Na/(Ca+Mg) molar ratios above 10 show no distinct correlation with EC. To illustrate the salinization process, we present chemical data for the East Point and Plumper Sound flow regions on Saturna Island (Fig. 6). Because of the low topographic relief and small catchment area, East Point peninsula tends to receive less precipitation than adjacent flow regions. The Plumper Sound flow region also receives low rainfall because of restricted recharge associated with steep cliffs to the north.

Figure 6: Geological setting of Saturna Island showing sample locations and the location of selected geophysical borehole logs. Geology from Mustard (personal communication).
Groundwater with a low EC typically plots in the left-center portion of the diamond on the Piper plot (Fig. 7), reflecting a Ca-HCO₃ composition. Allen and Suchy (accepted) demonstrated that most fresh groundwaters are recharged locally, and gain HCO₃⁻ while dissolving minerals in the shallow subsurface. As EC increases, Cl/HCO₃ ratios increase and reflect a gain of Cl⁻, rather than a loss of HCO₃⁻. The highest EC waters plot to the far right on the Piper diamond, immediately below ocean water. In general, salinization occurs without cation exchange, or with minor cation exchange (Path 2 in Fig. 3). However, samples EP-27A, EP-29C, and EP-6 all have very high EC (>2000µS/cm), and a lower percentage of Na than the other East Point samples. These data plot slightly above the ocean water point on the diamond (Fig. 7), suggesting that waters from these wells may be directly influenced by seawater.

Figure 7: Piper diagram for East Point and Plumper Sound flow regions on Saturna Island.

Origin of Saline Groundwater

Dakin et al. (1983) calculated that Na⁺ and Cl⁻ could originate in the mudstone units on Mayne Island (Fig. 1) at concentrations that could support long-term release to the circulating groundwater, and be released by diffusion through sandstone and into the fractures over many thousands of years. The fractures would undergo significant flushing, and a concentration gradient could be maintained through the rock mass. Shallow bedrock units would be flushed, and at the present time would contain little remaining salt, while deeper bedrock would still remain at high salinity. However, if this diffusion hypothesis is correct, then not only should there be a higher incidence of saline groundwaters in areas where mudstone units are dominant, but the highly saline groundwaters would be restricted to deeper wells. We do not see these
patterns. Our results indicate that salinization is largely independent of cation exchange. Dakin et al. (1983) discounted saltwater intrusion as a major factor in the origin of salinity, because the results on Mayne Island did not appear to support this process. We contend that saltwater intrusion (mixing) may account for a number of salinization problems on the Gulf Islands, but that recognition of the process is complicated by cation exchange and pre-existing sources of salinity.

Bivariate plots for Na\(^+\) and Cl\(^-\) (not shown) indicate that most samples with high EC plot along a freshwater-seawater mixing line. At low to moderate concentrations samples plot above the mixing line indicating an additional source of Na\(^+\) (likely due to cation exchange). Most East Point groundwater samples have high concentrations of both Na\(^+\) and Cl\(^-\) and lie near the mixing line, suggesting that a major proportion of the groundwater in this region is mixing with seawater in the absence of significant cation exchange.

One process that may account for the high Na\(^+\) currently adsorbed to the clays dates back to the Pleistocene. During the Pleistocene, glacial cover depressed the land by as much as 300 m below present day sea level along the Strait of Georgia (Clague, 1983). On Mayne Island (Fig. 1), Dakin et al. (1983) estimated that the island was submerged below the present-day 150 metre elevation. Mathews et al. (1970) estimated that ice cover left the area very rapidly at 13 000 BP, and that by 12 000 BP the land had risen to present day sea level. Since that time the land surface elevation has not changed significantly. One can speculate that during the Pleistocene, when the Gulf Islands were submerged ocean water intruded into the bedrock units, filling all the pores and fractures. This water would have remained resident for a long period of time (probably on the order of several tens of thousands of years) giving ample time for groundwater to attain equilibrium with the surrounding rock mass. Reverse cation exchange (water hardening), in which Na\(^+\) rich seawater exchanges for Ca\(^{2+}\) on exchange sites, or alternatively, just saturation of exchange sites by Na\(^+\) rich intruded water, may have taken place during island submergence (Brennan, 1956). This process could have left a significant amount of Na\(^+\) on shale exchange sites. In addition, a significant amount of other constituents found in seawater would have remained in the pores.

Once the islands became exposed following isostatic rebound at the end of the Pleistocene, fresh meteoric water would have begun to flush out the more mobile constituents like Cl\(^-\) and SO\(_4^{2-}\). This process is likely still ongoing, and represents a form of natural desalinization at a larger, island scale. In comparison, Na\(^+\) would be more difficult to mobilize, and only over a long period, with a steady supply of Ca\(^{2+}\) and/or Mg\(^{2+}\), would Na\(^+\) become de-sorbed (we now observe this cation exchange process). We might speculate that the longer the residence time (i.e., the deeper and more prolonged the circulation), the more cation exchange will occur, provided exchange sites are available. Shallow groundwater circulation will likely not result in extensive cation exchange, because the sites already have been occupied by Ca\(^{2+}\). On Saturna, we observe that most shallow groundwaters undergo no cation exchange, while intermediate depth waters (collected from deep wells in recharge areas, and some wells situated up slope from the coast) show evidence of cation exchange but no salinization.

To investigate further the relation between high salinity, clay layers and the possible influence of fractures, borehole geophysical logging was undertaken at several wells on Saturna Island.
BOREHOLE GEOPHYSICS

Borehole geophysical logging (using a Mount Sopris multi-parameter logging system) was undertaken in several open (new or discontinued use) wells on Saturna Island in order to investigate the subsurface physical parameters associated with saline groundwater. Two sites are selected for discussion (EP-29 and SB-4). These wells are also identified on the Piper Diagram in Figure 7 (with a red box).

Site EP-29

EP-29, which has been abandoned due to salinization, is located on the south side of East Point peninsula on the up dip side of the strata (Geoffrey Formation sandstone) (Fig. 6).

![Figure 8: Borehole geophysical logs for EP-29 on Saturna Island](image)

The resistivity logs (Fig. 8) show possible fractures at 28m, 35m, 41m, and 52m (fracture locations indicated by arrows). The gamma log shows little variability despite the occurrence of mudstone units within the Geoffrey formation. The absence of illite, a clay mineral that is typically associated with higher gamma radiation, is the likely cause for the low variability of gamma signature. The fluid resistivity log (Fig. 8) shows a shift in salinity at 52m, which appears to coincide with the depth of a fracture. Because the temperature log does not suggest significant fluid flow within the borehole, it can be concluded that the fluid resistivity shift is likely related to saline water entering the fracture at the same depth. This fracture does not appear to correspond with a major change in lithology; perhaps only a minor change to a more clean sand. The water chemistry at EP-29C (58m) suggests that salinization, associated with this particular fracture, is by direct mixing with seawater. Above 52m, there are several other fractures that may or may not be contributing to salinity. The groundwater composition at EP-29a and EP-29b (30m and 50 m, respectively), is saline (>800 µS/cm), and is more representative of fresh water mixing with mature saline water.
Site SB-4

SB-4, at which location there are three boreholes, is located on the south side of Saturna Island (Fig. 6). Results for borehole 2 are shown (Fig. 9). Water table elevations suggest that this is an area of groundwater recharge. Resistivity anomalies, likely associated with fractures, are indicated at 4m, 13m and 30m. Fluid resistivity logs demonstrate that the position of the interface does not coincide with either lithological contacts or with distinct fractures. However, downward fluid flow in the well has likely shifted the position of the interface (its position is determined by hydrostatic equilibrium of saline waters and fresh waters in a borehole).

![Figure 9: Borehole geophysical logs for SB-4 on Saturna Island](image)

The groundwater sample (SB-4) for borehole 2 was collected following a 6 hour constant discharge test. The chemistry of this sample reflects that of a young groundwater, and not that of the water at depth. This suggests that fresh groundwater may circulate in the shallow fractures.

CONCLUSIONS

The chemical character of most surface waters, springs and immature groundwaters (low EC) on Saturna and Hornby Islands suggests that groundwater is recharged locally, typically at high elevation. $P_{CO_2}$ levels are low to moderate, reflecting the low overburden cover and general absence of organic rich soil. Shallow groundwater appears to evolve under more-or-less closed system conditions, and reaches close to saturated conditions with respect to calcite and dolomite. These shallow groundwaters then undergo a compositional change (Ca-rich to Na-rich) as they mature while flowing deeper in the aquifer. This compositional change can be explained by cation exchange that occurs in clay-rich beds associated with most geological formations.

Immature groundwater encounters and mixes with residual mature saline groundwater at depth or directly with seawater near the shore. This mixing results in a significant increase in EC, reflecting higher concentrations of Cl$^-$ and Na$^+$. Water wells that are drilled beyond or completed to depths beneath the zone of mixing...
experience salinization. The occurrence of highly saline groundwaters is not consistent from region to region, and likely depends upon the amount of recharge, the nature of fracturing, and patterns of groundwater use.

Borehole geophysical logs used in combination with hydrochemical data provide information on the occurrence of saline waters at depth. The source of saline groundwaters does not appear to be linked to mudstone units, but rather to discrete fractures. The position of the interface, as measured by borehole fluid resistivity, does not necessarily coincide with inflow zones due to fluid motion up or down the borehole. Fresh groundwater circulating in shallow permeable (fractured) horizons may dilute saline groundwater entering at depth in the boreholes.

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