Long-term Dynamics of the Saltwater-Freshwater Interface on the Gulf Islands, British Columbia, Canada

Diana M. Allen and Emilia Liteanu

Abstract Transient density dependent flow and solute transport simulations were carried out for Saturna Island, Gulf Islands, southwest British Columbia, Canada using USGS SUTRA to model the behaviour of the freshwater saltwater interface over the last 12,000 years. Previous groundwater chemistry sampling indicated that cation exchange, whereby Ca HCO3 rich freshwater exchanges with Na, is a dominant chemical mechanism affecting the interaction of groundwater and the fractured bedrock aquifer. While Na enriched water is present in groundwater throughout most of the island, near the coast there are higher concentrations of Cl, consistent with the presence of a saltwater wedge. The origin of Na is speculated to originate from remnant seawater, which was introduced (along with Cl) into the rock sequence during the Pleistocene when the islands were submerged. Isostatic rebound, following submergence, has removed Cl by flushing the aquifer with fresh (HCO_3 rich) infiltrating groundwater. The Na has largely remained in place because of sorption to clay minerals, but is now being released as fresh water continues to infiltrate. This study aimed firstly to test the hypothesis that a 1,000 year period (between ice retreat and post glacial rebound roughly 12,000 years ago) was sufficient to result in at least partial saturation of the island with seawater. Secondly, the study aimed to test if Cl has had sufficient time to be removed from shallow and intermediate aquifer depths, and be at higher concentrations at depth near the coast. Simulation results show that, considering the approximations used for defining both the hydraulic properties of the aquifer and the amount of recharge to the aquifer, the conceptual model is consistent with the Pleistocene sea level history for the area. Saltwater is able to intrude and "saturate" the aquifer over a period of roughly 500 1000 years, and the current Cl distribution is consistent with that predicted by the model.

Index Terms Saltwater intrusion, numerical modeling, groundwater, coastal aquifers, sea level variation, Pleistocene glaciation, glacial rebound

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I. INTRODUCTION

DURING the late Pleistocene, roughly 12,000 years ago and following ice retreat, the Gulf Islands in southwest British Columbia (BC), Canada were at least partially submerged below seawater for a period of time of about 500 to 1000 years (evidence in support of this time frame is provided later). This theory is supported by the groundwater chemistry [1] and stable isotope data (18O and 34S in dissolved sulphate, and 18O and 2H in water) [2]. Fresh groundwater, characterized by a high Ca-HCO_3 concentration (e.g., see samples WC in Fig. 2), undergoes cation exchange, whereby Ca exchanges with Na, to result in a Na-HCO_3 water (see Zone 2 green dots). This Na-enriched water is present in groundwater throughout most of the island. Some wells situated near the coast experience saltwater intrusion (e.g., EP-6, EP-27, EP-29C) (Zone 1 blue squares). These are characterized by a Na-Cl composition similar to seawater.

There are few instances of mixing between Ca-HCO_3 and Na-Cl water types (Path 2 in Fig. 2). However, mixing between Na-rich water and seawater is common (Path 1 in Fig. 2), which results in numerous samples having typically high Na, and variable Cl concentrations (Zone 3 red dots).

The origin of Na is speculated to originate from remnant seawater, which was introduced (along with Cl) into the rock sequence during the Pleistocene when the islands were submerged [1]. Isostatic rebound, following submergence, has removed Cl by flushing the aquifer with fresh (HCO_3 rich) infiltrating groundwater. The Na largely remained in place because of sorption to clay minerals, but is now being released as fresh water continues to infiltrate.

In order to demonstrate that this particular mechanism is viable, it is necessary to assess the time frame for the movement of the freshwater-saltwater interface. Specifically, it is necessary to determine how long it might take for sea water to intrude the island (given that the islands may have been at least partially submerged below sea level), and then, following re-emergence of the islands, to see if the present day distribution of Cl can be accounted for by the flushing of Cl from the aquifer over a prescribed time period.

This paper describes a numerical modelling study on Saturna Island, the southernmost Gulf Island (48’87” and 123’13”), to investigate the paleohydrogeological evolution of saltwater-freshwater interface and, hence, groundwater distribution, on that island.

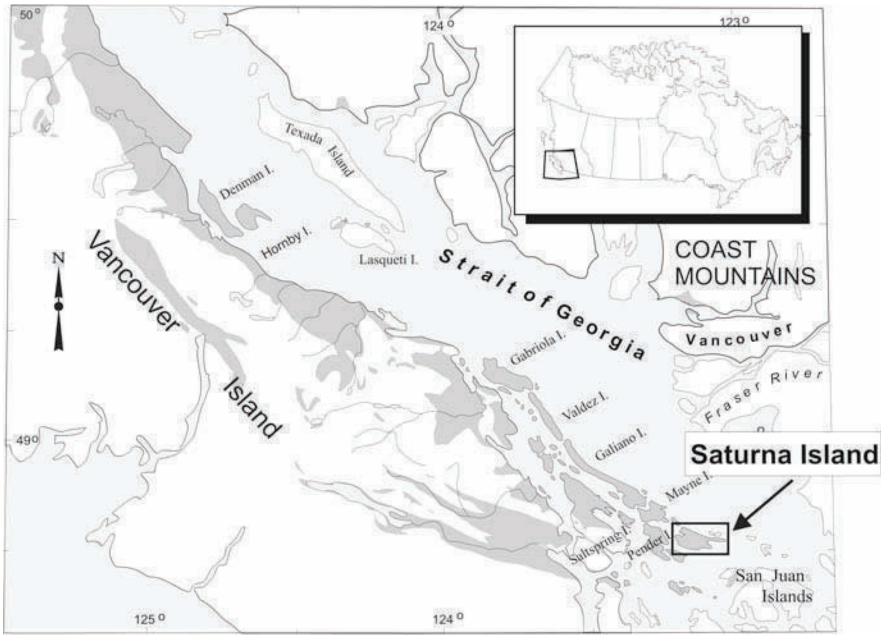

Fig. 1: Location map of the Gulf Islands of southwestern British Columbia, Canada. Shown is the model study area, Saturna Island. Also shown is the exposure of the Nanaimo Group sedimentary rocks (fractured interbedded sandstone and mudstone), which comprise the aquifers of the islands.

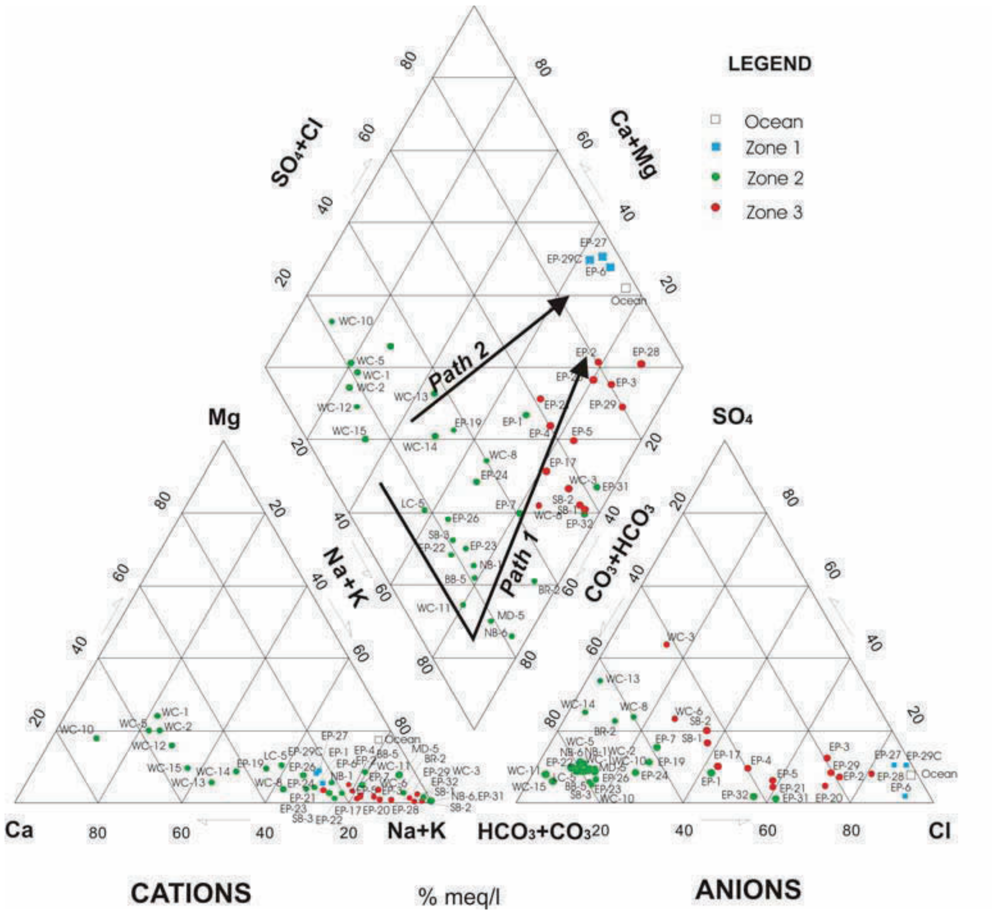

Fig. 2: Piper diagram showing the groundwater composition of selected samples from Saturna Island (data from [1]). Not shown are data that have significantly elevated sulphate.

Time-varying (transient) simulations were run to test the hypothesis "can the current distribution of dissolved chemical species in groundwater on Saturna Island be explained by a period of submergence followed by rapid re-emergence at the end of the Pleistocene?" The simulations involved a two step process:

1. Determining how long it takes for the island, under a prescribed condition of an instantaneous rise in sea level, to become fully saturated with saltwater. In other words, given a change in boundary conditions equal to a step change in sea level elevation, how quickly does it take seawater to fully intrude the island? For the purposes of this simulation, it is assumed that "fully intrudes" equates to the position of the interface under steady state conditions. However, steady state conditions are not a necessary condition for explaining the presence of Na and Cl in the aquifer.
2. Determining if the present day distribution of Cl (as measured by Total Dissolved Solids (TDS)) in groundwater is consistent with that predicted for an evolution to present time given the initial condition prescribed by the above simulation.

If the proposed mechanism is correct, then two conditions should be met:

1. In relation to process 1 above, saltwater must be able to intrude the aquifer to a sufficient degree and in a prescribed time period of roughly 1000 years to result in NaCl water inland and at moderate to high elevation.
2. In relation to process 2 above, the current distribution of Cl should be consistent with that predicted by the paleohydrogeology.

II. PLEISTOCENE HISTORY OF THE GULF ISLANDS

A. Glaciation

The Pleistocene history of Saturna Island (Fig. 1) is described and interpreted within the context of prescribing model boundary conditions that might serve to test the hypothesis. The sea level history of the study area is important because sea level controls the amount of saltwater intrusion in coastal aquifers.

The latest major glaciation that affected southwestern BC was the Late Wisconsinan, Fraser Glaciation ca. 30-10 ka [3]. Ice built up rapidly, especially during the climatic Vashon Stade (18,000-12,000 C^{14} years) of the Fraser Glaciation. Thus, in less than 4,000 years, mountain ice sheets had coalesced to form a continuous continental ice sheet that covered the entire province. At the maximum of this glaciation, the Cordilleran Ice Sheet covered BC, Yukon, and Southern Alaska and extended south to Puget Sound, Washington State [3]. The ice sheet developed in the high areas of the Coast Mountains (Fig. 1) and extended across the entire coast of BC, achieving a thickness of 2000 m.

Ice sheet decay was much more rapid than ice sheet growth. Retreat began at the continental shelf, and proceeded eastward and northward. Near the end of the Fraser Glaciation, glaciers were active, and were restricted to valleys and fjords. In less than 1,000 years after the beginning of deglaciation the present day Vancouver and Victoria were ice free. Lowlands were free of ice 12,500-13,000 ^{14}C years ago, and by about 9,500 years ago glaciers had the same extent as they do today.

Growth and decay of glaciers was not uniform and, consequently, the sea level history is complex. As an ice sheet advances, surface loading increases and causes isostatic depression and crustal deformation in a region. Land depression is typically more intense where the ice sheet is thicker. Ice retreat is accompanied by rebound of the land due to the ice melting. On the west coast, isostatic depression advanced towards the coast and lowlands, but did not have the same intensity in all areas due to variations in ice sheet morphology.

A consequence of ice loading is relative sea level variation. In general, sea level is lower when the land is not covered by ice and higher when the land is depressed. However, sea level changes are also influenced by other factors. The combined effect of isostasy (crustal adjustment to surface loading), eustasy (global sea level change), and diastrophism (sea level change due to tectonism) must be considered. Total isostatic depression due to the Cordilleran ice sheet is estimated to be on the order of 300 m at Vancouver [3]. When the ice sheet melted, the land rebounded, causing isostatic uplift and changes in relative sea level.

B. Relative Sea Level Curves

Sea level evolution for different areas on the west coast of BC has been determined based on studies on the Cordilleran Ice Sheet, terrestrial and marine sediments, and landforms [4, 5]. Relative sea level curves were determined for specific parts of the BC coastal region [6]. For ease of interpretation, the southwestern region of Canada was divided into three zones [4]:

- Inner coast, which includes the mainland and adjacent islands,
- Middle coast (the area of concern), which includes eastern Vancouver Island and Gulf Islands,
- Outer coast, which consists of the Queen Charlotte Islands and western Vancouver Island.

Relative sea level curves were determined for two locations adjacent to Saturna Island; the area of concern (Middle coast) is approximated to be somewhere in between these two. Figure 3 shows the best approximation of sea level evolution for the last 13,000 years for Saturna

In the early stages of deglaciation, sea level may have risen to cover the Gulf Islands to an elevation of around 150 metres above sea level (masl). Thus, only the highest elevations on Saturna Island may have been above sea level (Fig. 3). As deglaciation continued, about 13,000 years ago, sea level started to drop as an effect of the isostatic rebound. The rate of drop was higher on the outer coast as the glaciers retreated from these areas. By 11,500 years BC, isostatic rebound was a dominant mechanism, and sea level was almost 11 m lower than present [6]. All evidence suggests low sea level between

5,000-11,000 years BP (Fig. 3). As a consequence of sea level rise, saltwater likely intruded the Gulf Islands, as the islands were, at least, partially submerged. Following rebound, seawater was displaced by freshwater; a consequence of the influx of fresh rainwater.

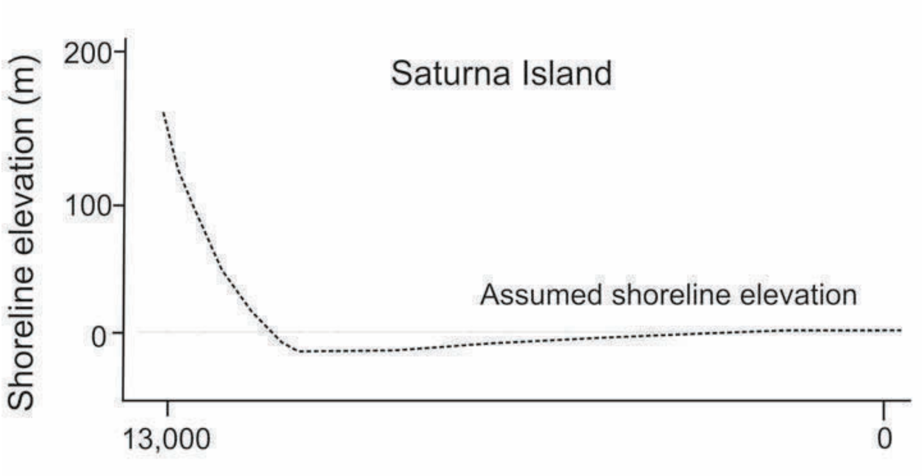

Fig. 3: Relative sea level curve for Saturna Island for the last 13,000 years.

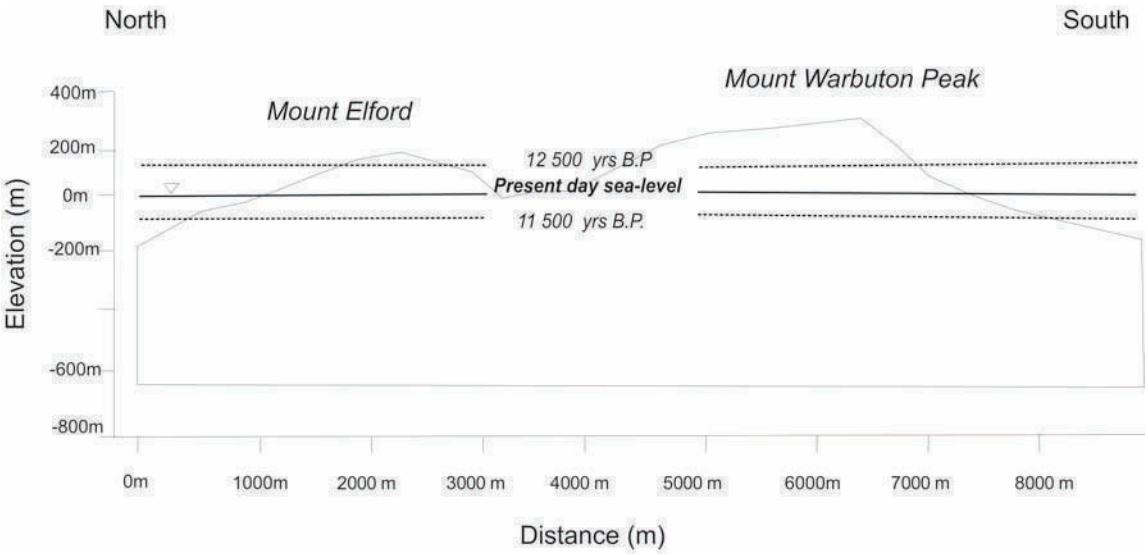

Fig. 4. Shoreline evolution during the last 12,500 years on Saturna Island. The island is submerged 12,500 years ago when sea level was approximately 150m above the actual position, followed by rapid rebound 11,500 yrs ago.

III. Numerical Modelling

A. The Code

Modeling for this research was performed using SUTRA [7]. The US Geological Survey's graphical-user interface, SUTRA GUI, was also used as a plug-in extension (PIE) to Argus ONE (Argus Interware software). The results were visualized using SUTRA Plot 2D3D, a USGS post-processing graphic utility [8]. SUTRA simulations require input data in terms of pressure and salinity distribution with depth, hydraulic parameters, dispersivity and recharge estimates, as well as topographical profiles. The output files allow an interpretation of saltwater intrusion magnitude in terms of salinity (expressed as a mass fraction in kg/kg) and pressure distribution.

B. The Conceptual Model

The Gulf Islands range in area from approximately 20 to 60 km^2 with elevations up to 400 masl. The topography of the islands is dominantly northwest-southeast trending ridges and valleys formed by accelerated weathering of underlying, less competent mudstone sedimentary bedrock. The cross-section across Saturna Island (see Fig. 4) shows two points of high elevation: Mount Warburton Pike (~410 masl) and Mount Elford (~200 masl). A shallow valley extends down the center of the island. No major rivers or lakes are present. Average annual precipitation is 800 mm and it is relatively homogeneously distributed.

The geology of the Gulf Islands is represented by Upper Cretaceous Nanaimo Group (~91-66 Ma) consisting of fractured sedimentary rocks (Fig. 1). The Nanaimo Group consists of an alternating sequence of sandstone-dominant and mudstone-dominant formations (with minor siltstone and conglomerate). Contacts between formation types are characterized by wide transitional zones where bed thickness is reduced; these are referred to as interbedded sandstones and mudstones. Generally, the primary porosity of the Nanaimo Group is low and considered to be of minor importance in the storage and transport of groundwater [9, 10]. As a result, permeability is derived primarily from fractures. Surficial deposits are generally present as a thin veneer and, consequently, are not included in the model; however, it is recognized that these sediments may be significant for recharge.

The Gulf Islands underwent a complex history of deformation, resulting in regional folding and faulting. At a local level, there are numerous bedding perpendicular fractures, fracture zones, and bedding plane fractures. Following a detailed fracture mapping study, sandstone-dominant formations were found to have a low fracture density. Interbedded mudstones and sandstones were found to be more intensely fractured [11]. Massive mudstone units are rare, and are generally interbedded with sandstone. Fault and fracture zones were also shown to have high fracture intensities, comparable to those of the interbedded mudstone and sandstone units.

In recognition of the importance of fracturing on the hydrogeology, a hydrostructural domain conceptual model was developed [11]. In this approach, hydrogeologic units are defined on the basis of their fracture characteristics, specifically fracture intensity, rather than their primary porosity, as is typically the case with hydrostratigraphic conceptual models. Hydrostructural domains, therefore, characterize the distribution of relative permeability in the aquifer system [12, 13].

On the Gulf Islands, three hydrostructural domains were identified: sandstone-dominant, interbedded sandstones and mudstones, and fault and fracture zones. More than 100 pumping tests (constant discharge tests and recovery tests) in the Gulf Island region were analyzed to determine representative transmissivity (T) values for each hydrostructural domain. The T values ranged from 3.4×10^{-7} to 7.2×10^{-5} m^2/s, with a geometric mean of 1.8×10^{-5} m^2/s. Ultimately, T was converted to hydraulic conductivity for each well test, using borehole open lengths as aquifer thickness; the implications are discussed later.

Using an equivalent porous media approach, preliminary k values were assigned to each hydrostructural domain: $k_s = 2 \times 10^{-14}$ m^2 and $k_m = 2 \times 10^{-13}$ m^2, where the subscripts s and m correspond to sandstone-dominant and mudstone-dominant, respectively.

Subsequent work by Reference [14] used stochastic discrete fracture modelling within the FRACMAN modelling environment [15] to determine k for each domain. For the interbedded sandstone and mudstone domain, k ranged 1×10^{-14} m^2 to 4×10^{-13} m^2 (geometric mean of 1×10^{-13} m^2). A similar range of 3×10^{-14} m^2 to 6×10^{-13} m^2 (geometric mean of 1×10^{-13} m^2) was calculated for the fracture zone domain. In contrast, the sandstone domain had a lower average permeability on the order of 10^{-14} m^2. These values translate to T values that are slightly lower, on average (geometric mean = 3.30×10^{-6} m^2/s), but certainly within the range of values derived from the pumping tests. This is not unexpected because of the scale difference between the two approaches (large scale pumping test versus the 20m by 20m model domain used for stochastic modelling).

Of course, a limitation of the equivalent porous media approach when dealing with fractured aquifers is the inability of the model to simulate the complex behaviour of fluid flow and salt transport within discrete fractures. At a local scale, this is potentially a significant limitation, but at a regional scale, such as that used here, and over a sufficiently long time period (tens of thousands of years), the local effects of fracturing should be less important. Therefore, for the purposes of this study, the role that fractures play at a local scale is down-played, and the larger-scale dynamics of the wedge simulated at a regional scale. Nonetheless, fracturing is recognized as an important factor.

C. Model Domain

The modelling was conducted in 2-D (cross-section) due to the complexity that would be introduced in the third dimension (see Fig. 5 for cross-section location). The cross-section was constructed using a topographic map of the island, as well as bathymetric maps. The thickness of the model is 1m. On the east side, the coastline is gently sloping, and on the west side it is mostly rugged, consisting of wave-cut cliffs and steep promontories (Fig. 6). The base of the model was set to a depth (700 m below sea level) sufficient to represent groundwater flow and saltwater intrusion patterns.

Hydrostructural domains (layers) were determined based on geologic cross-sections constructed for the island. There are no precise data on the thickness of each layer; therefore, thicknesses were approximated from previous geological studies [16] and from geophysical logs [17]. Layering was based on formation boundaries, showing primarily sandstone- and mudstone-dominant formations, at the island scale (see Fig. 6). Because of the uncertainty in basement depth, the lowest known formation was extrapolated to the base of the model domain.

D. Mesh Discretization

An irregular mesh was used; this consisted of irregular quadrilaterals that have a variable density and variable dimensions at specified locations. SUTRA determines automatically an optimized bandwidth for the mesh, in order to optimize the efficiency of the solver. A grid optimization study was conducted, but is discussed elsewhere [18].

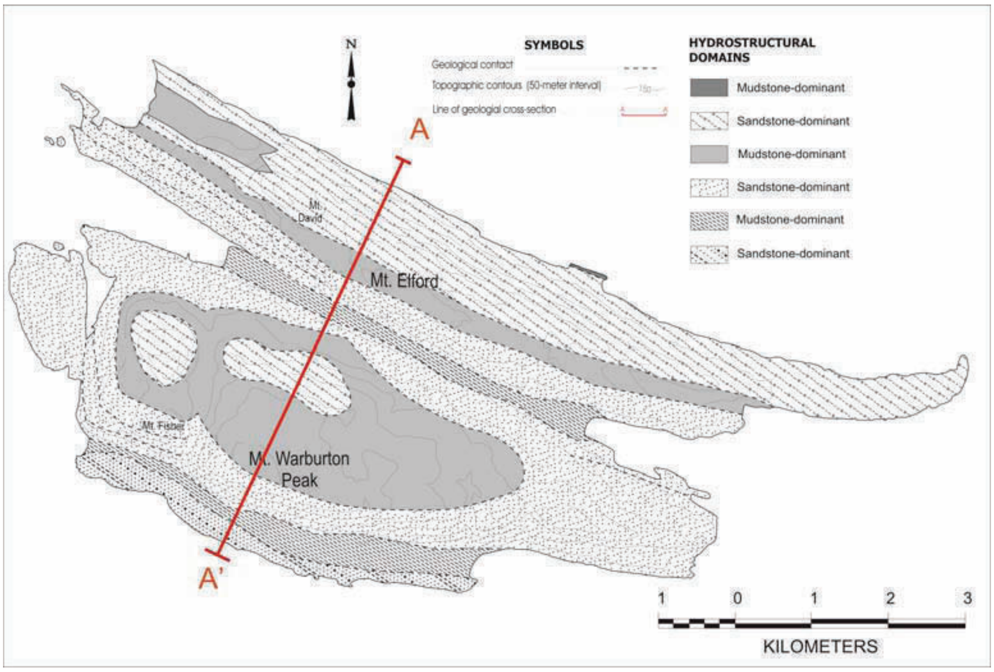

Fig. 5. Cross-section location on Saturna Island. Shown also are the hydrostructural domains corresponding to sandstone- and mudstone- dominant units.

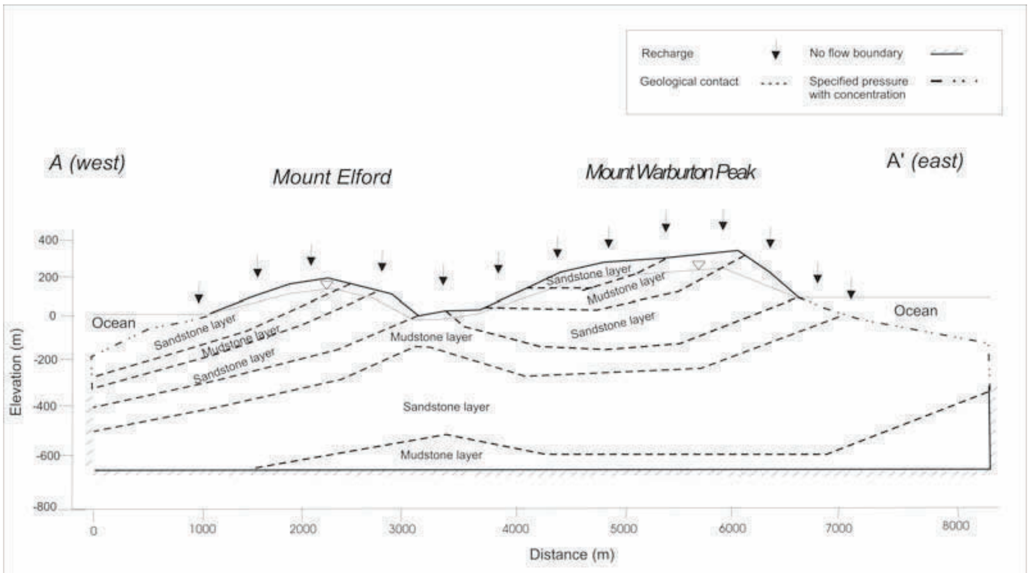

Fig. 6. Cross section across the Saturna Island (A-A') showing hydrostructural domains and relevant boundary conditions.

E. Boundary Conditions

The boundary conditions for flow and solute transport for the cross-section are shown in Figure 6. The lateral boundaries from the sea level to -300 m below msl are specified pressure boundaries. Specified pressures were assigned where the aquifer is in contact with the ocean down to the depth measured on bathymetric maps. To account for the difference in salinity of ocean water compared to freshwater, the specified pressure nodes were also assigned a solute concentration consistent with seawater (0.0357 kg/kg).

A uniform recharge flux of 160 mm/year was applied at the top boundary, and it represents roughly 20% of the annual precipitation rate, which varies between 600 and 850 mm/year. It is assumed that the rate of recharge to the aquifer is spatially and temporally constant. The recharge flux boundary is defined by zero concentration, as no solute disperses or advects across this boundary.

A no-flow boundary was specified along the bottom of the mesh. No internal sinks or sources of water were specified in the model.

F. *Initial Conditions*

Preliminary simulations were done in order to determine pressure and velocity distributions that could be used as the initial conditions for a transient simulation. Thus, at time zero, seawater starts to intrude the system across the sea boundary, and the "true" steady-state position is reached by progressive intrusion through time. The model is run until the system stabilizes (i.e., until there is no significant change in concentration contours with time). The equilibrium position indicates that both the flow and the transport mechanisms have reached the steady-state [7].

G. *Input Parameters*

Permeability values were defined previously. Vertical permeability (k_z) is assumed to have the same value as horizontal permeability (k_x), and likewise, k_x is assumed the same as k_y (isotropic medium). As well, each domain is considered homogeneous. A diffusion coefficient of 1×10^{-9} m^2/s was specified. Longitudinal and transverse dispersivities were 100 m and 10 m, respectively. However, dispersivity was varied during a sensitivity analysis within a smaller model domain. The domain corresponded to a portion of the island where numerous chemical data are available. Dispersivity was varied between 10 and 400 in longitudinal direction (α_L), and between 1 to 100 in transverse direction (α_T), keeping the ratio of changes to 1/10. Longitudinal dispersivity has the most significant effect on the length of the transition zone. The best match to observed concentration data was obtained for α_L =100 and α_T =10, values that were used for further simulations [18].

No specific measurements of porosity are available for the Gulf Islands. However, the literature mentions low porosity values, in the range of 5%, which is enhanced by fractures. Therefore, a value of 5% was used. Other model parameters are summarized in Table 1.

H. *Total Dissolved Solids (TDS) Concentration*

The chemical data obtained for Saturna Island [1] were used to derive the calibration curve for the model (i.e., total dissolved solids as a function of depth). Water samples were drawn from domestic water wells (open boreholes) – there are no piezometers on these islands from which to draw depth-specific samples; although well EP-29 was sampled at discrete depths using a bailer. The depth for the well salinity was taken to be the total depth of the well – for lack of any better information, thus, only data for which a well depth was available could be used. Ground elevations were determined roughly from a digital elevation model, thus there is some uncertainty in the sample depth. Groundwater samples with high SO_4 concentrations were not included, as other chemical processes are occurring (sulphide oxidation) [2].

TABLE 1
MODEL PARAMETERS FOR FLOW AND TRANSPORT SIMULATIONS

Parameter	Value
Fluid compressibility (β)	4.47×10^{10} ms^2/kg
Fluid base concentration	0 mg/l
Dissolved solids base concentration of freshwater as a mass fraction	0 kg salt/kg of sea water
Dissolved solid base concentration of seawater as a mass fraction	0.0357 kg salt/kg of seawater
Density of freshwater (ρ_f)	1000 kg/m^3
Density of seawater(ρ_s)	1025 kg/m^3
Fluid viscosity (μ)	0.001 kg/m s
Fluid diffusivity (D_m)	1×10^{9} m^2/s
Coefficient of fluid density change with concentration	700 kg^2/kg
Cell thickness	1 m
Matrix compressibility(α)	10^{8} Pa^{1}
Porosity (n)	5%
Longitudinal dispersivity (α_L)	100 m
Transversal dispersivity (α_T)	10 m

The results for TDS variation with depth (relative to sea level) are interesting, and three distinct zones can be identified (Fig. 7):

- Zone 1 is characterized by higher TDS concentrations (>1000 mg/l) associated with direct salinization. Site EP-6 has been abandoned due to high salinity. Site EP-27 was sampled at various intervals during a pumping test (to provide 3 values). Site EP-29C was a depth-specific sample situated adjacent to a dominant saltwater fracture. Concentration data for Zone 1 are the values of interest for the purpose of calibration. The linear trendline equation (represented by y = 0.03x; y-intercept of zero) is used as the calibration equation to determine the bulk position of saltwater wedge along the coast.
- Zone 2 is characterized by TDS concentrations that increase only slightly or not at all with depth (over the full range of depths). These correspond primarily to Ca-HCO_3 and Na-HCO_3 waters. Typically, these groundwater samples were collected inland.
- Zone 3 is interpreted to be a mixing zone between Zone 2 and Zone 1. These groundwaters are characterized by slightly higher TDS concentrations compared to Zone 2, but there is a tendency for these waters to be evolving towards a seawater composition (see Fig. 2). However, TDS concentrations are strongly influenced by freshwater.

The calibration curve was derived from a rather sparse dataset, and is based largely on 5 sample points situated over a narrow depth range (30 to 75 m). Nevertheless, the Piper Plot (Fig. 2) shows these wells to be distinctly affected by saltwater intrusion. The results for Zone 2 and 3 waters can likely be explained by a combination of fracturing and dilution. The fact that TDS does not increase with depth in Zone 2 is likely the result of fractures delivering freshwater to greater depths than would otherwise occur in a non-fractured media. If a well is situated near a vertical fracture zone, then it is likely that deep groundwater will be relatively fresh. The fact that TDS is higher in Zone 3 waters is likely the result of mixing between Zone 1 and Zone 2. There is certainly some degree of mixing within the boreholes themselves that would result in water becoming more dilute (due to freshwater from shallow fractures mixing with saline water from deeper fractures). Well drillers normally drill wells until they hit a dominant fracture, therefore, it is likely that the dominant water-bearing fracture will be at depth, and will carry a salinity close to that of the depth of interest.

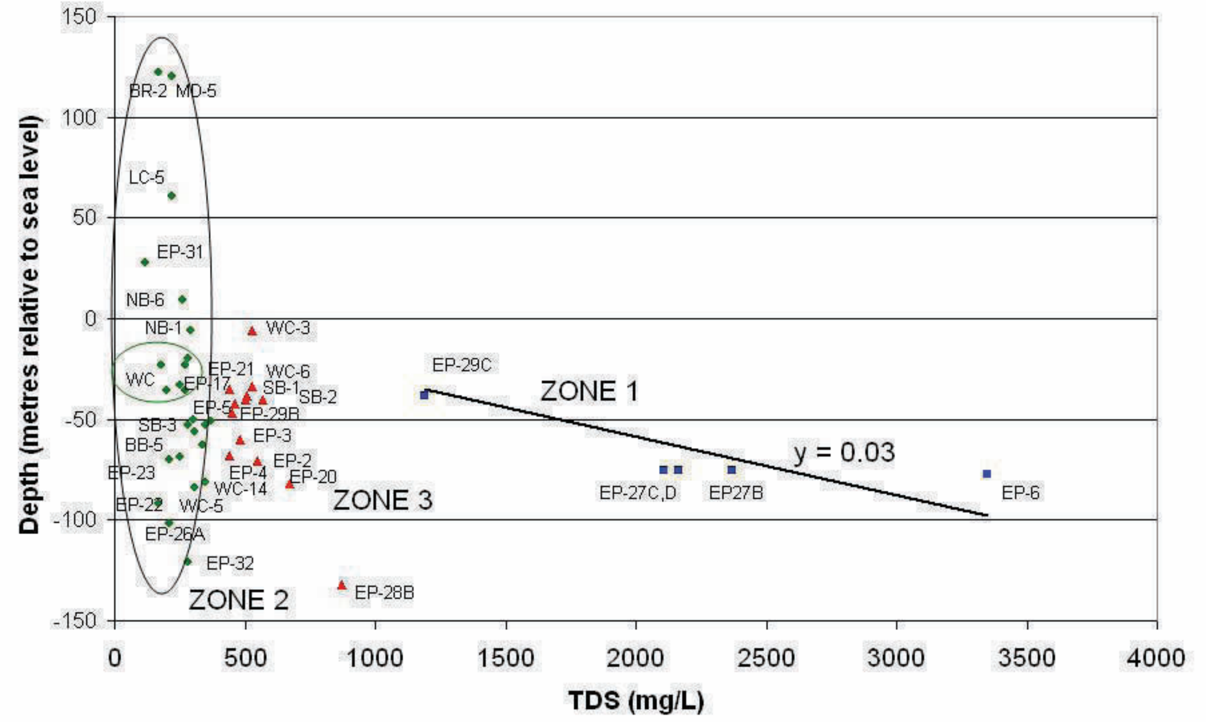

Fig. 7. Total dissolved solids variation with depth (relative to sea level).

IV. Results

A. Model Calibration

A series of simulations were undertaken both for a local scale model domain and the island scale model domain in order to establish the most appropriate model parameters, particularly the range of permeability needed for calibration. At each step, the concentration distribution was compared to the observed calibration curve. Calibration was difficult to achieve. Full results are described elsewhere [18].

The best results were obtained when permeability values were increased 4 orders of magnitude relative to the values determined from pumping tests and discrete fracture modelling:

$$K_s = 2 \times 10^{-10}\ m^2$$
$$K_m = 2 \times 10^{-9}\ m^2$$

Steady state conditions were achieved after approximately 700 years. The results are shown for 1000 years. Figure 8 shows the calibration results for the near shore region. The calibration curve (log scale) is represented by the solid line, while simulated concentrations as a function are depth are shown for different distances from the shore (here 100 m and 600 m from the shoreline). The calibration is rather good. Figure 9 shows the calibration results for distances further inland (see Fig. 6 for location of distances). Unlike the near shore region, the inland results are not as good. This is likely a direct result of the fact that the calibration curve was derived from wells that situated near to the shore (mostly within about 100m). It is in this near shore area that most of the residential development has occurred.

While perhaps suspect, the significant increase in k relative to the measured values can be justified in two ways. First, K values were calculated from pumping test T values using the open hole length. Given that the fractures are believed to form the only permeability, then only the fractured portion of the borehole should be considered as the aquifer thickness when calculating K. Based on geophysical borehole logs [19], it is reasonable to approximate that only 1-10% of the entire borehole length is actually fractured. In fact, the percentage of fracturing may be significantly less. Thus, if aquifer thickness is actually 1/100th or less than the open borehole length, this would account for the K values being under-estimated by 100 times or more. As well, scale effects should normally be taken into account (up-scaling) when using the hydraulic properties from pumping tests in a regional scale model. It is not uncommon to have to increase K by a couple of orders of magnitude. Similarly, fracture modelling using FRACMAN was undertaken for 20 m by 20 m blocks, significantly smaller than the scale of the model. Given these two potential sources of error, a discrepancy of perhaps 4 orders of magnitude in K between those required for calibration and those derived from field testing is not unreasonable.

B. Transient Simulations for Submergence / Rebound

Given the reasonable calibration results, the next step was to attempt to simulate the transient behaviour of the saltwater interface over the past 12,000 years following submergence and rebound. This involved a two-step simulation process: 1) submergence and 2) rebound, consistent with the two objectives described earlier.

In both cases, the conceptual model for Saturna Island was modified to incorporate sea level changes as reflected in changes to the boundary conditions. All the other parameters, as described previously, were kept the same. Post-rebound recharge is assumed to be similar to present values; however, a sensitivity analysis showed that the model is not particularly sensitive to the amount of recharge.

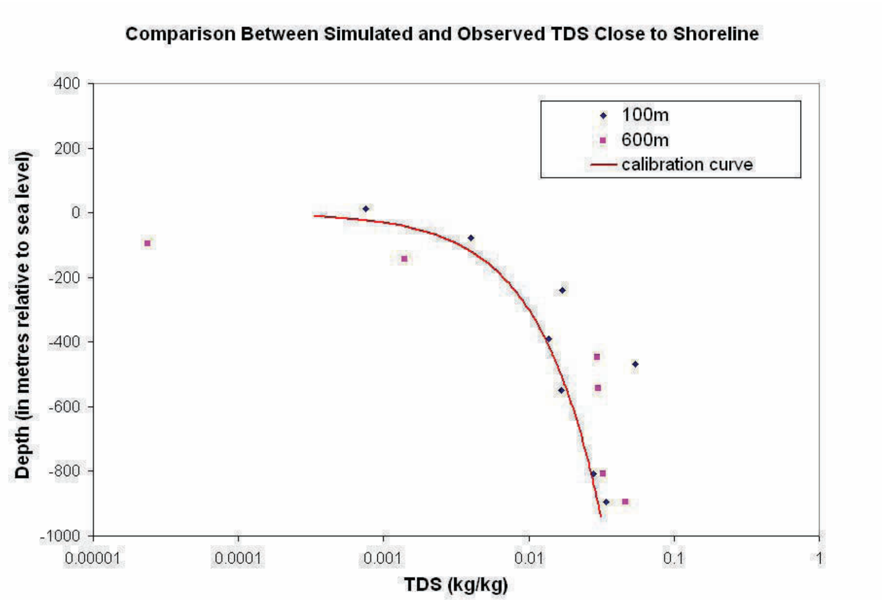

Fig. 8. Comparison between simulated TDS concentrations and the TDS calibration curve in the near shore region (entire island).

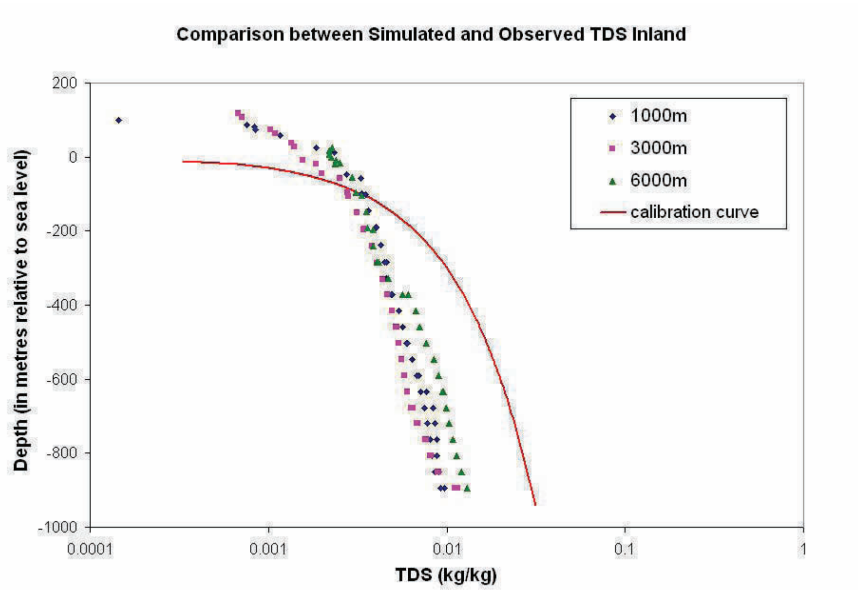

Fig. 9. Comparison between simulated TDS concentrations and the TDS calibration curve in inland locations (entire island).

1) Submergence Simulations

Specified pressure boundaries are used to represent sea level elevation 12,000 years ago. For the purposes of the simulations, it is assumed that the initial sea level was 150 m above its current elevation, consistent with the sea level curve for the Gulf Islands (Fig. 3). Sea level was kept constant at this elevation for 1000 years, because the purpose of this first simulation was to determine how much saltwater would intrude the island under submergence conditions.

TDS contour plots are shown for each of 500 and 1000 years of submergence (Figs. 10 and 11, respectively); there is little difference between the two. At 500 years, saltwater is present to depths 100-200 m below ground surface (Fig. 10). A longer simulation, for a period of 1000 years (Fig. 11), results in a slightly greater degree of intrusion. Freshwater is confined to the upper portions of the aquifer (150-200 m in the centre and southern areas). On the northern part of the island freshwater is present at greater depth due to the presence of higher permeability layer that dips towards north.

The results of these simulations suggest that a time frame of 500-1000 years of submergence would have been sufficient to result in intrusion of saltwater into the island, assuming that the island was entirely filled by freshwater prior to submergence. This is a reasonable assumption given that the islands had been covered by freshwater glaciers over 1000 m thick for several tens of thousands of years.

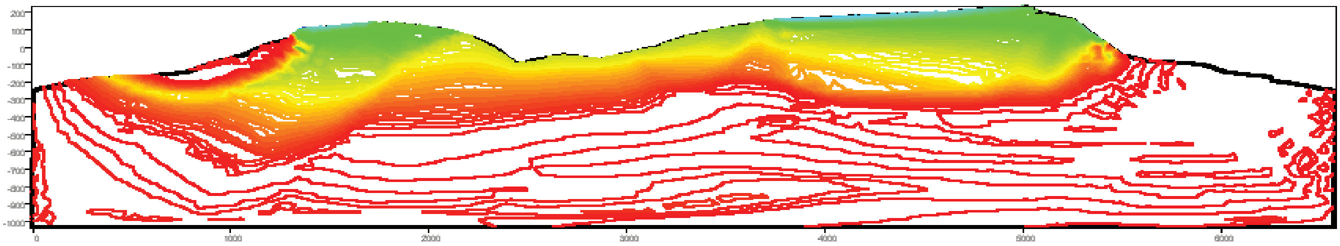

Fig. 10. TDS concentrations after 500 years of submergence of to a level of 150 m above present day sea level.

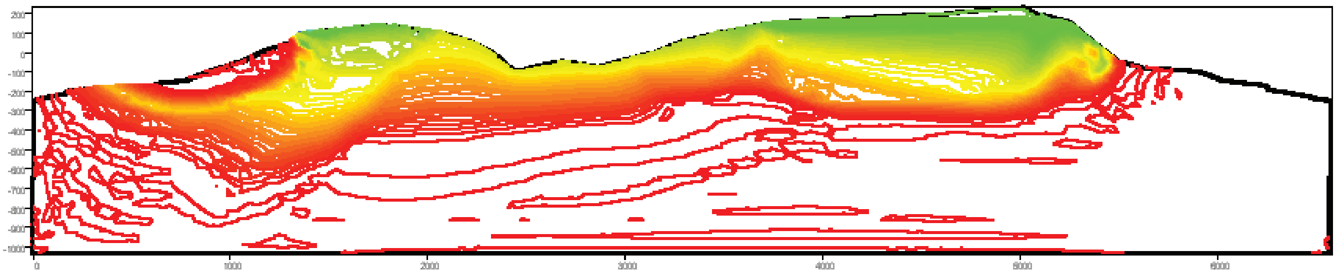

Fig.11. TDS concentrations after 1000 years of submergence to a level of 150 m above present day sea level.

2) Rebound Simulations

Based on the sea level history, relative sea level dropped after approximately 500-1000 years of submergence. Thus, the more conservative concentration distribution after 500 years of submergence was used as initial concentration conditions for a transient simulation to determine the effect of rebound on the movement of the interface.

A gradual decrease of sea level over this short rebound period could not be simulated because numerical instabilities occurred and the model did not converge to a solution. Therefore, a step decrease in sea level was used. This instantaneous drop in sea level is consistent with reported “rapid” rebound in the region. Therefore, sea level was dropped from 150 m to its present level (0 m), and the model was run until it reached steady-state. Note that sea level actually dropped to a sea level below present day elevation and gradually recovered to its present level over a period of 10,000 years (see Fig. 3). This gradual recovery was not included in the model because the difference in elevation is minimal.

Simulations were undertaken in two time intervals, whereby the concentration distribution at the end of the first 3000 years was used as an initial condition for the second 3000 year simulation. After 3500 years (corresponds to 9500 years ago) freshwater flushed the saltwater rapidly from the upper layers, and the interface was “pushed” 100-150 m below actual sea level (Fig. 12). After 6000 years (Fig. 13) the system reaches steady-state.

The steady-state TDS concentrations are compared with the TDS calibration curve in Figure 14. The calibration results are generally rather good, suggesting that the evolution of the saltwater interface is likely the result of the change in sea level that occurred following rebound of the Gulf Islands. This result supports the hypothesis that submergence followed by rebound is a viable mechanism to explain the current salinity distribution on the island.

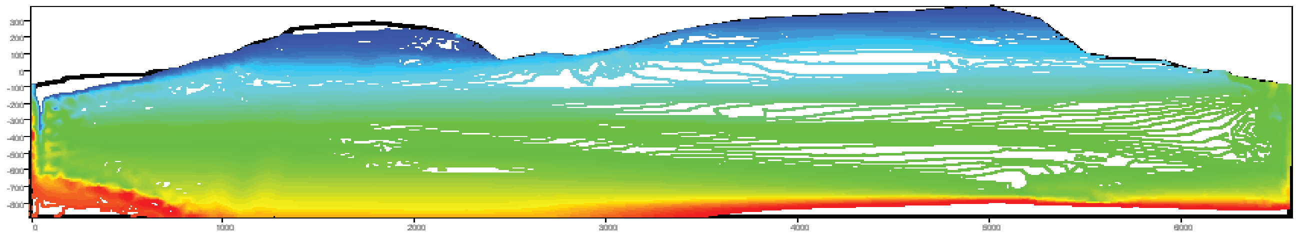

Fig. 12. TDS concentrations after 3000 years following island rebound considering a submergence period of 500 years (corresponds to 6500 years ago).

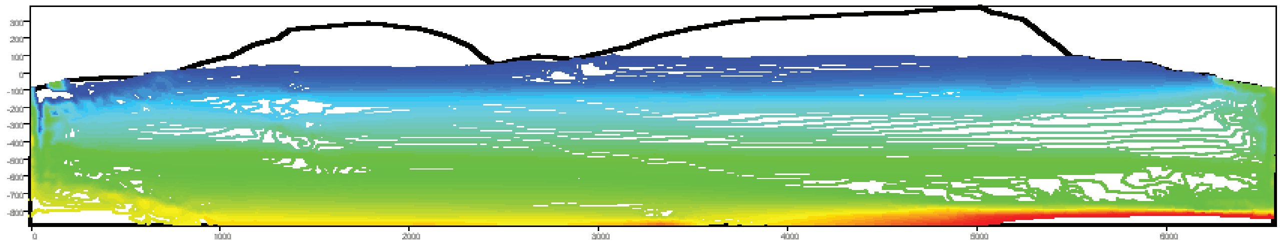

Fig. 13. TDS concentrations after 6000 years following island rebound considering a submergence period of 500 years (corresponds to 9500 years ago) the system has reached steady-state.

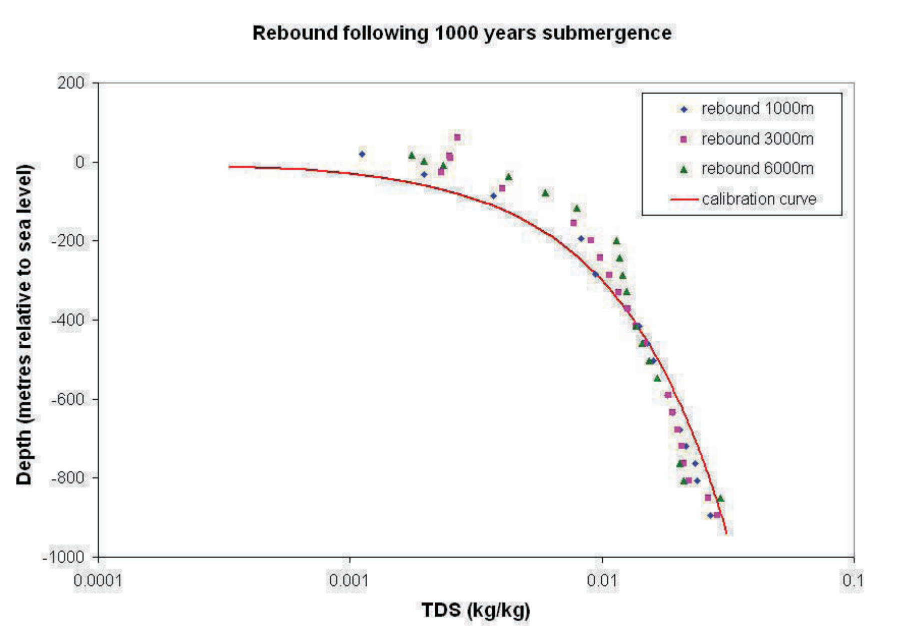

Fig. 14. TDS concentrations comparison between simulation results for a rebounded island following 500 years of submergence and the present day TDS calibration curve.

V. Conclusion

Many coastal regions at northern latitudes have undergone a complex glacial history and its associated sea level variations. The Gulf Islands in southwestern British Columbia, Canada were used as a case study area to investigate the dynamics of the saltwater interface over a period of 12,000 years following submergence of the islands and subsequent rebound at the end of the last glaciation.

Total dissolved solids (TDS) plotted as a function of depth show three distinct chemical zones: 1) Zone 1 is characterized by direct saltwater intrusion, 2) Zone 2 is characterized by groundwater that are either fresh or have undergone cation exchange; TDS does not increase with depth likely due to fracturing, and 3) Zone 3 is a mixed zone between zones 1 and 2 in which salinity is diluted by freshwater likely as the result of borehole mixing. The Zone 3 waters are used to determine a TDS versus depth calibration curve that is representative of the near shore region of the island.

Preliminary cross-section models at a local and island scale were constructed to constrain model permeability values. Generally higher model permeabilities than those derived from pumping tests were needed to best reproduce the assumed current TDS distribution. This is not unexpected due to the fact that hydraulic conductivity values were calculated from transmissivity values using an aquifer thickness value representative of the entire open borehole, when likely only a fraction of the hole provides suitable conduits for flow. This would lead to an underestimation of permeability. As well, upscaling (to larger aquifer property values) is commonly required in regional scale numerical models.

Transient density-dependent flow and solute transport models were run using the most representative aquifer properties to test two hypotheses: 1) that saltwater can intrude the island aquifer to a sufficient degree and in less than a 1000 year period to result in NaCl water inland and at moderate to high elevation, and 2) that the current distribution of Cl is consistent with that predicted by the paleohydrogeology. Model boundary conditions (changes in relative sea level) were constrained by the Pleistocene history for the southern Gulf Islands, in which the islands were partially submerged (to roughly 150 m above present day sea level) under seawater for 500 years. Submergence was followed by rapid emergence. Transient simulations showed that under submergence conditions it takes more than 1000 years to "fully" saturate the island with saltwater. Following rebound, with the application of fresh recharge to the island surface, steady-state conditions are achieved within a period of about 6000 years. Considering the degree of uncertainty in the permeability values, the amount of recharge and the actual sea level history the TDS concentrations for the transient model appear to agree well with the measured values.

While these models appear to represent, in general, the configuration of the interface at a regional scale, local variations in the interface, brought about by fracturing at the local scale, cannot be adequately represented using an equivalent porous media approach. Recognizing the important role of fractures as providing conduits for entry of saltwater into a freshwater aquifer, future work could aim to model solute transport flow through discrete fractures. This would require a large number of measurements, in terms of fracture orientation, spacing, aperture, etc.; data that are difficult to collect at any more than a local scale. A discrete fracture, density-dependent flow and solute transport model would be required.

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