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Research Monitoring Well on Salt Spring Island

A summary of the drilling, testing and chemical/isotopic results for the Research Monitoring Well on Salt Spring Island for a study conducted by Simon Fraser University and BC Ministry of Forests, Lands and Natural Resource Operations as part of a project "Risk Assessment Framework for Coastal Bedrock Aquifers"

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1 Introduction

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

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

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

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

This report summarizes the results of drilling, hydraulic testing and sampling (for water chemistry and isotopes) of a research monitoring well on Salt Spring Island.

2 Purpose of Research Monitoring Well

The well was drilled for the purpose of collecting water samples for chemical and isotopic analysis from specific depth intervals. Prior to drilling this well, there were no existing multi-level wells on the Gulf Islands. Multi-level wells are wells that are completed at specific depths and enable sampling from discrete intervals. An open borehole, which is the most common well type on the Gulf Islands, leads to mixing along the borehole length and, consequently, a mixed chemical and isotopic composition. The lack of depth-specific chemical and isotopic data has been a significant limitation to research efforts for 1) understanding the chemical evolution of groundwater on the Gulf Islands, 2) understanding the residence time of groundwater, and 3) providing a salinity dataset that can be used for calibrating numerical groundwater models. In addition to obtaining depth-specific chemical and isotopic data, the well offered an opportunity to apply the saltwater intrusion indicators proposed in this research project (Klassen et al. 2014). Moreover, the monitoring well will ultimately be converted to a provincial observation well that can be used for monitoring groundwater levels and salinity into the future.

3 Strategy for Identifying a Suitable Site

At the outset of the project, the goal was to drill a deep borehole near the coast. Being situated near the coast would increase the likelihood of intersecting the zone of diffusion, which characterizes the transition from fresh to salt water at the freshwater-saltwater interface (Figure 1). This zone of diffusion may be thick (gradually changing from fresh to salt water over many metres), or abrupt (such that there is a sharp interface between the fresh and salt water). The characteristics of the zone of diffusion in the Gulf Islands are unknown, and indeed may be more complex due to fracturing of the aquifer.

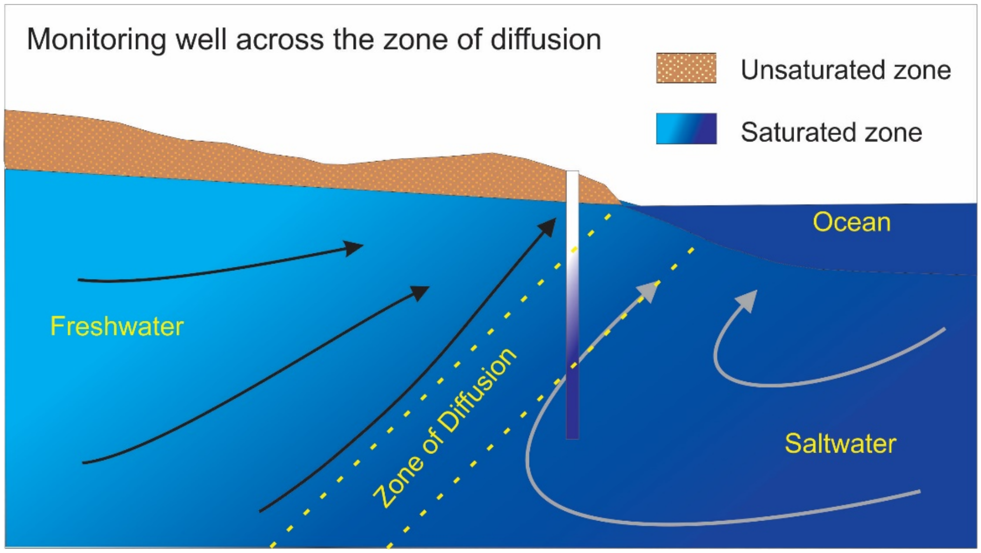

Figure 1. Monitoring well situated across the zone of diffusion of the freshwater-saltwater interface. The salinity distribution varies according to depth. Note: the monitoring well employs white to dark blue shading to represent the salinity transition in the aquifer (light blue to royal blue).

The research team employed various strategies for identifying a suitable site for this monitoring well. Initially, the team considered using an abandoned water well. The team established different criteria (geological formation: Nanaimo Group sedimentary rocks; proximity to coast; depth). BC FLNRO staff reviewed the BC WELLS database and consulted with water well drilling contractors to identify wells near the coast that had been abandoned following drilling due to high salinity. While a few potential wells were identified as potential targets, site visits confirmed that the wells were not suitable. Given that no suitable existing wells were available, the team decided to drill a new well. To this end, SFU and BC FLNRO staff identified an ideal site on Salt Spring Island. The site was at the coast, therefore the likelihood of intersecting the zone of diffusion was high. Unfortunately, when the drilling contractor visited the site, access was not adequate. Ultimately, a site situated about 300 m from the coast was identified on Salt Spring Island.

4 Well Location and Drilling

4.1 Well Location

On January 14 2014, a new well identified as SSI-1 (Well Plate Number 39196) was drilled on the road easement on the east side of Ross Road, approximately 100 m north of the intersection of Walter Hook Road on Salt Spring Island (Figure 2). UTM Zone 10N: 463257, 5415367.

Figure 2. Location of research monitoring well SSI-1 on Salt Spring Island (BC) on Ross Rd.

4.2 Drilling and Well Lithology Log

Drilling was carried out by Drillwell Enterprises. The 6 inch diameter well is constructed in bedrock (open hole) from the base of the 10 inch diameter surface casing (~19 m) to a depth of ~122 m (Table 1). Bedrock was encountered at a depth of ~18.5 m (Table 2).

Rock chip samples were collected every 5 ft. during drilling (Figure 3). The cuttings were rinsed, logged and bagged (Figure 4). From ~18.5 m to 44.5 m, the bedrock is described as fine grained quartz sandstone/siltstone of the de Courcy Formation (Table 2). From 44.5 m to the bottom of the hole, the bedrock is described as massive mudstone of the Cedar District Formation (Table 2). Well yield was estimated periodically by capturing water under the cyclone (Figure 5) for a fixed time, and filling a 20 L bucket (Figure 6). Figure 7 shows the approximate location of the monitoring well SSI-1 on the geological map of Salt Spring Island. Figure 8 shows the geological legend for the map.

Figure 3. Photograph of collection of rock chips during drilling

Figure 4. Photograph of rock chip samples being logged.

Figure 5. Cyclone employed during drilling.

Figure 6. Estimating flow rate.

Table 1. Well construction details

From (ft. bgl[1])	To (ft. bgl)	Diameter	Casing Material/Open hole
0	20	10	Steel
0	62	6	Steel
62	400	6	Open hole

[1] bgl – below ground level; Casing stickup – approx. 3ft.

Static water depth (measured from top of casing) – 22.80 m. Estimated static water table elevation following drilling (31 m- 22.80 m = ~8 m above mean sea level)

Table 2. Lithology descriptions from rock chips logged during drilling of SSI-1

From (ft. bgl)	To (ft. bgl)	@ (ft. bgl)	Description	Estimated Cumulative Water Yield[1]
0	15		**Fine Sandy Silt** – grey, dry	
15	31		**Fine Sandy Clay with medium sized mafic gravel**, grey, rounded, dry	
		25	Making small amounts of water	<1 USGPM
31	35		**Medium Grained Sand** – very homogeneous, brown, dry	“
35	45		**Clay** - stiff, grey	“
45	55		**Medium Gravel Some Fine Sand –** grey, moist	“
55	61		**Silty Sand with Gravel** – rounded medium grained gravel clasts, grey, moist	“
		61	Bedrock Contact	“
61	146		**Fine Grained Quartz Sandstone/Siltstone (de Courcy Formation)** – grey, very hard, interbedded black mudstone	“
146	400		**Mudstone Unit (Cedar District Formation) –** dark grey, soft, massive, minor dolomite veins, interbedded sandstone layers	“
		238	Water Yield[1]	14 USGPM
		300	Water Yield	15 USGPM
		320	Water Yield	29 USGPM
		340	Water Yield	31 USGPM
		360	Water Yield	33 USGPM
		380	Water Yield	35 USGPM
		400	Water Yield	32 USGPM

[1] Estimated periodically by capturing water under the cyclone for a fixed time, and filling a 20 L bucket. Converted to US GPM. Some water loss at well casing.

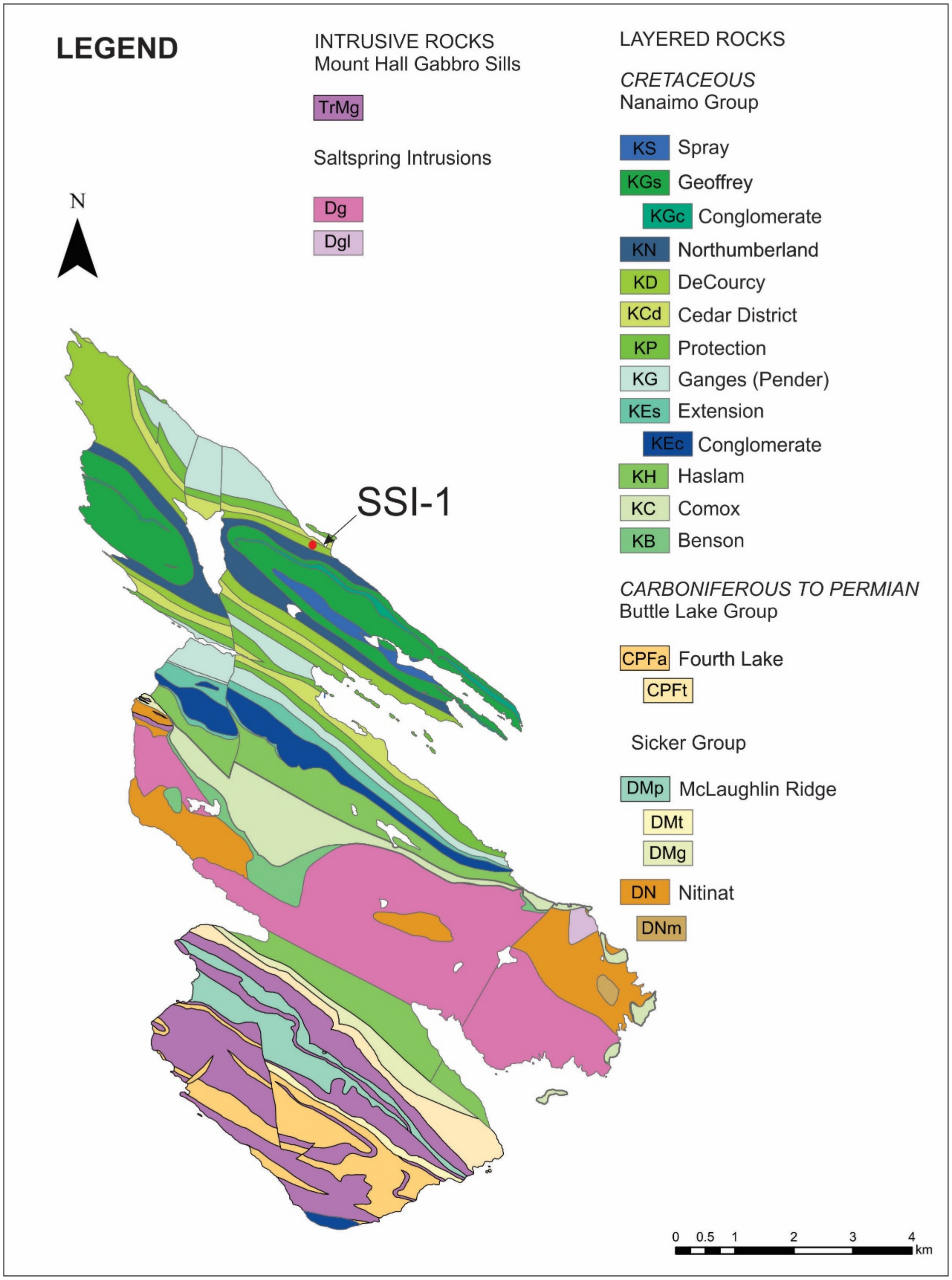

Figure 7. Salt Spring Island geology showing the location of SSI-1 (geology from Greenwood and Mihalynuk 2009). A detailed description of the various rock units is given geological legend in Figure 8.

LAYERED ROCKS

CARBONIFEROUS TO PERMIAN
Buttle Lake Group

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

Sicker Group

DMp	McLaughlin Ridge Formation. Well-bedded volcaniclastic sediments gradationally overlying the Nitinat Formation. Pyroclastic breccia with ovoid vesicular clasts 1- to 15 cm floating in a matrix of ash-sized fragments.
DMt	Thin-bedded light-coloured felsic tuff. In many places very fine-grained and cherty in appearance.
DMg	Volcanic-rich greywacke with tuffaceous components.
DN	Nitinat Formation. Pyroxene-phyric mafic aglomerate, pyroxene bearing tuffs, lapilli tuffs and flows. Individual sub units and flows are difficult to trace confidently. Pyroxene crystals are commonly altered to actinolite.
DNm	Massive greenstone unit may in large part be intrusive rocks of dioritic composition.

INTRUSIVE ROCKS
Mount Hall Gabbro Sills

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

Saltspring Intrusions

Dg	Granite and granodiorite, undivided (Dg) commonly protomylonitic with conspicuous quartz 'eyes'. Produces a hornfels texture in Nitinat Formation country rocks.
Dgl	Leucocratic granite (Dgl) occurs near Yeo Point with no clear contact relations.

LAYERED ROCKS

CRETACEOUS
Nanaimo Group

KS	Spray Formation. Recessive-weathering sandstone-mudstone tubidite and massive mudstone. Platy habit and Bouma sequence bed forms are typical. Inoceramid bivalve fossils are present, but commonly broken.
KGs	Geoffrey Formation. Thick bedded sandstone: bed forms indicate deposition from turbidity currents.
KGc	Conglomerate: central interbed within Geoffrey Formation sandstone
KN	Northumberland Formation. Recessive-weathering mudstone and fine-grained sandstone. "Ribbed" couplets of sandstone and mudstone display turbidite features.
KD	DeCourcy Formation. Thick-bedded sandstones and arkosic arsenite with minor pebbly conglomerate.
KCd	Cedar District Formation. Interbedded sandstone and mudstone with soft sediments deformation features. Sandstone-mudstone couples are interpreted as deposited from turbidity currents. Ammonites are locally common.
KP	Protection Formation. Thick-bedded medium-grained sandstone displaying cross-bedding, sole-marks and burrows. Thin-bedded siltstone marks a transition to the underlying unit.
KG	Ganges (Pender) Formation. Thin-bedded mudstone, siltstone and fine-grained sandstone with excellent turbidite structures.
KEs	Extension Formation. Pebble and cobble conglomerate (Kec) with coarse-grained sandstone facies (Kes) at both top and bottom of the unit. Coal debris is common.
KEc	Conglomerate with clasts dominated by mafic volcanic rocks, chert and granite.
KH	Haslam Formation. Massive concretionary fossiliferous black shale and mudstone. Locally contains coal fragments.
KC	Comox Formation. Fine to medium-grained sandstone with trace fossil borings near Arnell Park. Where the Benson is absent, Comox sandstone rests directly on Paleozoic rocks.
KB	Benson Formation. Coarse boulder conglomerate with clasts including granite, greenstone, chert, quartzite and granodiorite. Variable thickness due to its deposition on an irregular paleotopography consisting of Paleozoic granitic, volcanic, and sedimentary rocks.

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

5 Hydraulic Tests

Four different hydraulic tests were conducted on SSI-1: a step discharge test, a constant discharge test, a recovery test (immediately following the pumping test), and a tidal response test. The step test was conducted to determine an optimum pumping rate for the constant discharge test as well as to determine if there was any drawdown response in an observation well (a domestic well 30.5 m deep with no pump installed) located approximately 42 m west of the pumping well.

5.1 Step Discharge Test

The step test was conducted on January 16, 2014 (start time 14:00: end time 15:30). Three 30-minute step increments were planned, but only two rates were achieved due to difficulties in adjusting the pumping rate. The pumping rate for the first 30-minute step was 0.870 L/s (13.8 USGPM), followed by 1 L/s (15.85 USGPM) for 60 minutes. Figure 9 shows the data from the pumping well. At 30 minutes, the increase in pumping rate is barely noticeable as a minor increase in the drawdown.

The specific capacity (pumping rate/drawdown) is estimated at 0.12 L/s/m.

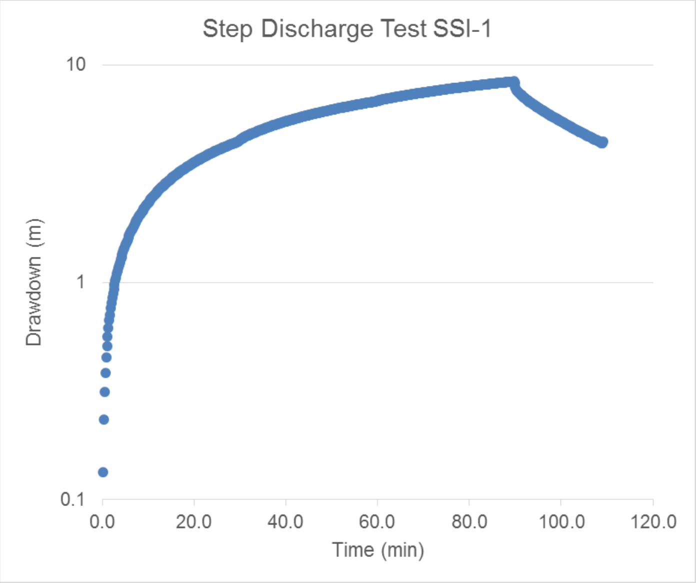

Figure 9. Step test data. A minor increase in the drawdown at 30 minutes was an attempt to increase the pumping rate.

5.2 Constant Discharge Test

A constant discharge test was conducted on January 17, 2014 (start time 9:00: end time 15:00). The pumping rate was maintained at 1 L/s (15.85 USGPM) for the duration. Flow rates were measured by estimating the time to fill a 20 L pail. The observation well was also monitored throughout the pumping test. Pressure transducers and manual measurements of water levels were recorded. Shown here are the pressure transducer data. Figure 10 shows the semi-log plot of the drawdown versus time for the pumping well. Figure 11 shows the semi-log plot for the observation well.

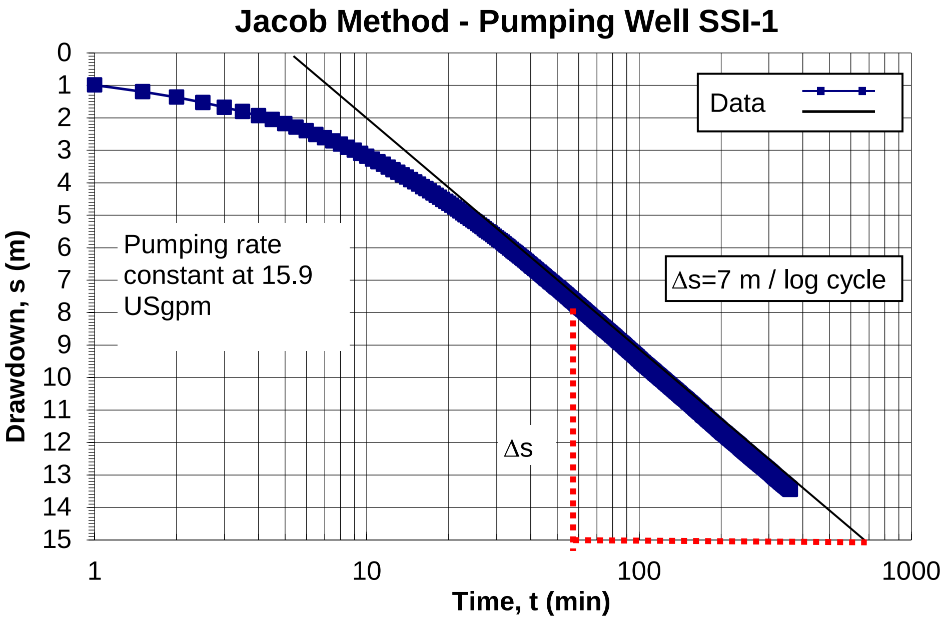

Figure 10. Constant discharge test data for the pumping well, SSI-1.

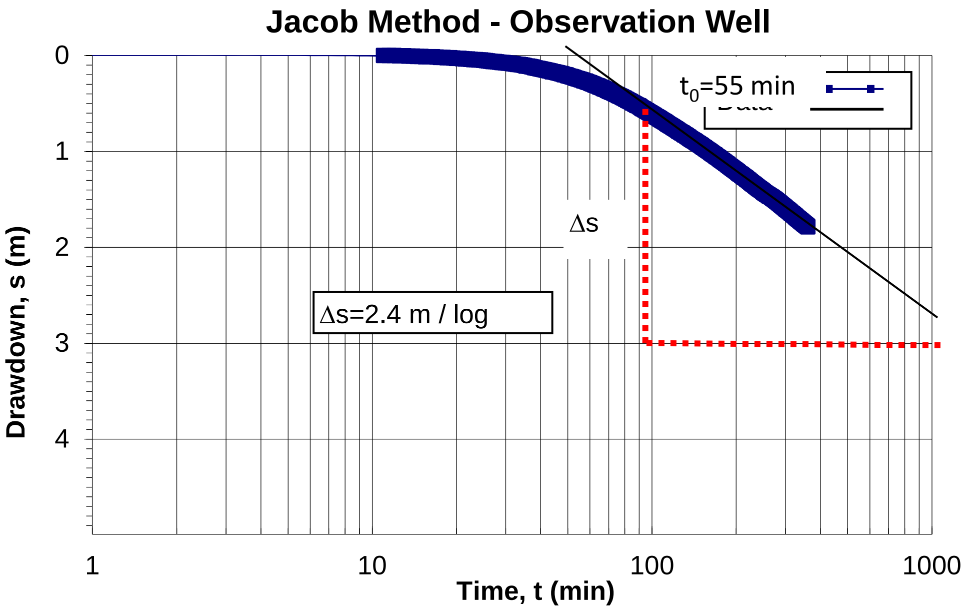

Figure 11. Constant discharge test data for the observation well.

The test data were first interpreted using the Derivative method (not shown), which allows the flow regime to be identified. An appropriate method of analysis for pumping test data should be determined based on the conceptual model of the site (i.e. whether the aquifer is confined, leaky, unconfined). Radial flow models are most commonly used to analyze data for confined aquifers (e.g. Theis method or Jacob method), but the data should exhibit radial flow for these methods to be used. Previous analysis of pumping test data for the Gulf Islands region (Allen et al. 2002) indicates that many pumping tests are influenced by vertical fractures and faults, which result in a period of linear flow near the beginning of the test. If a radial flow period is observed following the linear flow period, a radial flow model can be used to estimate the hydraulic properties of the aquifer (Allen 1999). Linear flow, and other factors such as wellbore storage, can be distinguished from radial flow using a derivative plot (Allen 1999).

A Jacob analysis was performed using the radial flow portion of the data (30 - 360 minutes for the pumping well). Figures 10 and 11 show the radial flow portion of the drawdown curve identified using the derivative analysis. The drawdown over one log cycle (Δs) is shown on each graph, and used to calculate the transmissivity (T) of the aquifer using the Jacob equation:

$$T = \frac{2.3Q}{4\pi\Delta s} \tag{1}$$

where Q is the pumping rate (Table 3). The aquifer storativity (S) can be calculated from the observation well data using Equation 2:

$$S = \frac{2.25Tt_0}{r^2} \tag{2}$$

where t_0 is the x-intercept (shown on Figure 11) and r is the radial distance from the observation well to the pumping well (Table 3). Using the aquifer thickness (b: defined as the length of the open hole from the base of casing to bottom of the hole), the hydraulic conductivity of the aquifer can also be calculated (Table 3):

$$K = T/b \tag{3}$$

5.3 Recovery Test

A recovery test was also carried out following pump shutdown. Water levels were recorded in both the pumping well and the observation well. Full recovery did not occur after 1121 minutes (18 hours) when the pressure transducers were retrieved. The recovery data (plotted as residual drawdown version recovery time t/t’) are shown in Figures 12 and 13 for the pumping well and observation well, respectively. The radial flow portion of recovery data typically corresponds to the same interval during the pumping test (for the pumping well from 30-360 minutes). The Theis Recovery method was used to analyze this portion of the data. Only T can be calculated (Table 3).

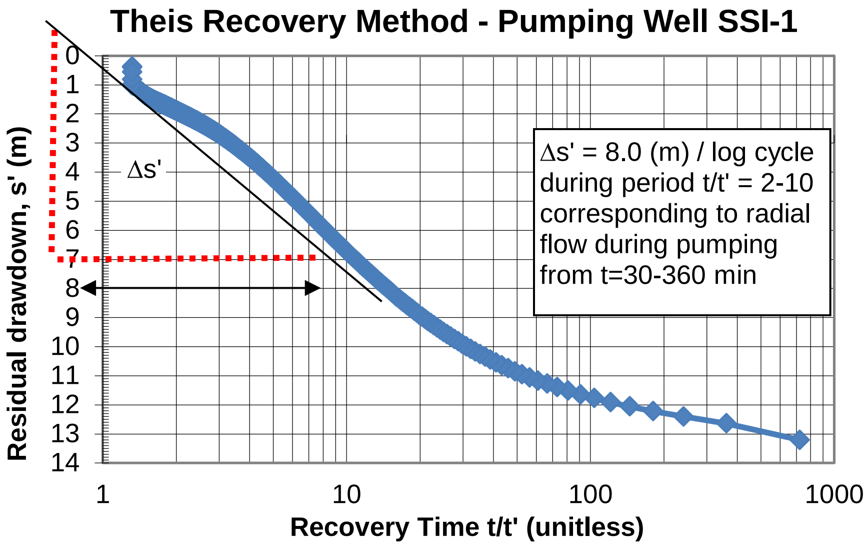

Figure 12. Recovery test data for the pumping well.

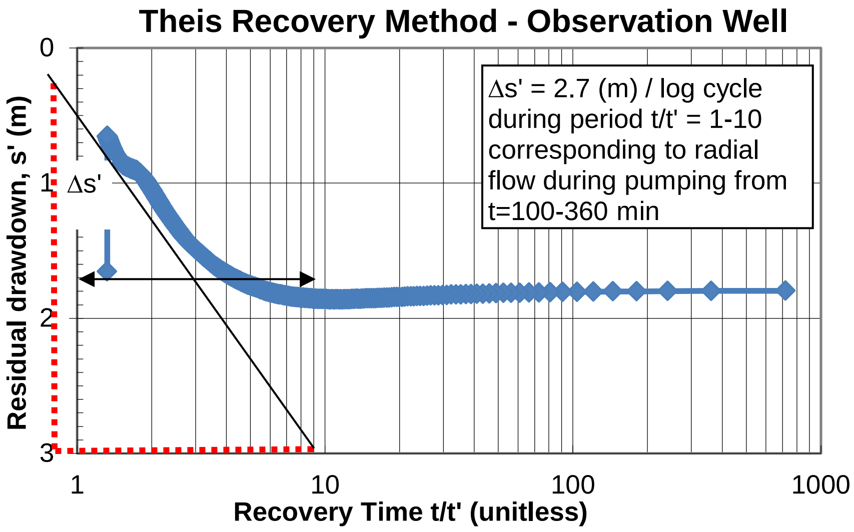

Figure 13. Recovery test data for the observation well.

5.4 Tidal Response Test

A tidal response test was also attempted at SSI-1. Tidal response tests are used to estimate T/S for the aquifer (Jacob 1950; Ferris 1951). Unfortunately, the well was situated far enough from the coast that a tidal signal was not evident.

5.5 Interpretation of Hydraulic Test Results

Overall, the results of the pumping and recovery tests gave consistent results for both the pumping well and the observation well (Table 3). In addition, the transmissivity and storativity values are of the same order of magnitude as the averages for the Gulf Islands region (Larocque 2014). The average transmissivity of the mudstone formations in the Gulf Islands is 9.5E-06 m^2/s. The average storativity (for all rock types in the Gulf Islands) is 2.9E-04.

Table 3. Aquifer hydraulic properties estimated from the pumping and recovery tests.

Analytical Method	Well Function	Transmissivity (m^2/s)	Storativity	Aquifer Thickness (m)	Hydraulic Conductivity (m/s)
Jacob	Pumping	2.5E-05	-	103	2.4E-07
Jacob	Obs	7.7E-05	3E-04	21	3.6E-06
Theis Recovery	Pumping	2.3E-05	-	103	2.2E-07
Theis Recovery	Obs	6.8E-05	-	21	3.2E-06
Average	Pumping	2.4E-05		103	2.3E-07
Average	Obs	7.2E-05	3E-04	21	3.4E-06

6 Water Chemistry Sampling

6.1 Sampling Procedures

During drilling, 18 water samples were taken every ten feet by grab sampling; seven samples (collected every 20 feet) were bottled (SSI-1-2 to SSI-1-8), but these were not submitted for analysis (Table 4). Electrical conductivity (EC) corrected to 25°C (Specific Conductance) was measured on all samples using an Orion 5-Star Conductivity Meter. One sample (SSI-1-9) was collected during the constant discharge test after six hours of pumping (Table 4).

From January 20-24, eight water samples were collected from discrete depth intervals using an inflatable packer assembly (SSI-1-9 to SSI-1-17: note that sampling depths are not sequential). The packers were separated by 10 ft (~3 m) allowing for a relatively narrow sampling interval. Water was pumped from the packer interval using a Redi-Flow 2 system and a Grundfos pump. An attempt was made to purge the interval by one volume; however, in some cases the yields were so low that pumping could not be sustained (no sample collected). Multiple attempts often had to be made (which accounts for the inconsistent sample numbers with depth shown in Table 4). Table 4 also shows the estimated purge rate and a relative descriptor of the relative flow rate. A summary of the lithology of the well and the location of the discrete depth interval samples is shown in Figure 14.

Water that was pumped from the discrete depth interval passed through a flow through cell and EC, pH, temperature, dissolved oxygen (DO) and oxidation-reduction potential (Eh) were measured. Once these parameters became relatively constant, a discrete depth interval sample was collected. The water samples were filtered. NH_4^+, S^{2-} and Fe^{2+} were measured in the field using a spectrophotometer (Hach DR 2800). Samples were then bottled for various lab analyses (1 L for ^{14}C, two 500 mL for ^{3}H, 500 mL for ^{34}S, 250 mL for ^{13}C, 250mL for anions and stable isotopes, and 125 mL for dissolved metals). Total Dissolved Solids (TDS) was computed from the lab results.

Table 4. Summary of water samples collected through various methods

Date	Sample ID	Depth (ft)	Purge Rate (gpm), descriptor	EC[1] (µS/cm)
Samples Collected During Drilling (only EC measured)				
January 14	SSI-1-2	238		884
January 14		245		820
January 14		255		800
January 14		265		863
January 14		275		790
January 14		285		860
January 14		295		840
January 14	SSI-1-3	300		911
January 14		310		880
January 14	SSI-1-4	320		960
January 14		330		950
January 14	SSI-1-5	340		1000
January 14		350		940
January 14	SSI-1-6	360		1000
January 14		370		996
January 14	SSI-1-7	380		992
January 14		390		962
January 14	SSI-1-8	400		1000
Sample Collected at the End of the Pumping Test				
January 17	SSI-1-9	400		1011
Samples Collected at Discrete Depth Intervals				
January 21	SSI-1-10	327	>3, high	977
January 21	SSI-1-11	345	>3, mod	906
January 21	SSI-1-12	316	>3, high	963
January 21	SSI-1-13	285	>3, high	939
January 22	SSI-1-14	243	>3, very high	868
January 23	SSI-1-15	117	<0.25, very low	688
January 23	SSI-1-16	222	<0.25, mod to low	873
January 24	SSI-1-17	264	>3, very high	1095

[1] EC corrected to 25°C – specific conductance.

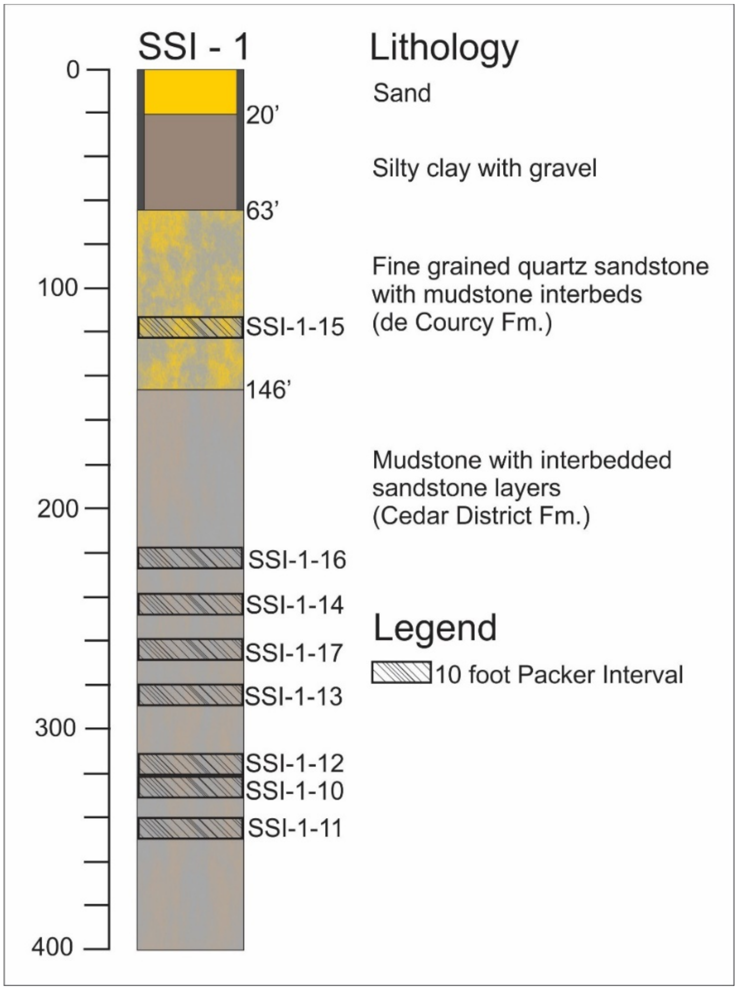

Figure 14. Simplified lithology of SSI-1 and the location of the discrete depth water samples taken using the packer system.

6.2 Water Chemistry Results

The water samples collected for chemical analysis were analyzed at Simon Fraser University. Alkalinity was measured by titration. Anions (F^-, Cl^-, Br^-, NO_3^-, PO_4^{-3} and SO_4^{-2}) were measured by ion chromatography (IC) on a Dionex ICS-3000 chromatography system (error ± 3%) and dissolved major, minor and trace elements were measured using a Horiba Jobin-Yvon Ultima II inductively coupled plasma atomic emission spectrometer (ICP-AES) (error ± 3%). NH^{4+}, S^{2-} and Fe^{2+} were measured in the field using a spectrophotometer (Hach DR 2800) (error ± 5%). The various parameter values and concentrations are reported in Tables 5-7. Charge balance errors were less than 2%.

In all data tables, the samples are arranged according to increasing depth, with the exception of SSI-1-9, which was collected at the end of the pumping test.

Table 5. Parameters measured in the field for SSI-1 samples.

Sample ID	Depth (m)	EC (µS/cm)	pH	Temp (°C)	DO (mg/L)	Eh	NH_4 (mg/L)	S^{2-} (mg/L)	Fe^{2+} (mg/L)
SSI-1-15	117	688	9.18	11	6.67	270	0.08	0.005	0
SSI-1-16	222	873	9.59	10.4	0.33	77.4	0.04	0.069	0
SSI-1-14	243	868	9.39	11	2.35	55.5	0	0.586	0
SSI-1-17	264	1095	9.59	10.9	0.23	125	0.13	0.133	0
SSI-1-13	285	939	9.41	11	3.43	88.5	0.1	0.825	0.01
SSI-1-12	316	963	9.44	11.2	3.34	157	0.16	0.29	0
SSI-1-10	327	977	9.34	11.1	5.82	114	0.14	0.515	0.01
SSI-1-11	345	906	9.47	9.2	7.78	436	0.13	0.031	0.02
SSI-1-9*	400	1011	9.3	10.7	0.008	-46	0.34	0.588	0

* pumping test sample

Table 6. Anions for SSI-1 samples

Sample ID	Cl (mg/L)	Br (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)
SSI-1-15	99	0.49	19.9	249
SSI-1-16	126	0.59	14.2	325
SSI-1-14	121	0.51	1.5	320
SSI-1-17	259	1.14	8.9	267
SSI-1-13	140	0.53	2.8	318
SSI-1-12	145	0.56	2.6	331
SSI-1-10	145	0.53	2.2	327
SSI-1-11	101	0.44	2.4	342
SSI-1-9*	145	0.46	1.8	331

* pumping test sample

Table 7. Dissolved elements for SSI-1 samples

Sample ID	Al (mg/L)	As (mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Fe (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)
SSI-1-15	0.006	0.012	1.405	0.300	6.1	0.007	0.8	0.05	1.1
SSI-1-16	0.009	0.007	2.435	0.086	1.5	0.022	0.3	0.06	0.1
SSI-1-14	0.008	0.005	2.462	0.059	1.3	0.024	0.2	0.06	0.1
SSI-1-17	0.008	0.008	2.321	0.156	2.0	0.031	0.3	0.07	0.1
SSI-1-13	0.012	0.004	2.561	0.037	1.3	0.100	0.3	0.06	0.1
SSI-1-12	0.014	0.010	2.581	0.032	1.3	0.075	0.3	0.06	0.1
SSI-1-10	0.006	0.006	2.617	0.033	1.3	0.089	0.2	0.06	0.1
SSI-1-11	0.006	0.007	2.673	0.002	1.1	0.211	0.2	0.06	0.1
SSI-1-9*	0.006	0.006	2.478	0.065	1.5	0.019	0.2	0.06	0.1

Table 7.
cont'd

Sample ID	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	SiO_2 (mg/L)	Sr (mg/L)	Zn (mg/L)
SSI-1-15	0.0050	0.001	154.9	9.4	0.24	0.001
SSI-1-16	0.0010	0.001	213.5	6.2	0.07	0.001
SSI-1-14	0.0020	0.001	200.0	7.2	0.08	0.001
SSI-1-17	0.0020	0.001	266.9	7.1	0.12	0.001
SSI-1-13	0.0030	0.001	205.0	6.9	0.08	0.001
SSI-1-12	0.0020	0.001	210.0	6.4	0.08	0.001
SSI-1-10	0.0030	0.001	212.0	6.7	0.08	0.001
SSI-1-11	0.0020	0.001	190.7	1.7	0.03	0.001
SSI-1-9*	0.0020	0.001	212.0	7.4	0.09	0.001

* pumping test sample

The monitoring well data are plotted on a Piper plot in Figure 15, along with available groundwater chemistry data for Salt Spring Island (Klassen et al. 2014). Samples from Salt Spring Island collected from sedimentary rocks are shown as green triangles, from igneous rock as pink inverted triangles, and from discrete depths in SSI-1 as black circles. Also shown are the average rainfall composition determined from the Environment Canada Saturna Island Station CAPMoN (Canadian Air and Precipitation Monitoring Network; Environment Canada 2013)) dataset and local ocean water samples. Symbols are scaled in the upper diamond according to TDS.

The groundwater chemical evolution on Salt Spring Island is consistent with that from the other Gulf Islands (Larocque 2014). Figure 15 shows four pathways:

1) carbonate dissolution (from rain to a Ca-HCO_3 composition)
2) Cation exchange (from a Ca-HCO_3 to Na-HCO_3 composition)
3) Salinization pathway 1 (from a Na-HCO_3 to Na-Cl composition)
4) Salinization pathway 2 (from a Ca-HCO_3 to Na-Cl composition)

Samples from the igneous rocks almost exclusively have a Ca-HCO_3 composition, while the samples from sedimentary rocks show varying chemical compositions reflecting immature (Ca-HCO_3) waters to waters that have or are undergoing cation exchange, to waters that are variably mixed with saline water. The samples from the monitoring well have water types that range from Ca-HCO3 to Na-HCO_3 and NaCl, and plot along Salinization pathway 1, indicating that they have undergone cation exchange and are evolving toward a Na-Cl composition (Allen and Suchy 2001).

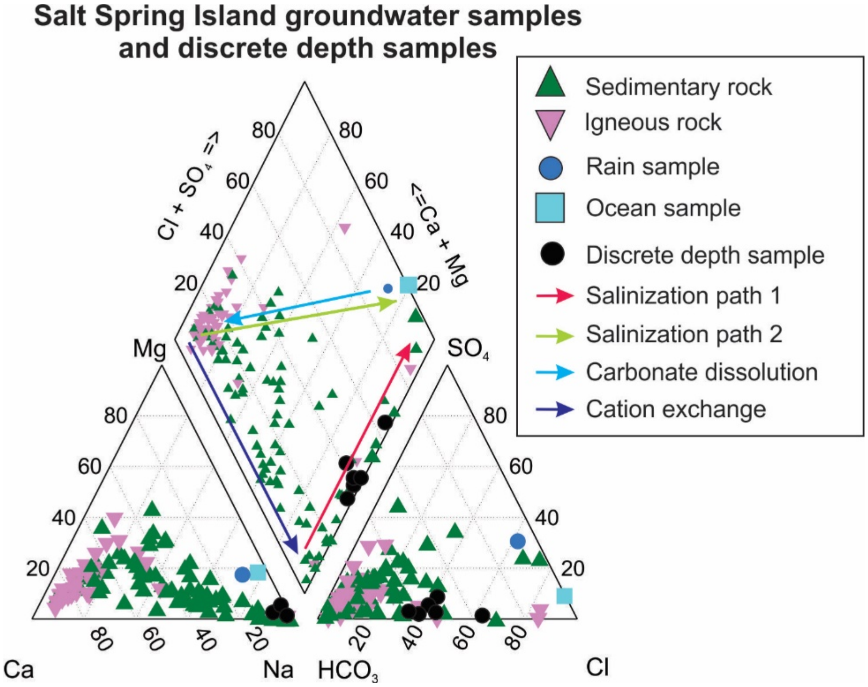

Figure 15. Piper plot showing the monitoring well chemistry along with chemistry from Salt Spring Island samples (Klassen et al. 2014). Symbols are scaled according to TDS in the upper diamond.

6.3 Analysis of Indicators

One of the objectives of this study was to assess indicators of salinity using the various methods described in Klassen et al. (2014). The various approaches (graphical and statistical) are described in more detail in that report.

Figure 16 shows a comparison of EC between the water samples taken during drilling (measured on site) and during the packer sampling (measured in the lab) with depth. The EC values follow a similar trend, generally increasing with depth in a consistent fashion. Only one discrete depth interval sample (SSI-1-17) plots off the trend. The EC values are very consistent, which suggests that EC could be measured during drilling as a relatively inexpensive means to monitor salinity.

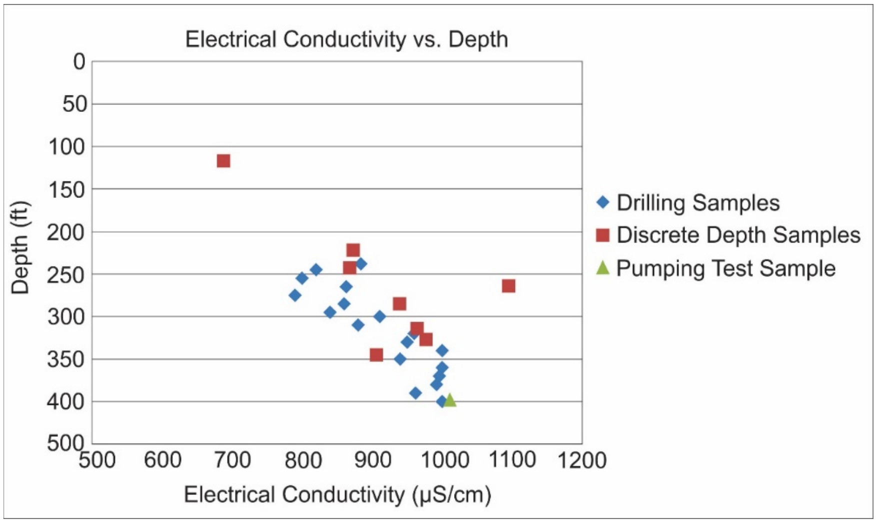

Figure 16. Comparison of EC in samples taken during drilling and at discrete depths using the packer equipment. Discrete depth interval samples are plotted at the mid-point of the packed interval.

The lab analysis results for the pumping test sample and the discrete interval samples were used to evaluate various indicators of SWI as per Klassen et al. (2014). Two ion ratio indicators were tested:

(1) The ratio of Cl/(HCO_3 + CO_3), which includes five classes that evaluate the level of salinization (good quality [<0.5], slightly salinized [0.5-1.3], moderately salinized [1.3-2.8], injuriously salinized [2.8-6.6], and highly salinized [6.6-15.5]); and
(2) Base Exchange Index (BEX =Na+K+Mg-1.0716 Cl [meq/L]), which can be used to distinguish if the aquifer is undergoing salinization (negative BEX) or freshening (positive BEX). Table 8 summarizes the results for both the monitoring well and the Salt Spring Island groundwater chemistry database (as reported by Klassen et al. 2014).

Table 8. Summary of ion ratio results for the monitoring well and the Salt Spring Island (SSI) database

	Cl/(HCO_3 + CO_3)		BEX	
Water Sample	#	Result	#	Result
Monitoring Well	7	Good	9	Freshening
Monitoring Well	0	Slightly Salinized	0	Salinization
SSI Database	42	Good	98	Freshening
SSI Database	2	Slightly Salinized	4	Salinization

Overall, the results of these indicators are consistent between the monitoring well and the Salt Spring Island database. The ratio of Cl/(HCO_3 + CO_3) indicates that 95% (42/44) of water samples in the Salt Spring Island database are of good quality. The water samples from the monitoring well are all of good quality. All of the samples from the monitoring well also indicate freshening based on the BEX.

Several graphical approaches were also applied to the monitoring well samples. The first graphical approach is that of Panno et al. (2006) for Cl and Br (Figure 17). The data all plot close to the seawater-rainwater dilution trend indicating that mixing of recharge and a seawater-like endmember is occurring.

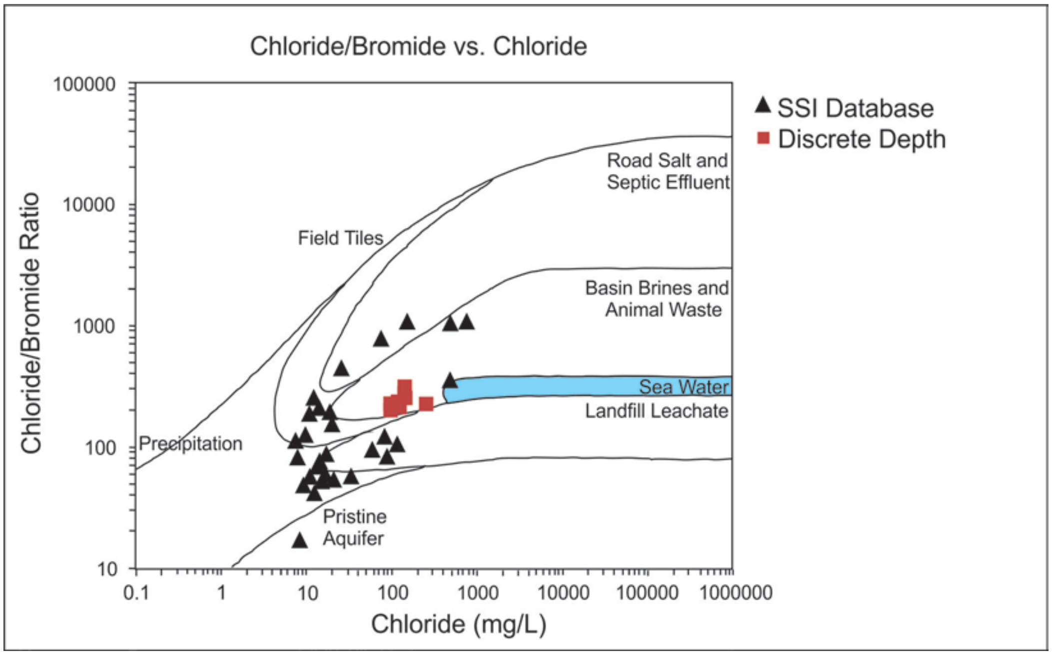

Figure 17. Ratio of Cl/Br vs. Chloride (method from Panno et al. 2006)

The second graphical method is Na vs. Cl (Figure 18). The monitoring well samples have a similar range as the Salt Spring Island database. The average ratio of Na/Cl for the monitoring well is 1.52, which is above the global seawater mixing line (ratio of 0.86).

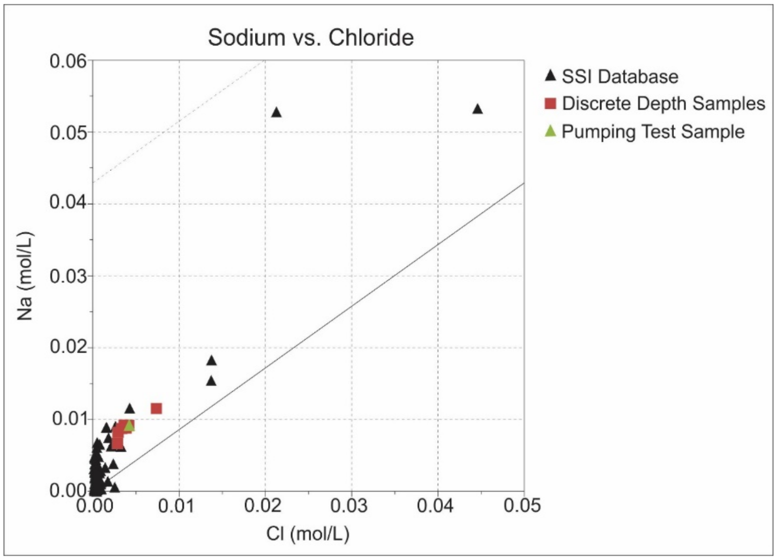

Figure 18. Ratio between sodium and chloride

The third graphical approach is Cl vs. EC with different zones identified according to the Washington State Department of Ecology (2005) (Figure 19). The majority of the water samples from the Salt Spring Island database fall in the normal groundwater zone. The water samples from the monitoring well have higher Cl and EC values and fall within the mixing zone and saltwater intrusion zone. One sample (SSI-1-17) falls in the saltwater intrusion zone.

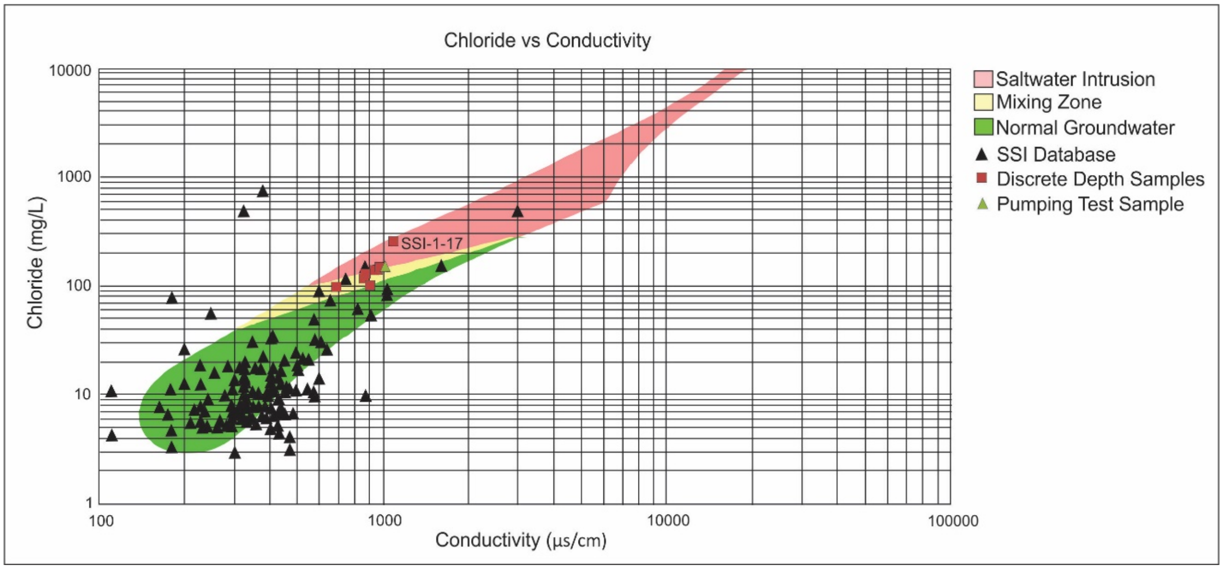

Figure 19. Cl vs. EC for the monitoring well (method from Washington State Department of Ecology 2005)

Finally, depth vs. TDS was plotted (as used by Allen and Liteanu 2006) (Figure 20). The monitoring well samples are located in Zone 3, which is indicative of mixing between Zone 2 (simple cation exchange) and Zone 1 (direct salinization). The approach could not be compared to other water samples from the Salt Spring Island database because no well depth measurements were available.

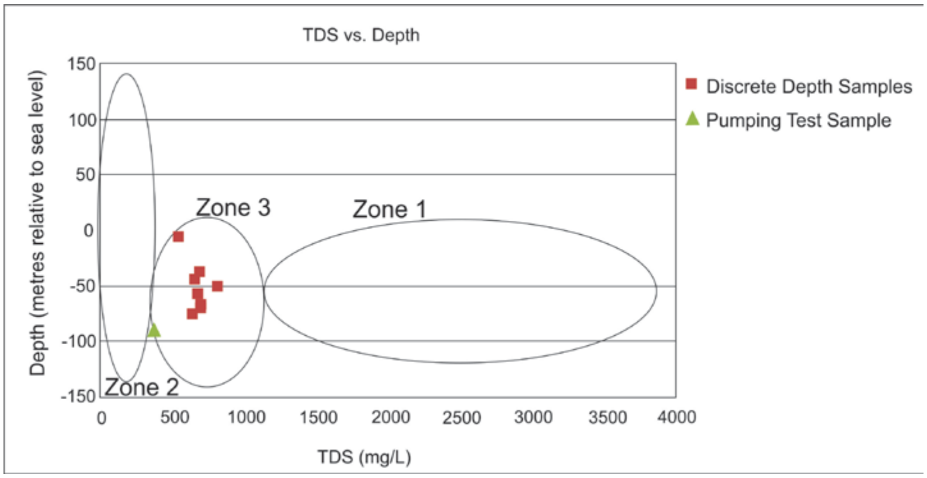

Figure 20. Depth vs TDS for monitoring well (method from Allen and Liteanu 2006). Zone 1 is direct salinization, Zone 2 is simple cation exchange, and Zone 3 is mixing between the two types.

A statistical approach (percentile ranking) was also applied to the monitoring well data. Klassen et al. (2014) had ranked each of Cl concentration, EC and TDS (percentile ranking) using the complete groundwater chemistry database for the Gulf Islands. Samples that were identified as having undergone SWI or salinization using the graphical approaches described above were used to determine threshold values for each of Cl, EC and TDS based on the data falling within the 95th and 90th percentile. These values correspond to 95% confidence or 90% confidence, respectively, 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.

The threshold values for Cl, EC and TDS were compared with the lab analysis results. The majority of the water samples from the monitoring well are above the 90th percentile (Table 9). None are above the 95th percentile.

Table 9. Summary of the Statistical Approach for monitoring well data. Shown in shaded cells are the respective indicator thresholds at the 95th and 90th percentiles determined from the Gulf Islands groundwater chemistry database.

Sample ID	Cl	Sample ID	EC	Sample ID	TDS
95th Percentile	480	95th Percentile	2090	95th Percentile	970
SSI-1-17	259	SSI-1-17	1095	SSI-1-17	830
SSI-1-9*	145	SSI-1-9*	1011	SSI-1-12	721
SSI-1-10	145	SSI-1-10	977	SSI-1-10	720
SSI-1-12	145	SSI-1-12	963	SSI-1-16	707
SSI-1-13	140	90th Percentile	960	SSI-1-9*	705
90th Percentile	130	SSI-1-13	939	SSI-1-13	698
SSI-1-16	126	SSI-1-11	906	SSI-1-14	673
SSI-1-14	121	SSI-1-16	873	SSI-1-11	667
SSI-1-11	101	SSI-1-14	868	90th Percentile	620
SSI-1-15	99	SSI-1-15	688	SSI-1-15	553

* pumping test sample

6.4 Isotope Results

Selected water samples were submitted to specialized laboratories for isotope analysis. Oxygen-18 and hydrogen-2 (deuterium) were analyzed at the University of British Columbia Earth and Ocean Sciences Department using laser absorption spectroscopy on a Los Gatos Research (LGR) DT-100 instrument. Accuracy and precision of the $\delta^{18}O$ and $\delta^{2}H$ measurements were ± 0.2 and 1.0 ‰ (V-SMOW), respectively. The tritium content, helium-3 content and dissolved gas composition were analyzed at the Dissolved and Noble Gas Lab University of Utah. Tritium was determined using the helium ingrowth method with at least 2 months decay time followed by measurement using a Mass Analyzers Products – Model 215-50 magnetic sector mass spectrometer (error ± 3%). The total gas content was measured on a Stanford Research SRS – Model RGA 300 quadrupole mass spectrometer, and the dissolved ^{3}He was measured on the magnetic sector mass spectrometer. Radiocarbon and δ^{13}C were measured at the University of Georgia Centre for Applied Isotope Studies on a National Electrostatics Corporation Model 1.5SDH-1 Pelletron Accelerator Mass Spectrometer (error ± 0.3% and 0.2‰, respectively). Results are shown in Table 10.

The stable isotopes of groundwater (^{18}O and ^{2}H) from the Gulf Islands generally plot in a cluster on or near the global meteoric water line (Craig 1961) and the Saturna Island local meteoric water line (Canadian Network for Isotopes in Precipitation (CNIP) 1997-2010 data). The stable isotopic composition of the sampled waters is consistent with waters from Saturna and Hornby Islands (Allen 2004) and reflects recharge from meteoric waters.

Tritium content ranges from 0.04 to 0.85 TU, with the highest value in the shallowest sample and a rapid decrease with depth. The carbon-14 content (expressed as a percent modern carbon pmC) and δ^{13}C show a similar trend with the highest pmC and lowest δ^{13}C value in the shallowest sample. The dissolved gas and ^{3}He analysis failed, and no results were produced. The copper tube samples provided to the laboratory had very high concentrations of dissolved gases and new extraction system at the lab failed because the gas pressure in the tubes was too high. Since then, the lab has redesigned the extraction system to be able to withstand positive pressures but our samples were compromised.

Table 10. Isotope results for SSI-1 samples. Samples arranged according to increasing depth.

Sample ID	**^{18}O (‰ V-SMOW)**	**^{2}H (‰ V-SMOW)**	**Tritium (TU) ± 1σ error (DL 0.05 TU)**	**^{3}He**	**δ^{13}C (‰ V-PDB)**	**Percent Modern Carbon (pmC ± 1σ error)**	**Radiocarbon Age (YBP)**	**δ^{13}C corrected Radiocarbon Age (YBP)**
SSI-1-15	-11.9	-84	0.87±0.04	N/A	-15.0	36.333±0.132	8370	8214±29
SSI-1-16	-12.2	-85	0.12±0.01	N/A	-13.3	19.644±0.099	13454	13167±40
SSI-1-14	-11.9	-84	0.02±0.03	N/A	-13.5	19.163±0.089	13659	13365±37
SSI-1-17	-11.9	-80	0.05±0.02	N/A	-13.3	19.027±0.139	13718	13424±57
SSI-1-13	-11.7	-84	0.05±0.01	N/A	-12.3	18.834±0.131	13802	13514±56
SSI-1-12	-11.4	-84		N/A	-12.3	19.466±0.088	13529	13249±36
SSI-1-10	-10.5	-83	0.05±0.01	N/A	-11.5	16.069±0.080	15114	14796±40
SSI-1-11	-11.1	-83	0.04±0.01	N/A	-12.0	18.049±0.085	14154	13858±37
SSI-1-9*	N/A	N/A	N/A	N/A	-12.7	18.379±0.085	14004	13707±37

N/A – not analyzed or analysis attempted (for ^{3}He) but unsuccessful.

* pumping test sample

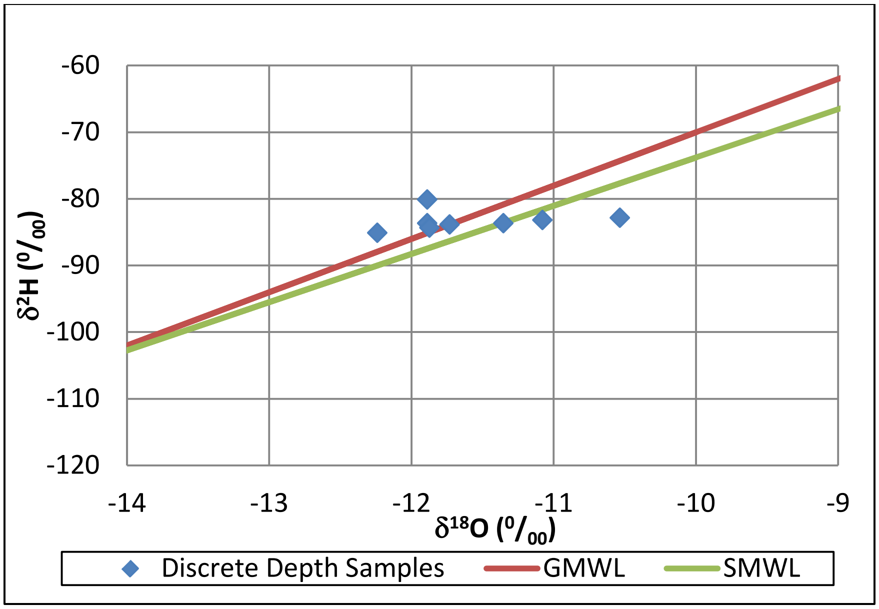

Figure 21. δ^2H vs. δ^{18}O for SSI-1 samples plotted with the global meteoric water line and the Saturna local meteoric water line (data from Environment Canada Saturna Island Station CAPMoN (Canadian Air and Precipitation Monitoring Network)).

6.4.1 Interpretation of Isotope Results

Determining the mean residence time or 'age' of groundwater using tritium requires knowledge of the initial tritium content (Clark and Fritz 1997). Without an initial input value, measuring the current tritium and ^{3}He content produced through the decay of tritium will allow the initial tritium to be estimated and mean residence time based on the tritium decay can be calculated. Currently, there are no data available for the tritium content of precipitation from the Gulf Islands or the entire region. And, we were unable to determine the ^{3}He content due to instrument problems. So, an alternative method was used to estimate the initial tritium content of the recharge. We used unpublished data from precipitation at three locations in the Okanagan (2009-2012), which yields an average tritium content of ~5 TU for fall and winter precipitation. This value is used for all calculations of estimated mean residence time.

Another common problem encountered when trying to calculate mean residence time is mixing, particularly if the mixing involves waters of very different ages. The major ion composition of SSI-1-15 suggests that this sample is dominated by mixing between the deeper groundwater and relatively recent recharge. Using the Cl content, a mixing model was generated, wherein the SSI-1-14 Cl content (121 mg/L) was assumed to represent the evolved endmember water and a value of 1 mg/L Cl was assigned to the recharge (the other endmember). Calculating the mixing ratio of the two endmembers that contribute to sample SSI-1-15 gives 32% recharge and 68% evolved water, or a ratio of 0.47. This number is fairly robust as even increasing the recharge to 10 mg/L Cl results in 34% recharge and 66% evolved water. Using this mixing ratio, the tritium content of the recharge can be calculated to be 2.7 TU, slightly more than one half of the estimated precipitation tritium content. This suggests that the recharge endmember has a mean residence time of between 10 and 20 years (18 years based on the precipitation at 5 TU). The evolved groundwater samples are at or below the reported detection limit and thus can be assumed, at least initially, to be older than 50 years.

For waters with mean residence times of greater than 50 years, age determination using ^{14}C is commonly applied (Clark and Fritz 1997). In order to use the ^{14}C of dissolved inorganic carbon (DIC) in groundwater to calculate an age, numerous corrections have been proposed (see Clark and Fritz 1997; Geyh 2000). The most critical observations that come from the literature are that there are no set formulas to conduct corrections for ^{14}C age and that the characteristics of the systems being investigated predicate the methodology. For the SSI samples, two pieces of information are required: 1) the initial ^{14}C content of the recharge and 2) the fraction of the DIC that was added to the water as dead carbon from organic and inorganic reactions. Using the mixing ratio calculated above, the amount of DIC in the recharge endmember can be calculated as well as the pmC ^{14}C. Accordingly, these are 98 mg/L DIC as HCO_3^- and 72.9 pmC. If we assume that the recharge in the past had approximately the same controls as those currently impacting the recharge composition, then the amount of 'dead' carbon added as the groundwater moves through the aquifer is simply the difference between the recharge and the sampled waters.

The ages calculated in Table 11 are based on various scenarios:

1) DIC 100 mg/L and initial ^{14}C at 73 pmC
2) DIC 120 mg/L and initial ^{14}C at 73 pmC
3) DIC 100 mg/L and initial ^{14}C at 83 pmC
4) DIC 100 mg/L and initial ^{14}C at 63 pmC

The calculated ages range from a few hundred to nearly 4500 years before present (ybp). These results are in stark contrast to the uncorrected ages given in Table 10. The calculation was very sensitive to the initial DIC, more so than the pmC. However, changes in the initial DIC invariably mean that the pmC will also change as either more or less dead carbon is involved. Systematically changing both the DIC and the pmC correspondingly resulted in far smaller variations in the calculated age from that of the initial age 1 value. At this point, it is proposed that the best estimate lies between the ages calculated in age 1 and age 4 values.

Accordingly, based on the tritium content and the estimated 14C age, SSI-1-15 (the shallowest sample) is a relatively young water, recharged likely 10-20 years ago. The deeper samples are interpreted to range in age from ~2000-4000 ybp, with SSI-1-10 and SSI-1-17 having the oldest ages. The pumping test sample SSI-1-9 has an intermediate estimated age, consistent with water that would be abstracted over multiple depth intervals. Interestingly, SSI-1-17 had the highest EC, Cl and Br, and the lowest DO, distinct from the other samples, while SSI-1-10 had a similar chemistry to the other samples despite it having a similar age to SSI-1-17. Of all the sampled intervals, SSI-1-17 achieved the highest purge rate (see Table 4), suggesting that this zone was highly fractured. Overall, apart from the shallowest sample (SSI-1-15), the isotopic ages are generally uniform with depth in this monitoring well.

Table 11. ^{14}C calculated ages in years before present determined using varying initial inputs. Samples arranged in order of increasing depth.

SampleID	Depth (ft)	^{14}C age 1	^{14}C age 2	^{14}C age 3	^{14}C age 4
SSI-1-15	117	0	0	0	0
SSI-1-16	222	1103	2610	2164	0
SSI-1-14	243	1432	2939	2493	214
SSI-1-17	264	2982	4489	4043	1764
SSI-1-13	285	1628	3135	2689	410
SSI-1-12	316	1025	2532	2086	0
SSI-1-10	327	2719	4226	3780	1501
SSI-1-11	345	1375	2882	2436	157
SSI-1-9*	400	1890	3397	2951	672

* pumping test sample

7 Water Level Variations

7.1 Water Level Record

Shortly following drilling and testing of SSI-1, the BC Ministry of Forests, Lands and Natural Resource Operations installed a pressure transducer and datalogger in the well to record water levels. Water levels were recorded starting at 14:00 on February 20, 2014, and have been recorded hourly since. Figure 22 shows the record. Similar to other groundwater observation wells completed in bedrock on the Gulf Islands, the annual variation is approximately 5 m. The seasonal high is from early winter to late spring. This is followed by a recession from late spring to late summer. The lowest groundwater levels are in August and September. In early fall, the groundwater levels begin to rise as the fall and winter rainy period begins.

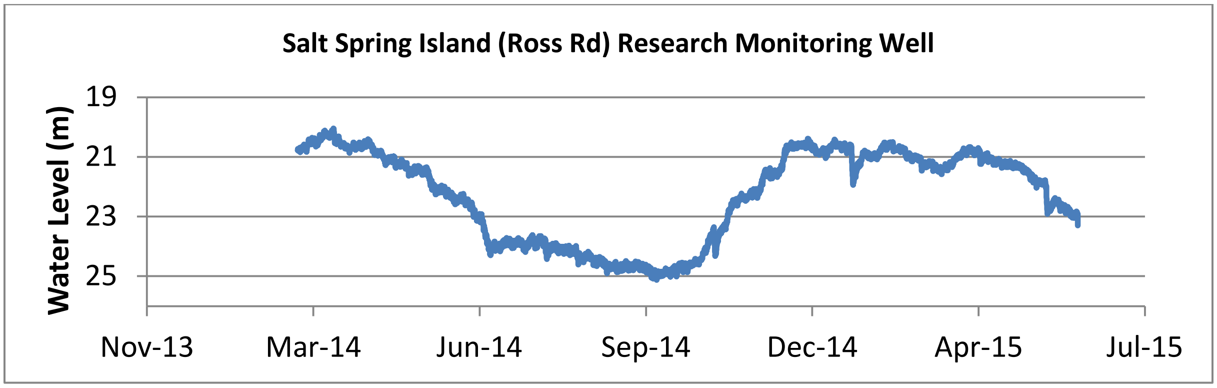

Figure 22. Groundwater level in SSI-1 from January 2014 to December 2014. The x-axis represents the date and time, the y-axis is the depth to water level from ground surface. Drier periods are represented by lower depth to water values, wetter periods by higher values.

8 Conclusions

Overall, the drilling and testing of the monitoring well on Salt Spring Island proved not only to be a valuable learning experience for the researchers, but also provided critical data to substantiate the findings of previous research efforts and increased our confidence in the conceptual hydrogeological model for the Gulf Islands. The main objective of the drilling and testing program was to collect water samples for chemical and isotopic analysis from specific depth intervals. Prior to drilling this well, there were no existing multi-level wells on the Gulf Islands that would enable sampling from discrete intervals. The lack of depth-specific chemical and isotopic data has been a significant limitation to research efforts for 1) understanding the chemical evolution of groundwater on the Gulf Islands, 2) understanding the residence time of groundwater, and 3) providing a salinity dataset that can be used for calibrating numerical groundwater models. In addition to obtaining depth-specific chemical and isotopic data, the well offered an opportunity to apply the saltwater intrusion indicators proposed in this research project (Klassen et al. 2014). Moreover, the monitoring well will ultimately be converted to a provincial observation well that can be used for monitoring groundwater levels and salinity into the future.

The main conclusions of this study are:

1. The transmissivity and storativity values determined from the pumping and recovery tests are of the same order of magnitude as the averages for the Gulf Islands region (Larocque 2014). For the pumping well the average transmissivity based on the various methods of analysis is 2.4E-05 m2/s, and for the observation well 7.2E-05 m2/s. The storativity is 3E-04.
2. The electrical conductivity (EC) of water samples collected during drilling appear to be consistent with the EC values measured on the discrete interval samples. This suggests that EC could be measured during drilling as a relatively inexpensive means to monitor salinity.
3. The various chemical indicators of salinity as proposed by Klassen et al. (2014) were evaluated. Overall, the results of these indicators are consistent between the monitoring well and the Salt Spring Island groundwater chemistry database.
4. On the basis of the geochemical and isotopic results, there appears to be mixing between meteoric water and a seawater endmember to different degrees down the depth of the well. However, the relative amount of seawater is generally quite low.
5. The tritium age dating indicates mixing between a modern (< 50 years) groundwater with an older groundwater (> 50 years). 14C age dating was uncertain, but different models for dissolved inorganic carbon content resulted in ages as old as 4000 ± 1000 years. These results substantiate the conceptual model proposed by Allen (2004) and Allen and Liteanu (2006), which suggested that the groundwater chemistry evolution can be explained by the aquifers of the Gulf Islands becoming inundated by seawater post-glaciation when the islands were submerged below sea level and then being flushed out by meteoric water following emergence. According to this conceptual model, there could be very old groundwater at depth that is somewhat saline – trapped water that was not sufficiently flushed following emergence. The age dates determined in this study appear to support this conceptual model.

9 Acknowledgements

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10 References

Allen, D.M. (1999). An assessment of the methodologies used for analyzing hydraulic test data from bedrock wells in British Columbia. Report prepared for the Groundwater Section, BC Ministry of Environment, lands and Parks, Queen's Printer, 91 pp.

Allen, D.M. (2004). Sources of ground water salinity on islands using stable isotopes of 18O, 2H and 34S. Ground Water, *42(1)*, 17-31.

Allen, D.M. and Liteanu, E. (2006). Long-term dynamics of the saltwater-freshwater interface on the Gulf Islands, British Columbia, Canada. In Proceedings of *SWIM-SWICA Conference, Cagliari, Italy*, September 24-29, 2006.

Allen, D.M., Liteanu, E., Bishop, T.W., and Mackie, D.C. (2002). Determining the hydraulic properties of fractured bedrock aquifers of the Gulf Islands, B.C. Final report. Department of Earth Sciences, Simon Fraser University. Submitted to Al Kohut, BC Ministry Water, Land and Air Protection.

Allen, D.M. and Suchy, M. (2001). Results of the groundwater geochemistry study on Saturna Island, British Columbia. Report submitted to the Island Trust, Victoria, B.C., 127 pp.

Clark, I.D. and P. Fritz (1997). Environmental isotopes in hydrogeology. CRC Press, 342 pp.

Craig, H. (1961). Isotopic variations in meteoric waters. *Science* 133 (3465), 1702–1703.

Environment Canada. (2013). The Canadian National Atmospheric Chemistry (NAtChem) Database And Analysis System. https://www.ec.gc.ca/natchem/ (Accessed August, 2014)

Ferris, J.G. 1951. Cyclic fluctuations of water level as a basis for determining aquifer transmissivity. IAHS Publications 33: 148-155.

Geyh M. (2006). An overview of ^{14}C analysis in the study of groundwater. Radiocarbon**,** *42(1*), 99-114.

Greenwood, H.J. and Mihalynuk, M.G. (2009). Saltspring Island geology (adjoining quadrants of NTS 93B/11, 12, 13 &14). BC Ministry of Energy, Mines and Petroleum Resources, Open File 2009-11, 1:25 000 scale.

Jacob, C.E. 1950. Flow to groundwater. New York: H. Rouse, John Wiley.

Klassen, J., Allen, D.M. and Kirste, D. (2014). *Chemical Indicators of Saltwater Intrusion for the Gulf Islands*, British Columbia. Final Report submitted to BC Ministry of Forests, Lands and Natural Resource Operations, and BC Ministry of Environment, June 2014.

Larocque, I. (2014). *The hydrogeology of Salt Spring Island, British Columbia* (Masters thesis). Simon Fraser University, Burnaby, Canada.

Panno S. V., Hackley K.C., Hwang H. H., Greenberg S E., Krapac I G., Landsberger S. and O'Kelly D J. (2006). Characterization and Identification of Na-Cl Sources in Ground Water. Ground Water, *44*, 176-187.

Washington Department of Ecology (2005). Water Resource Inventory Area 06 Islands. Seawater Intrusion Topic Paper. Retrieved from:
https://fortress.wa.gov/ecy/publications/SummaryPages/1203271.html (Accessed July 10, 2013).