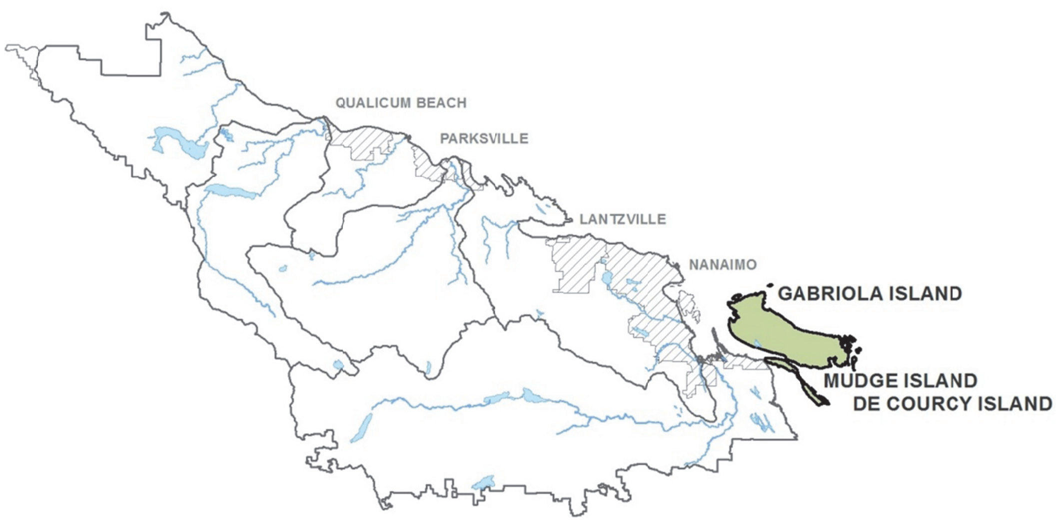
Water Budget Project: RDN Phase One (Gabriola, DeCourcy & Mudge Islands)

Report Prepared for

Regional District of Nanaimo



Report Prepared by

SRK Consulting (Canada) Inc.
1CR010.000
April 2013

THURBER ENGINEERING LTD.

Water Budget Project: RDN Phase One (Gabriola, DeCourcy & Mudge Islands)

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1 Introduction

In 2012, The Regional District of Nanaimo (RDN) initiated the Water Budget project to better understand the sustainable availability of water within a number of local water use areas. The project consists of two phases: Phase 1, which includes development of hydrogeological conceptual models and water budgets, and Phase 2, which will include a more detailed analysis, such as groundwater numerical modeling based on the results of Phase 1. This report presents results of Phase 1 for the Regional District's Electoral Area B, which encompasses Gabriola, Mudge, and DeCourcy islands (Figure 1).

Most of the study area relies on groundwater as its primary source of drinking and irrigation water. On Gabriola Island, groundwater in the fractured rock aquifers is recharged from rainwater and, in light of increased development and climate change, there are concerns about the groundwater resource and its sustainability and quality; a view shared by many of the islands' residents.

Several water resource studies concerning the islands have been completed to date. Phase 1 seeks to improve the understanding of regional water resources and, in particular, provide better descriptions of the hydrological cycle, available water quantity, the flow system, and water demand, along with a discussion of factors affecting sustainability.

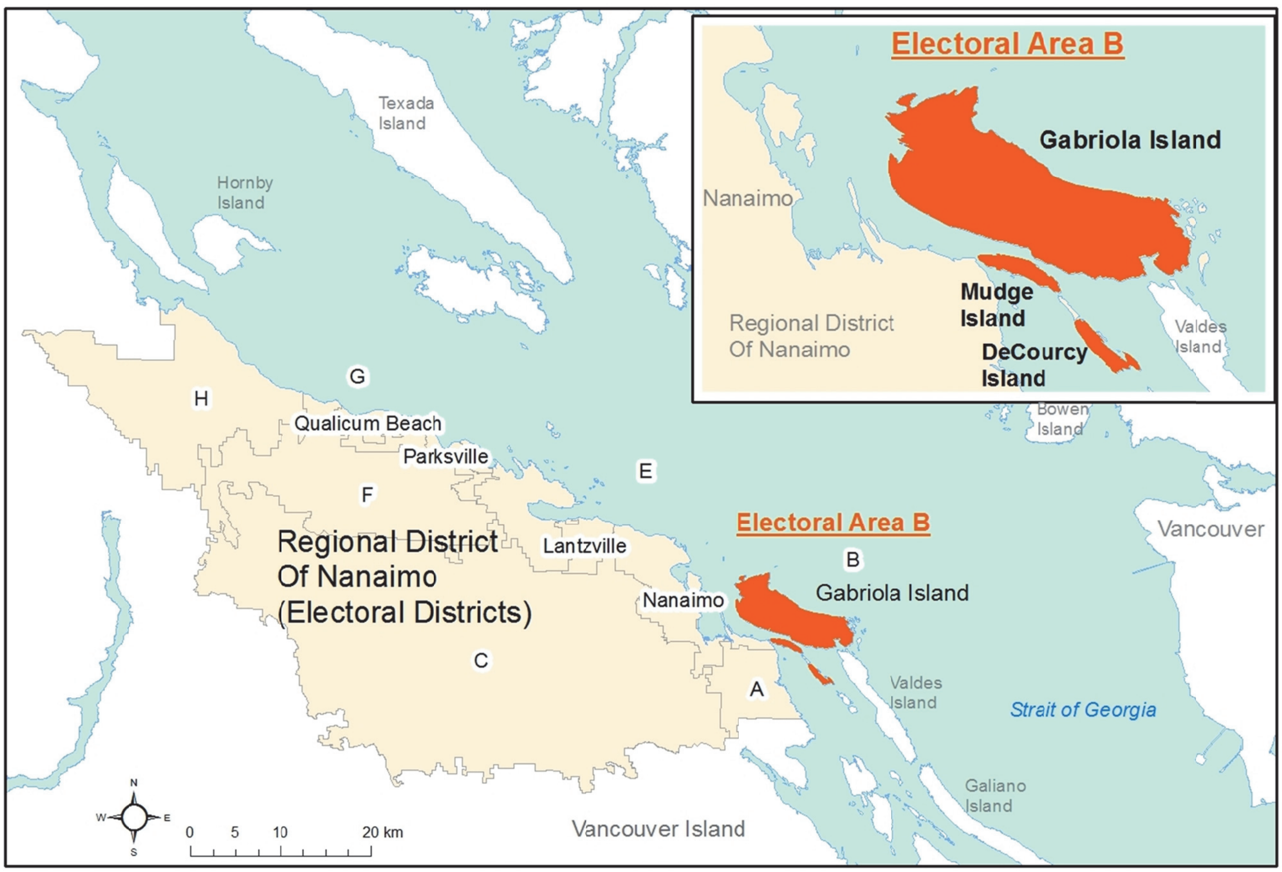


Figure 1: Regional District of Nanaimo and Electoral Area B.

1.1 Objectives

The specific objectives of the Phase 1 project for Gabriola, Mudge, and DeCourcy islands are:

- To update and review the existing hydrogeological information to improve the understanding of the groundwater system on Gabriola Island and nearby islands and to link all available information within one updated conceptual model.
- To develop a three-dimensional representation of the geological and hydrogeological system.
- To develop a water budget as a first step in understanding current groundwater and surface water utilization, as well as sustainable extraction.
- To assess groundwater extraction “stress” on aquifers.
- To identify data gaps or additional requirements that can be used to improve the RDN’s plans for expansion of the long term groundwater observation well network.

1.2 Project Scope and Tasks

As specified in the Request for Proposals (Water Budget Project: Phase One—RDN Gabriola, DeCourcy, & Mudge Islands), the scope of work for the SRK/Thurber Engineering team included:

1. Development of an updated hydrogeological conceptual model
2. Completion of a data gap analysis and suggestions for additional data collection
3. Estimation of groundwater and surface water balance components
4. Assessment of the water demand stress in each island water region
5. Presentation of results to the RDN and the Islands Trust

Over the course of the data gap analysis, a suggestion was made to conduct a short data collection program to provide additional information on hydraulic properties. This additional task was completed during late summer 2012.

1.3 Report Organization

This report has been formatted to present the Phase 1 findings of this project to a wide readership, including island residents, Island Trust members, and managers at the Nanaimo Regional District. The main report provides an overview of the hydrogeology of Gabriola, Mudge & DeCourcy Islands, water budget methods and results. As specified by the RDN, the text of this report was written in less technical language than typical engineering reports, but the text is based on technical information described in detail in the appendices. For this reason, in the main text of this report there are no specific references to journal papers or reports, except general references to work done previously and to the appendices of this report. Details on specific components, methodologies and calculations, and technical references are presented in the accompanying appendices.

Most figures presented in main document text are symbolic and designed to visually introduce some sections and to improve understanding of text by non-technical readers. There are detailed figures of technical graphs and maps in the Appendices.

2 Hydrogeological Conceptual Model

A hydrogeological conceptual model is a simplified representation of the essential features of the physical hydrogeological system and its hydraulic behavior, to an adequate degree of detail. In the case of this specific project, the hydrogeological conceptual model has been developed based on observations and measurements on Gabriola Island and other Gulf Islands, fundamental groundwater flow processes known in hydrogeology, and professional experience. The “model” is, by necessity, a simplification of actual, highly complex conditions used to help understand how the groundwater system operates on those islands, and what the range of properties of the aquifers is that characterizes the groundwater resource for residents and other uses.

At its most basic level, the conceptual model is based on the geological setting of Gabriola, Mudge, and DeCourcy islands and how these islands relate geologically to other Gulf Islands. Local geology provides the framework for characterizing the local hydrogeology. In terms of the hydrogeological system, the conceptual model describes the potential flow pathways and storage properties of the aquifers, the quantities of groundwater involved, and how these quantities relate to water demand on the islands.

2.1 Geological Setting

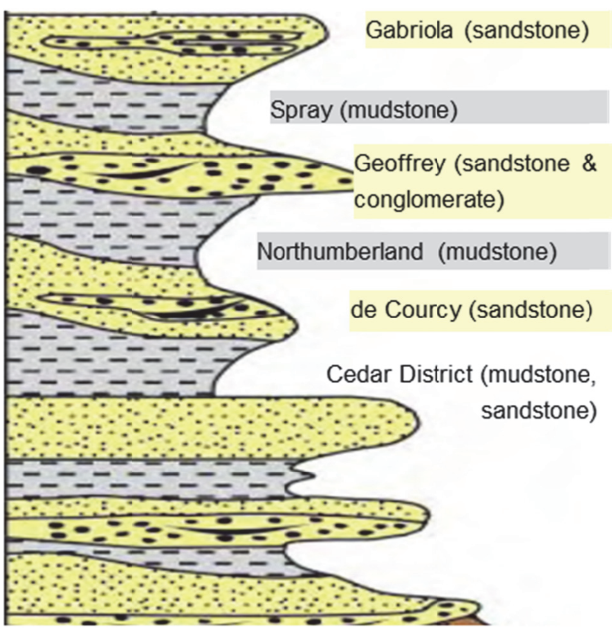


Figure 2: Nanaimo Group sequence of formations on Gabriola, Mudge, DeCourcy Islands.

(modified after Denny et al 2007 – see Appendix A)

The geology of the islands themselves, that is, the rocks and sediments that form the islands, is the framework in which the groundwater flows. Understanding the geology is thus the first step in developing the hydrogeological conceptual model.

The geology of the Gulf Islands is made up, to a large degree, of sedimentary rocks of the Upper Cretaceous Nanaimo Group. These sedimentary rocks consist of materials such as sand, silt, and clay that were deposited by water many millions of years ago. The way in which these sediments were deposited over time resulted in different thicknesses of various material types, which were later “lithified”, or compressed into sandstone and mudstone (locally called “shale”) rocks, with some areas of poorly sorted (large range in size of the grains, pebbles, and cobbles) materials forming what is known as conglomerate.

The rocks can be subdivided by their age into rock “formations” (certain marine fossils can be used to estimate the age of deposition). The typical sequence of these formations on the islands is shown in Figure 1, as a geological column. More details on geology are presented in Appendix A. The generalized column is a portion of the full sequence of formations mapped on the Gulf Islands. Since most of these formations include rocks of different types (e.g., sandstone, siltstone or mudstone), the formations appear as alternating units of what are considered sandstone-dominant and mudstone-dominant. There are no distinct "contacts", or boundaries between some formations, and most contain some sandstone and mudstone, often in alternating layers.

Of the eleven defined formations within the Nanaimo Group in the Gulf Island region, only some are visible at surface on Gabriola, Mudge, and DeCourcy Islands. This is because the rocks have been folded, tilted and eroded over time so that in some places only some rock formations exist above sea level. The formations observed on Gabriola, Mudge, and DeCourcy Islands include:

- The Gabriola Formation, which is usually a thick layer of sandstone. This is what is often observed forming higher elevation cliffs around Gabriola Island.
- The Spray Formation, which is composed mostly of siltstone and mudstone and is associated with steps or terraces in the overall ground surface on Gabriola. These rocks are usually observed at the bottom of cliffs, where past wave action or runoff has eroded the mudstone more easily than the sandstone.
- The Geoffrey Formation, which forms much of the lower elevation part of Gabriola Island, is composed of thick sandstone and conglomerate layers (or beds in geological terminology).
- The Northumberland Formation is found at even lower elevations, and outcrops along some shores of Gabriola Island and makes up the ocean bed between Gabriola, Mudge, and DeCourcy Islands. These rocks are similar to the Spray Formation in that silty mudstone is dominant, but there are also some layers that have been altered to clay, as well as some conglomerate layers. This rock formation is relatively thick.
- Deeper still is the DeCourcy Formation, which is made up mostly of sandstone with some siltstone and mudstone. This rock formation is found deep below Gabriola Island, and also, due to folding of the sedimentary rock layers, to the south of Gabriola along the shores of Mudge and DeCourcy Islands.
- Lastly, and exposed only on Mudge Island is the Cedar District Formation, which is a mix of thin layers of siltstone, mudstone, and sandstone.

The regional structural geology describes how the Nanaimo Group rocks were folded and faulted over time. On Gabriola Island, the largest geological structure is a syncline fold (Figure 3), in which the rock layers are deformed into a gentle u-shape, the lowest part of which occurs within the middle of the island.

The land shapes (surface topography) of Gabriola and the smaller islands were formed from the originally folded rocks by erosion, mostly by ocean waves, through chemical weathering above sea level, and by glacial ice scraping. Wave erosion was significant and eroded the weakest geological units, producing terrace-like steps corresponding to various historical mean sea levels.

The sandstone rocks are resistant to erosion because they are very strong and less fractured, allowing them to stand as nearly vertical cliffs. Cliffs along the Northumberland Channel, visible from the ferry, just around the corner from Descanso Bay, are made up of Geoffrey Formation sandstone and conglomerate, while those farther south toward Dodd Narrows are made up of sandstone of the Gabriola Formation. Cliffs along the north side of the island are mostly Geoffrey Formation sandstone.

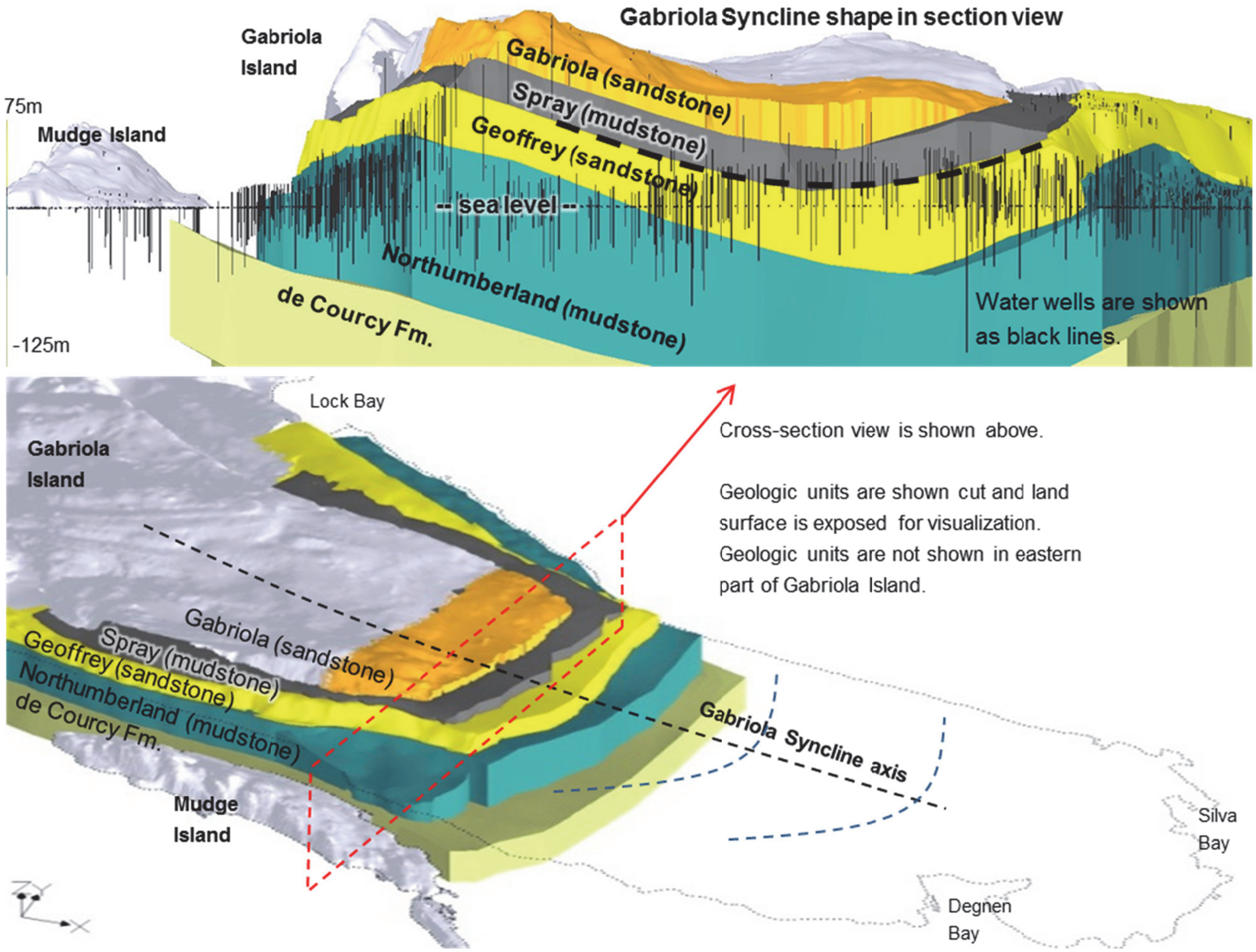


Figure 3: Gabriola syncline and geological units in cross-sections.

The mudstone rocks are less resistant to wave erosion and have been eroded back from the shore and form the sides and bottoms of some valleys. Along shores, mudstones do not form cliffs. Along the False Narrows and east of Lock Bay are mudstone outcrops of the Northumberland Formation rocks.

In parts of Gabriola Island, there are rock depressions that have been filled by glacial till and other surficial sediments (e.g., sand, gravel, silt, and clay). These sediments may also hold and transmit groundwater, but are generally above the water table. Small ponds and lakes may form on top of clay deposits which prevent water from draining to the underlying fractured rock. Most of the island is covered by relatively thin soils, and bedrock either outcrops or is covered by thin soils.

2.2 Hydrogeological Units and Properties

2.2.1 Fractured Rock Aquifers

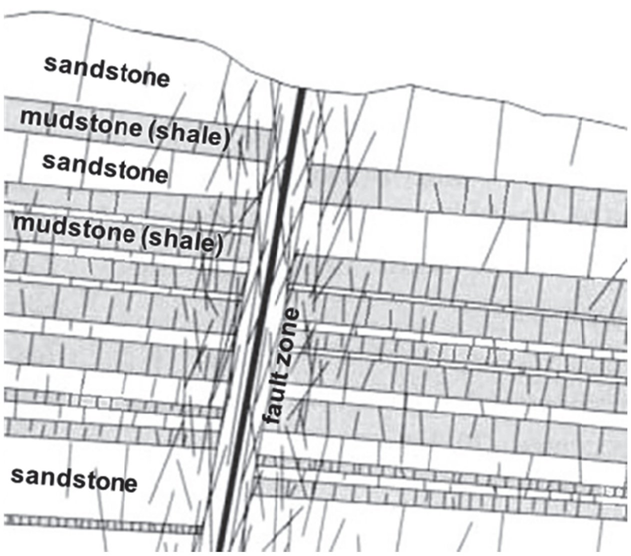


Figure 4: Fractured sandstone, mudstone, and fault zone.

(modified after Surette et al 2007 – see Appendix B)

In the Nanaimo Group rocks, groundwater flows and is stored almost exclusively within fractures or "cracks" in the rocks. These "fractured rock aquifers" occur all around the world and can be difficult to fully understand, so hydrogeologists often try to understand how fractures affect groundwater flow at large scales (by grouping fractures together). These groupings then become part of the conceptual model.

On Gabriola Island alone, there may be a billion different fractures of various sizes, some of which are interconnected to allow groundwater to move fast along them or allow precipitation to recharge the system. Others, which may be too small or sealed by mineral precipitates, may have no effect at all on groundwater flow. In addition, there is some groundwater between sand and silt grains themselves, where the cement holding the grains together to form the rocks does not completely fill spaces. Water flows extremely slowly in these pores; most water extracted by pumping wells on the islands comes from fractures. Hydrogeologists try to understand the different types of fractures to see if or how groupings can be made.

There are different types of fractures (joints or "cracks" in rock) on the islands depending on the type of rock (i.e., the lithologies) and location (Figure 4 and more detailed figures in Appendix B). Tectonic events caused uplifting and folding of sedimentary layers. The fractures originated from stresses within rocks during regional folding and faulting. Isostatic rebound due to glacier unloading at the end of the ice age may have also contributed to fracturing.

Mudstone is a fine-grained rock type which, on the Gulf Islands, is very finely fractured. The high frequency of fine fractures resulted from the way these rocks responded to stresses during deformation. Sandstones fractured differently, into larger blocks with large and nearly vertical fractures or some smaller fractures at other orientations. Vertical joints also formed in some places where sandstone strata became unevenly supported by underlying mudstone because of weathering. Vertical joints are important for allowing groundwater to infiltrate downward across sandstone layers.

The largest occurrence of fractures in sandstone is near faults and where the folding was the most intense. The largest fault on Gabriola Island is the Gabriola Fault. The geological units are shifted and appear to be tilted differently to the west of this fault. Faults may also act as barriers to flow when there is clay present within the fault; fault movement over a long time grinds the rock surface into clay. There is no specific information available for the faults, however, along the faults, on either side, the rocks are usually more intensely fractured and this usually corresponds to faster groundwater flow. Wells drilled near faults are often very productive, as seen on other Gulf Islands.

2.2.2 Hydraulic Properties

The fractured rocks have certain properties which describe how rapidly groundwater can move through the fractures and how much groundwater can be stored in them. These properties control how much water can be pumped and the properties can vary across different areas or between different rock units. To better understand these properties on the islands, published reports were reviewed and some testing was done as part of this project.

The review of published test data indicates that there is not much difference in these properties between different geological formations. It is difficult to tell how representative these test data may be; there has never been an island-wide test program to understand how these properties may vary between different rock types or between wells screened in specific geological layers. The tests on Gabriola and the other Gulf Islands were usually located in large fracture zones, which seem to have more groundwater flow than normally fractured rock. Observations of groundwater seepage and the shape of the water table suggest that there should be some differences in hydraulic properties between units.

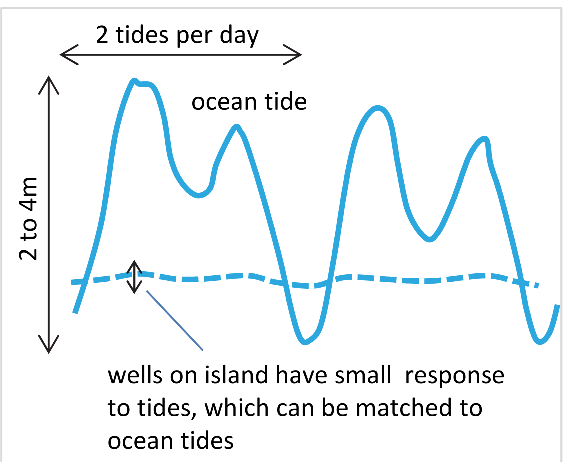


Figure 5: Ocean tides and water level fluctuations in wells.

(note: details are in Appendix C)

During the late summer of 2012, SRK installed 10 water level recorders in different pumping wells around the island to do a tidal analysis. Tidal analysis uses the response of the water level in wells to ocean tides to allow an estimation of hydrogeological properties. Figure 5 illustrates how water level in a well is compared to a local tidal cycle. Like any test method, it has its limitations, but as long as ocean tides are measured in well water levels, the hydrogeological properties of rocks can be calculated.

In most residential and Ministry of Environment observation wells the groundwater levels respond to ocean tides, some very slightly and a few very strongly.

The hydrogeological properties derived from these analyses show a lot of differences over Gabriola Island, with the most transmissive rock near fracture zones in sandstone. Along the north and south shores of Gabriola Island, where the Northumberland Formation is present, the test results suggest effects of “confining layers”, which are layers that do not allow much groundwater flow and which may be related to clay identified in drilling logs.

The results of all tests and other observations can be used to define different hydrogeological units.

2.2.3 Hydrogeological Units

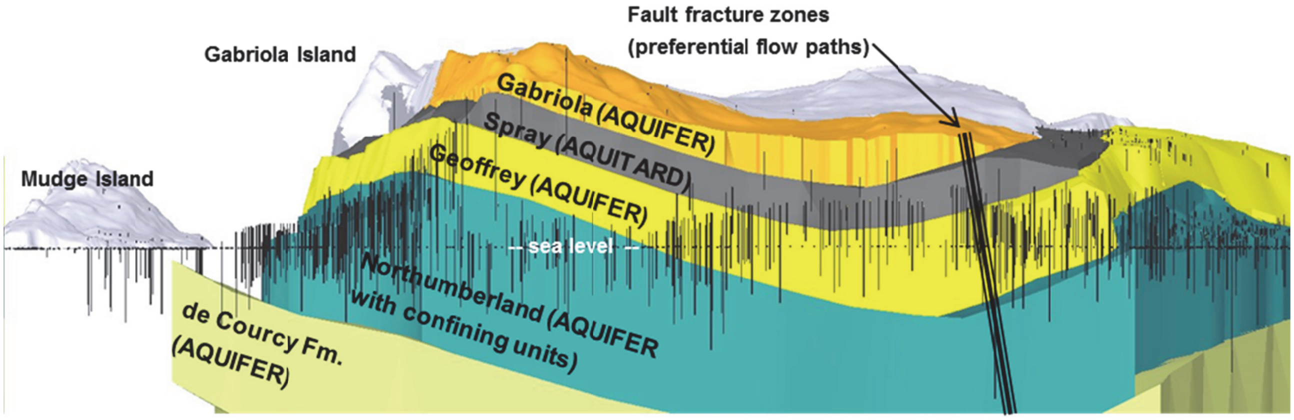


Figure 6: Hydrogeological units on Gabriola Island.

Using the information on geology and hydrogeological properties, groupings or "hydrogeological units" are defined. The more permeable units are classified as "aquifers" and the less permeable ones as "aquitards". These terms are only relative, and some islands as a whole may be better aquifers than other islands.

In previous reports, different approaches to these groupings were used. In certain instances, whole islands were considered to be groundwater aquifers. In others, zones of similarly fractured rock with similar hydrogeological properties were used to define "hydrostructural domains", a definition of aquifers linked to fracture occurrence and their ability to conduct water, rather than a more general description of a simple island aquifer. For this project, the main hydrogeological units (Figure 6) are generally considered to follow the geological formations, with fault zones cutting across all units and forming preferential flow pathways. A discussion of these units (shown in bold) follows.

Sandstone and conglomerate aquifers

These units are layered (following the geological formations) and bent along the u-shaped fold according to the geology on Gabriola Island. These aquifers have large, nearly vertical, fractures which are very conductive to groundwater but are also easily drained and refilled. Variations of lithology and fracturing can occur within these units. Mudstone interbeds are common and can act as local aquitards to groundwater flow across them. These are represented on Gabriola Island by the Gabriola Formation and Geoffrey Formation.

- The Gabriola Formation is an unconfined aquifer that receives most of the groundwater recharge from precipitation. Water infiltrates from rainfall and flows through fractures in sandstone.
- The Geoffrey Formation is an aquifer that is productive in many places. In the middle of Gabriola Island much of this aquifer is confined and unused because it is deep below ground. It is unconfined around the edges of the island and has a very steep water table within its fractures near cliffs. There may be a separate lower water table below the Spray Formation near some cliffs.

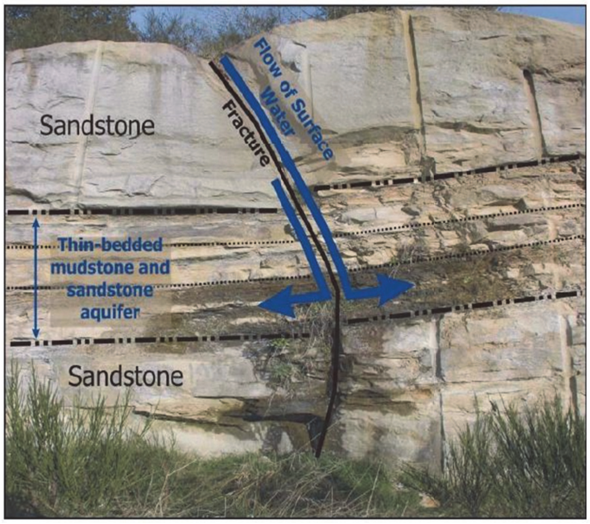


Figure 7: Flow through fractures in sandstone and mudstone at exposed cut rock slope.

(photo from Denny et al 2006 – see Appendix A)

Mudstone aquifers and aquitards.

These units are also consist of layers and are similar to the geometry of the sandstone units. There are many small fractures and larger weathered zones along the contact of mudstones and sandstones that can transmit water effectively. However, in many areas, the mudstones do not conduct water as easily as sandstones and are more difficult to drain. Small mudstone layers occur in many places within sandstones and contribute to complicated groundwater flow pathways (Figure 7). The Spray Formation and mudstone interbeds within sandstone units are good examples. The Spray Formation may act as an aquitard that acts as a water "bowl" and holds the water table high in middle of Gabriola Island.

Other, differently fractured mudstones, such as the Northumberland Formation, can store as much water as sandstones and can be more productive aquifers than less fractured sandstones. The Northumberland Formation is a productive aquifer with many thinner clay aquitard layers. This unit is present deep below the island, mostly below sea level. Groundwater discharge occurs along shores and below the sea bed from this unit because of the geometry of the aquifer and aquitard layers. It is also effective at limiting salt water intrusion in wells pumped near the shore from this unit due to presence of clay aquitard layers.

Clay-altered mudstone aquitards.

These units are present within the mudstone aquifer. Groundwater can only flow very slowly across clay layers and is forced to flow parallel to them through the mudstone or sandstone.

Large fracture zones associated with major faults.

These units are present in some locations and cut across sandstone and mudstone layers. The fracture zones are narrow and do not store very large quantities of water, but they can act as conductive channels between different parts of the aquifer. The effects of pumping or of ocean tides can be detected over long distances along fracture zones.

2.2.4 Well Yields and Aquifer Productivity

Water yields are a useful indirect measure of aquifer productivity.

On Gabriola Island, there is some clustering of wells with higher yields in some areas, but there is no clear pattern. Wells are drilled where residences are established and the pattern of development is clustered along shores, roads, tops of cliffs, and where new subdivisions were established.

The most productive areas appear to be in fracture zones near intersections of major faults, within the Northumberland Formation, along shorelines, and generally in west part of the island. Less developed areas may be as productive in the future and haven't been tested yet. Well yields were plotted (Appendix B).

2.3 Groundwater Flow System

2.3.1 Average Groundwater Levels

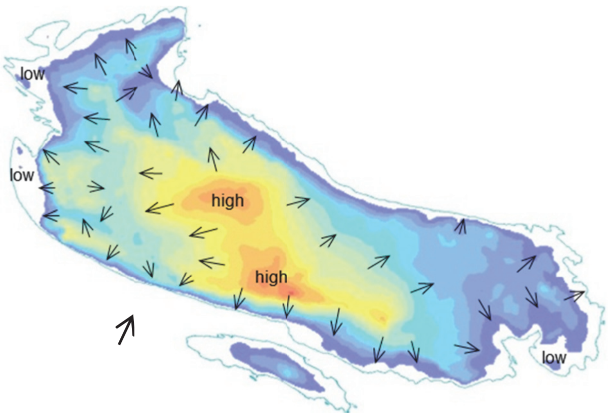


Figure 8: Water table elevation and assumed flow directions: Gabriola Island.

(note: detailed maps are in Appendix B)

Water levels measured in wells can be used to determine the direction of groundwater flow and to identify the presence of separate aquifers. The water table surface in an unconfined aquifer is a very important component of the whole flow system. Its shape can assist with the interpretation of the overall flow system and determine the directions of groundwater flow.

As part of this assessment, all available water level data were reviewed and an interpretation made of the water table surface. The water table surface was approximated using water levels in residential wells, existing observation wells on Gabriola Island, lakes, and ocean shores (Figure 8). The hydrogeological units and geology were considered in areas without measurements, where the water table surface had to be estimated. More detailed maps are presented in Appendix B.

The water table on Gabriola is generally similar in shape to topography, as interpreted in previous reports. At most locations the water table is 3 to 10 metres below ground, but there are some areas where it is deeper. In some locations along the northeast and southwest sides of the island, where the folded geological units are relatively higher in elevation, depth to water can generally be greater than 20 metres and, in some locations, up to 50 metres. These locations are typically topographically high (e.g., such as the top of cliffs) where wells are often deeper and show different, and lower, water levels than nearby, relatively shallower wells. Along the shoreline, the water table is close to sea level. At the northwest and southeast ends of the island, where the ground elevation is typically lower and there are many bays and peninsulas, water levels are often only a few metres or less above sea level. While these generalizations are reasonable at the scale of the island, the actual water levels are more complicated at a small scale, possibly indicating the presence of isolated perched water tables, but these are not likely to be very extensive.

The Spray Formation mudstone layer appears to contribute to holding up the water table at the higher elevation island centre, similar to a bowl of water that overflows and leaks (Figure 9). Most water wells in the central part of island do not penetrate below the Spray Mudstone so the water levels are only indicative of conditions above and in the Spray Mudstone. There might be a different water level in some places in the Geoffrey Sandstone that underlies the Spray Mudstone, especially near cliffs along shores. There are some small lakes and ponds in valleys where the Spray Mudstone is at the ground surface and below the valley (e.g., Hoggan Lake).

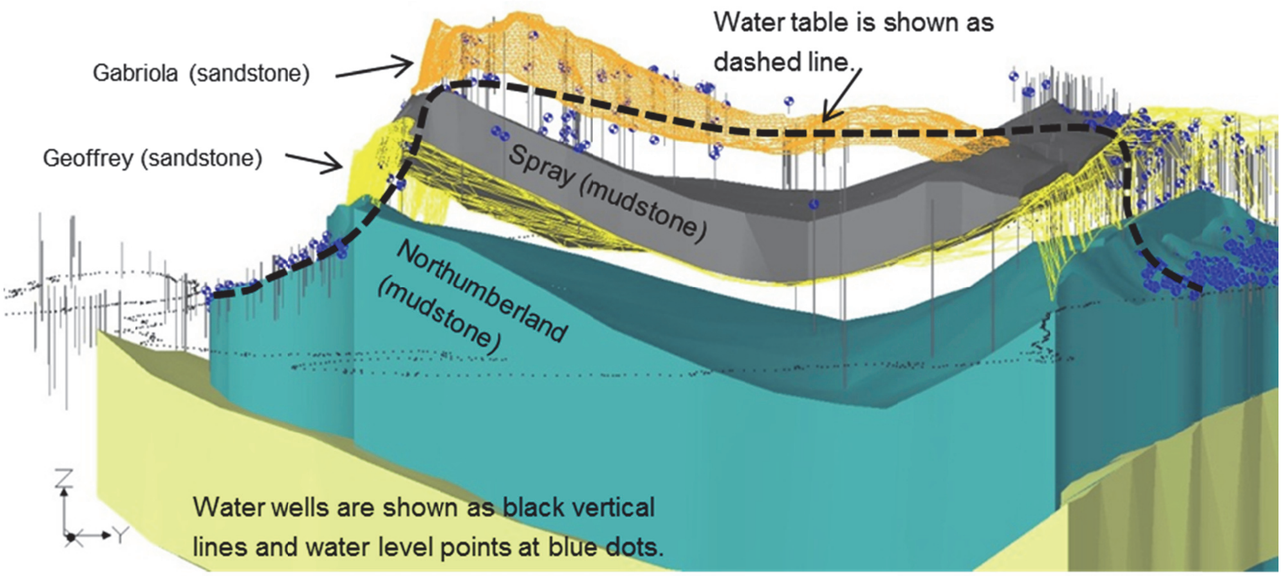


Figure 9: Cross-section of the Gabriola Island showing water table, water wells, and geological units.

The same general patterns are observed on Mudge and DeCourcy islands. The water table reflects the topography, and depth to water is generally greatest near the center of the islands.

The water table interpretation is considered to be sound, but some errors are expected to occur due to a number of factors:

- The residential wells are clustered in more densely populated areas and are not evenly distributed across the islands.
- There are very few wells in the middle, in the uplands, of Gabriola Island.
- Within the Ministry of Environment's wells database, the largest source of error is inaccurate positioning of wells recorded in the database. The water level was usually reported as depth to water; therefore, an accurate elevation of the well collar is needed to calculate the water elevation in a given well.
- Water levels are probably not always stable when recorded, but are measured following the drilling process but before the drilling influence has equilibrated (resulting in deeper water levels) or water levels may be measured when a large water-bearing zone was encountered.
- Water levels can also be affected by pumping of other nearby wells.

An average water table was fitted to all observations and anomalous levels were considered carefully, and often the surface was shaped as an average of various measurements.

2.3.2 Groundwater Flow

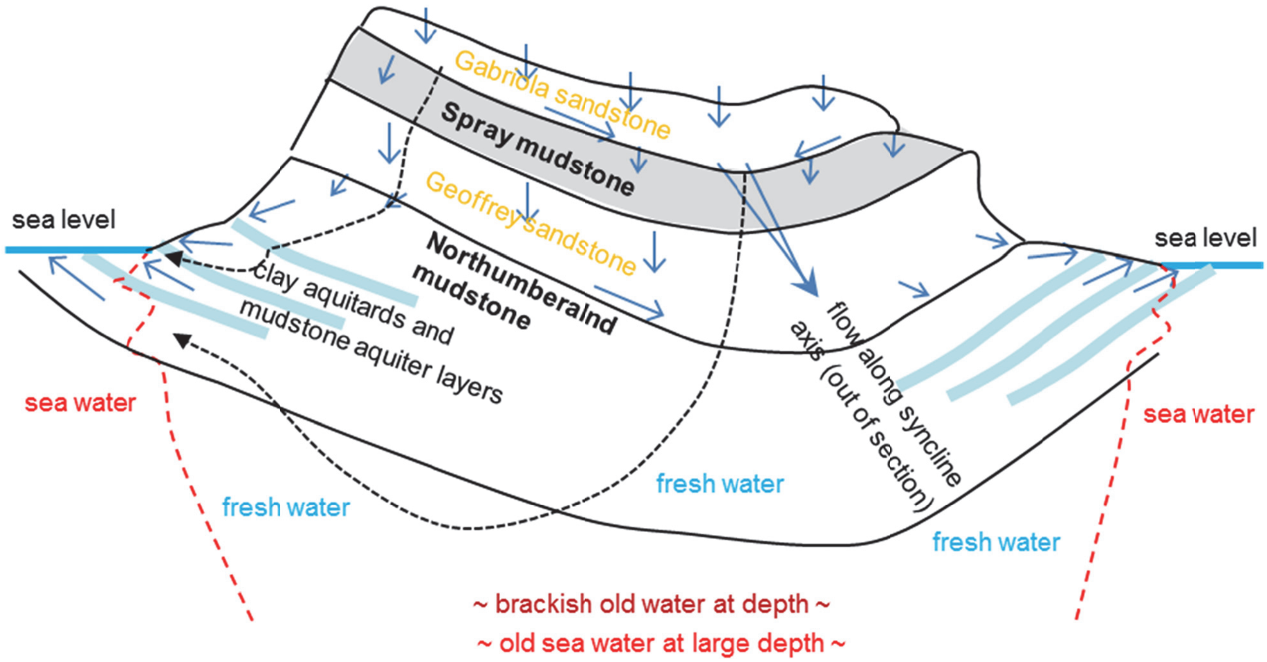


Figure 10: Groundwater flow in conceptual model of Gabriola Island.

The typical directions of groundwater flow are from areas with high water level (high hydraulic head) in the uplands to areas with low water level in valleys and along shorelines (low hydraulic head). The actual three-dimensional movement of water is not really known because there isn't much data for greater depths in Gabriola Island, but a reasonable flow pattern can be produced (Figure 10). There might occur a faster flow of groundwater along the top of the Spray mudstone along the contact with sandstone, and a slow downward flow perpendicular and across the Spray mudstone, except near fault zones where flow is faster. Flow is likely to also occur along the syncline axis.

At the base of the Geoffrey sandstone, flow might be preferable along the top of Northumberland mudstone. Within the Northumberland mudstone, flow is likely to be towards the ocean shores or ocean bed; perhaps in a slightly upward direction near shores because of the orientation of this unit and the presence of clay interbeds.

Complicating the flow pattern in three dimensions is the presence of sea water around the islands, and presence of salt or brackish water at some depth under the islands (Figure 11). Fresh groundwater flow occurs within a volume of water within the rock, often called the freshwater "lens" because of its theoretical shape under oceanic islands. The freshwater floats on top of salt water because of the water density difference (it is analogous to an iceberg floating in seawater). The presence of the fresh-seawater boundary deflects the groundwater flow along this boundary because fresh and salt water do not mix readily. There are aquitard layers of clay and mudstone that change the flow directions further to flow more parallel to those less permeable layers. The position of freshwater-saltwater boundary may be shifted further out to sea in some places because of aquitard layers, or it may be shifted inland because of active pumping in an aquifer.

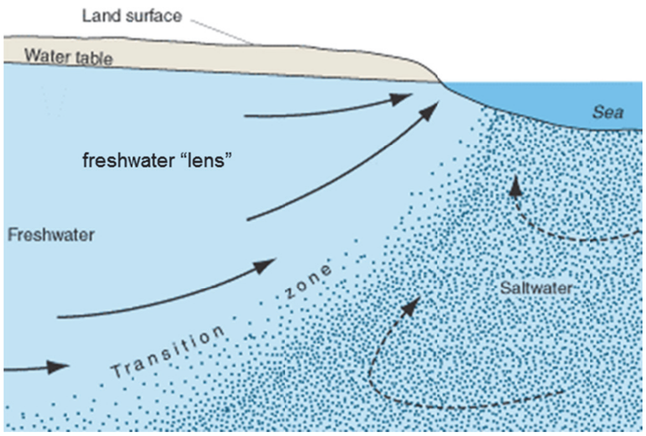


Figure 11: Freshwater-saltwater boundary and flow directions.

(modified from USGS drawing – see Appendix C)

The shape of the freshwater-saltwater boundary is not observed directly because only some wells near shores have brackish water due to saltwater intrusion, and wells in the middle of island are not deep enough to reach this boundary. The deepest water wells on Gabriola Island are less than 200 metres deep, and it is unlikely that an island water supply well will ever extend to a depth of hundreds of metres. There are no deep wells with measurements of salinity, and the position of freshwater-saltwater interface at depth below Gabriola Island is not well known.

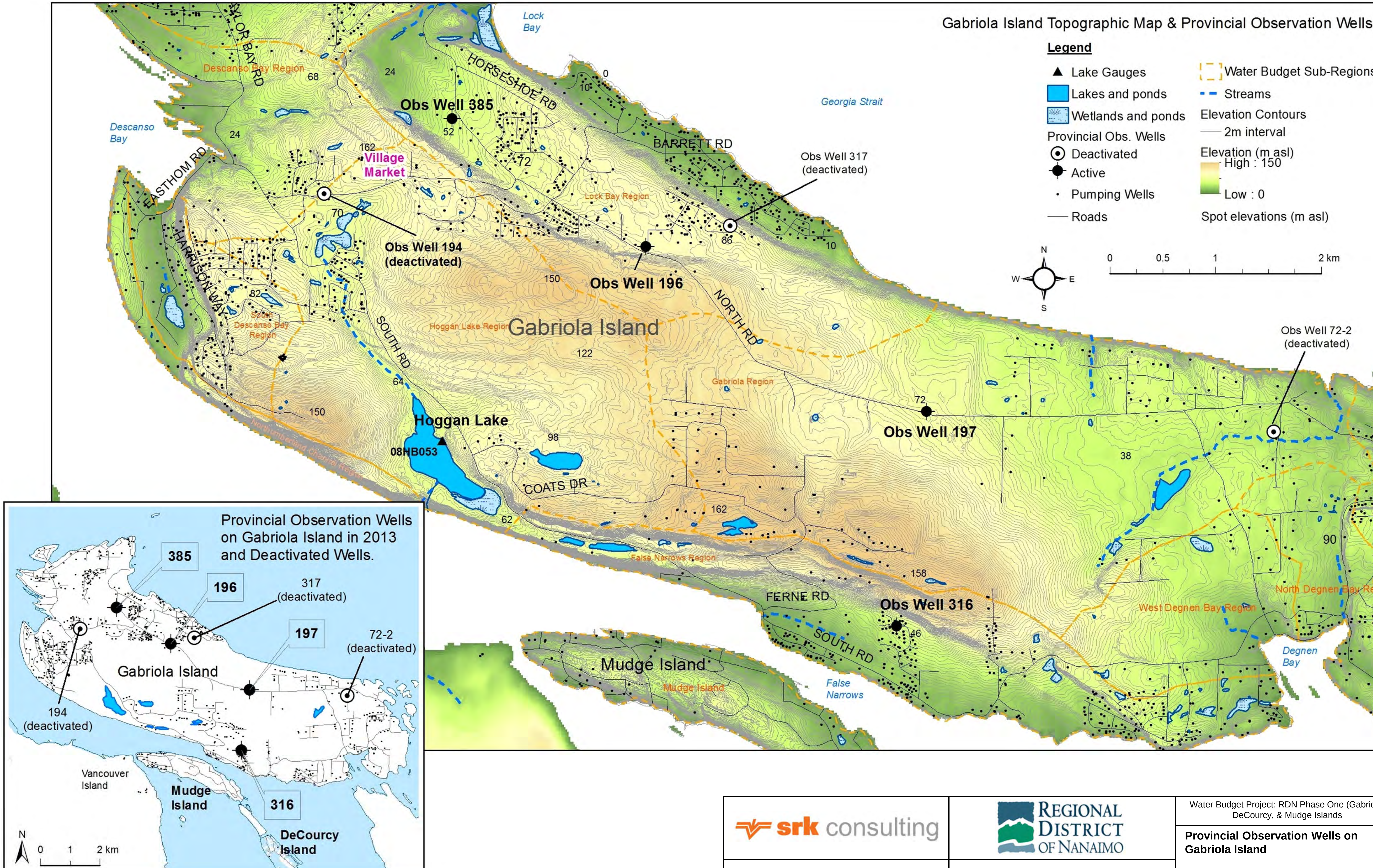
At present, seasonal changes in the water table level and daily changes in sea level cause the position of the freshwater-saltwater boundary to shift very slightly. During tides, this movement is relatively small because there is not enough time during tidal cycle oscillation for large quantities of water to flow. Appendix B contains a map of the water table and identifies locations where saltwater intrusion has been observed in the past.

2.3.3 Depth of Freshwater Lens

Under natural conditions the height of the water table above sea level determines the thickness of the freshwater lens under the island. The boundary of fresh and salt water is usually steep along the shore, close to vertical, and it begins to curve inland at larger depths. Only near the shore is the depth of salt water relatively shallow, and the depth of fresh water generally increases rapidly away from shoreline. The theoretical depth of the freshwater lens under Gabriola, Mudge, and DeCourcy islands was calculated using a formula described in Appendix B.

The calculated depth of fresh water under Gabriola Island is very large because the average water table is high above sea level for an island of this size. However, it is likely that old salt water or brine exists at some depth less than this. There may be old sea water at some depth below Gabriola Island that has not been flushed out by fresh water yet or the bottom part of the freshwater lens may be heavily mineralized and not useful for drinking water supply. There are no observations and no deep wells to confirm the depth and quality of the freshwater lens under Gabriola, Mudge, and DeCourcy Islands.

Over the last 12,000 years there have been large sea level changes on the coast of British Columbia caused by glaciation and deglaciation and melt of ice. These relative changes in sea level caused sea water to intrude and saturate the aquifer relatively rapidly, as suggested by computer simulations of numerical models of Saturna Island on the Gulf Islands through a study done at Simon Fraser University. Where the Gulf Islands' coastlines were submerged in the past by sea water after a sea level rise, it took between 500 and 1000 years to saturate the aquifer with salt water. Following a relative drop in sea level, fresh recharge from rainfall caused a reformation of a freshwater volume and the present conditions were achieved slowly. The shallow hydrogeological system is most likely in a "steady-state" condition and only small cyclical changes are occurring.



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands

Provincial Observation Wells on Gabriola Island

Job No: 1CR010.000	Gabriola Island	Date: April 2013	Approved: JS	Figure:	12
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2.4 Seasonal Groundwater Level Variation

2.4.1 Water Level

Figure 13: Provincial observation wells on Gabriola Island.

(photo: Gabriolan.ca, BC MOE)
(note: Appendix B contains Provincial observation well details)

Currently there are four active Provincial observation wells on Gabriola Island on managed jointly by the Ministry of Environment and the Ministry of Forests, Lands and Natural Resource Operations (map in Figure 12 and a photo Figure 13). These observation points provide frequent water level measurements that can be used to see how water levels vary during different seasons. There are also records from three de-activated observation wells. No observation wells are present on Mudge and DeCourcy Islands.

At all Provincial observation wells, the water levels have a seasonal cycle (see Appendix B for graphs), which is clearly related to seasonal precipitation. The lowest water levels occur at the end of summer and the highest water levels occur in autumn and winter when rainfall is abundant. The magnitude of seasonal water level variation is relatively small, typically less than 4 metres from minimum to maximum, and only 1.5 to 2 metres at some wells.

The changes in water levels are closely related to sustained weekly or monthly precipitation and/or dry periods. Water levels only respond to intermittent daily precipitation if the rain events are very large. Water level change is remarkably small compared to the amount of precipitation falling on the island. Water level rise typically lags behind the onset of autumn rain events from about 5 to 10 days.

There is a small amount of variation in water levels between different years: less than one metre. At Well 194, the mean water level was steady from 1973 to 1985, then declined slightly by less than one metre for next 10 years, and remained approximately the same until present, but since about year 2000 the summer minimum water levels have dropped about an additional 0.5 metre lower than in previous years. At other wells, the trends are different. At well 197 the mean water level has been more variable and there appears to be a shift in the recorder after year 2003. In well 196, the mean water level has been slightly increasing (by less than 0.5m)over the years since 1997. Well 316 has a much shorter record and does not show any consistent trends, just inter-annual variation. Well 317 also does not show any strong trends, but only about 10 years of data are available between 1992 and 2006. Overall, the long term trends are inconsistent between the Provincial observation wells so there is no strong suggestion of any long-term change on Gabriola Island as a whole. There is variability, but it appears to be small.

2.4.2 Seasonal Change in Volume of Stored Groundwater

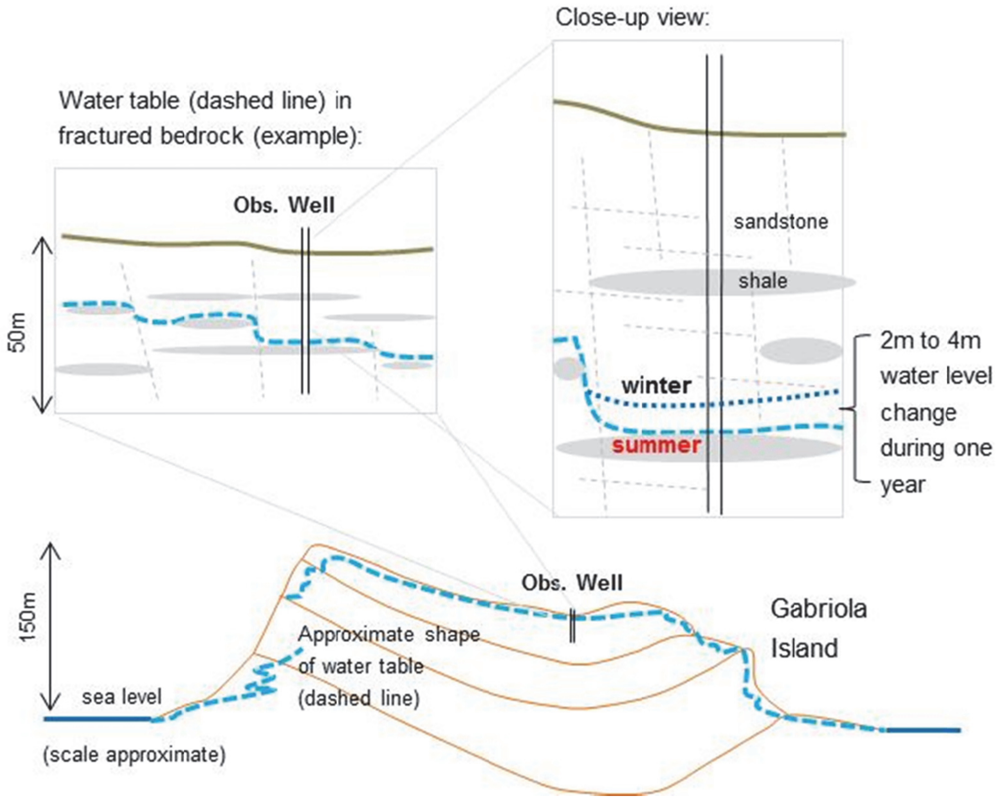


Figure 14: Conceptual drawing describing seasonal change in groundwater level observed on Gabriola Island at a well in fractured rock and stepped water table.

The seasonal change in groundwater volume was estimated for Gabriola, Mudge, and DeCourcy Islands. The average seasonal groundwater fluctuation was used, together with an assumed "reasonable" storage property of the aquifer and the area of each island. The upper estimate is approximately 2 million cubic metres, assuming a fairly high specific yield of fractured rocks (0.01) and a 4 metre annual water level variation everywhere. However; the specific yield is not known and could be much smaller. The lower ("conservative" from water management perspective) estimate seasonal change in water volume in aquifer is about 200 thousand cubic metres of water.

The volume of seasonal change in water in aquifer on Mudge and DeCourcy Islands was estimated using similar assumptions as for Gabriola Island, but because of much smaller areas of Mudge and DeCourcy Islands, the volume is much smaller. The upper estimate is about 80 to 90 thousand cubic metres of water. The lower estimate is about one tenth of that value .

These seem like large numbers, but when expressed as depth of water and percentage of annual precipitation falling on those islands, the volumes are quite small. The most conservative recharge rate on Gabriola Island is 10% and the volume of water recharging the aquifer annually is almost 5 million cubic metres. The high recharge estimate of 45% results is over 20 million cubic metres of water per year. However, most of the water falling on the islands runs off to the sea or evaporates, and of the infiltrated water which recharges the aquifer, much of it also quickly discharges to the sea and is not captured by pumping wells and cannot be stored.

2.5 Groundwater Recharge and Discharge

On islands surrounded by sea water, such as Gabriola, Mudge, and DeCourcy, groundwater recharge occurs only from precipitation that falls on the islands and not from any lateral flow from other land areas across the sea channels. This is widely recognized in observations and theory of groundwater flow in this geographic setting. Although precipitation is measured directly by rain gauges, the water that infiltrates to fractured rock aquifer is not measured directly by any instruments, only indirectly through observations of water level changes over time or through numerical groundwater flow models. Recharge is variable in space and may be low in some areas and much higher in other areas.

The fractured rock aquifers are transmissive enough to fill and drain rapidly, but in its “drained state” at the end of the summer season, the water table remains relatively high and not far below the ground surface. There is only a small variation in the water level over the seasons, so the low and high water level is very similar in terms of water elevation. For example, a well situated away from shore has water table elevation of 70m above sea level, and the variation of water table from summer to winter is only a few metres. That represents less than 5% of seasonal variation in water table elevation. Individual rain events also cause a rapid but relatively small change in water levels. After large rain events, the water table level increases quickly until it reaches a point where groundwater outflow balances the recharge inflow. The drainage might be occurring along bedding planes of large and small mudstone interbeds within sandstone or on top of the large mudstone units such as the Spray Formation. The overall shape of the water table resembles the ground topography and it does not change very much over the year.

2.5.1 Surface Water on Gabriola Island

There is a significant amount of surface runoff during the rainy season on Gabriola Island. Following each rain event and resulting quick rise in water level, groundwater discharge rates increase and more groundwater seeps out to springs, surface streams, and ocean shores. The island is covered with ephemeral creeks that flow for a period of only a week or two then dry up again until the next rainy period. Many small streams drain into the subsurface (a few to 20 metres below ground), flow through fractures, and discharge again at lower elevation as springs. Small springs feed the streams, but most springs are ephemeral as well. Discharge to the sea may be completely hidden from view, except where groundwater seeps from rock outcrops and onto shores. This would suggest that runoff is much larger on Gabriola Island than previously estimated and that groundwater recharge may be lower.

The largest surface water body on Gabriola Island is Hoggan Lake. Measurements of lake levels and outflow contribute to the only known catchment scale runoff estimate on Gabriola Island. Runoff from these data is estimated to be about 60% of annual precipitation. With a large evaporation rate for the Gulf Islands region, the recharge rate is not expected to be very large on average.

2.5.2 Estimating Groundwater Recharge from Precipitation

The annual recharge rate is the rain (and snowmelt) water which infiltrates below soil and into the fractured rock aquifer. Recharge supplies the groundwater which continuously flows through the aquifer and discharges to the sea, springs, or pumping wells. The annual recharge rates were expressed as a percentage of mean annual precipitation and were estimated using various methods and reviewed (Appendix B). The recharge rate considered here was calculated from water level fluctuation during large rain events. Results show that during the first prolonged rainy period in autumn, the aquifer is recharged rapidly as a large proportion of the recharge is converted to replenishment of aquifer storage (water level recovery).

During winter there is excess rainfall; however, this excess rainfall is not converted to increasing groundwater levels as rainfall increases. The seasonal maximum water level has a definite range of variation that is not related to how intense the rain storms are in autumn or winter. A wetter winter does not result in significantly more groundwater storage in the following summer. More rain causes more runoff to streams and springs and seepage of groundwater to the ocean also increases.

Recharge is very low during the dry season. A late onset of autumn rains or a very long dry period does not result in significantly lower water levels in the aquifer because the natural drainage rate slows down as water levels decrease. All that is needed is the first large rain period and then enough rain events during winter to maintain the high water level, which is approximately 2 to 3 metres above the annual minimum water level occurring during the dry period.

The analysis of water fluctuations on Gabriola Island showed (in Appendix B) that only a small volume of infiltrated water from precipitation from large rain events is stored in the aquifer, causing a change in water level. The recharge process is very dynamic and it must not only fill the rock fractures to raise water levels, but also to maintain the natural discharge of groundwater to the sea. The Gulf Islands, because of their small size and fractured rock properties, may receive a large recharge rate but almost all of the recharged groundwater quickly discharges to the sea. Although we cannot measure it, it is possible that as water demand increases over time due to population increase, more and more of the available recharge will infiltrate and replenish the aquifer and less and less will discharge to the sea. This might explain the observation that there are no significant long term trends of water levels on Gabriola Island but clearly more and more pumping wells have been drilled and used over the years.

The representative recharge-rate range for Gabriola and nearby islands is estimated to be between 10 and 25%. The lower value of 10% was estimated in various engineering studies on the Gulf Islands and on the east coast of Vancouver Island in the rain shadow climatic zone. This value assumes a low specific yield. The higher recharge estimate is larger than the upper limit of recharge values shown by the method of fluctuation in water table and is a typical value for many regional aquifers in south-western B.C. The true recharge rate is not known and is assumed to be in the selected range (of 10 to 25%).

Recharge, however, is a highly spatially variable depending on soil type, bedrock geology, vegetation cover, and depth to water table. Near fracture zones, the recharge rate may be significantly higher, whilst in lower permeability areas, it may be low.

3 Water Budget

3.1 Water Budget Sub-Regions

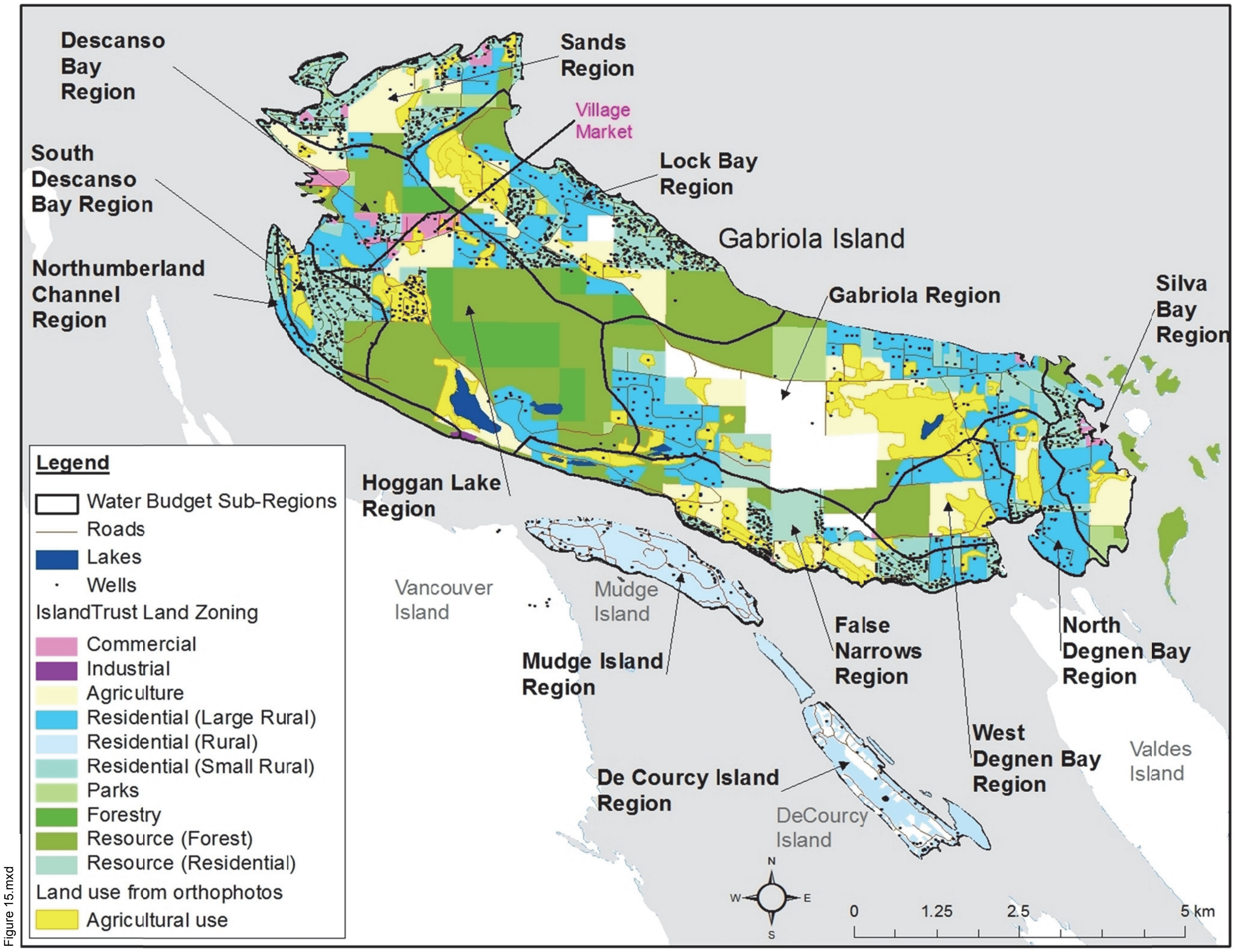


Figure 15: Water budget sub-regions for Gabriola, Mudge, and DeCourcy islands, showing simplified land use zoning and existing pumping wells (source: RDN, BC MOE).

The purpose of this water budget is to present estimates of the water demand and stress for each watershed sub-region on Gabriola, Mudge, and DeCourcy Islands shown on Figure 15. The sub-regions were updated for this report with the latest topographic map in 2012 obtained from the Regional District of Nanaimo. The watershed regions are used to tabulate water use and availability since 1978 and subsequent reports (see Appendix B for references).

The water budget was calculated for 12 months of an average year using average precipitation and a range of recharge rates (10 to 25%). Water demand was estimated for domestic and non-domestic users from water-use surveys conducted by the Gabriola Groundwater Management Society and the Regional District of Nanaimo in 2012, supplemented from values estimated from previous reports. This survey provided most of the information about pumping water demand used in water budget calculations in this report.

3.2 Estimation Method for Pumping Water Demand

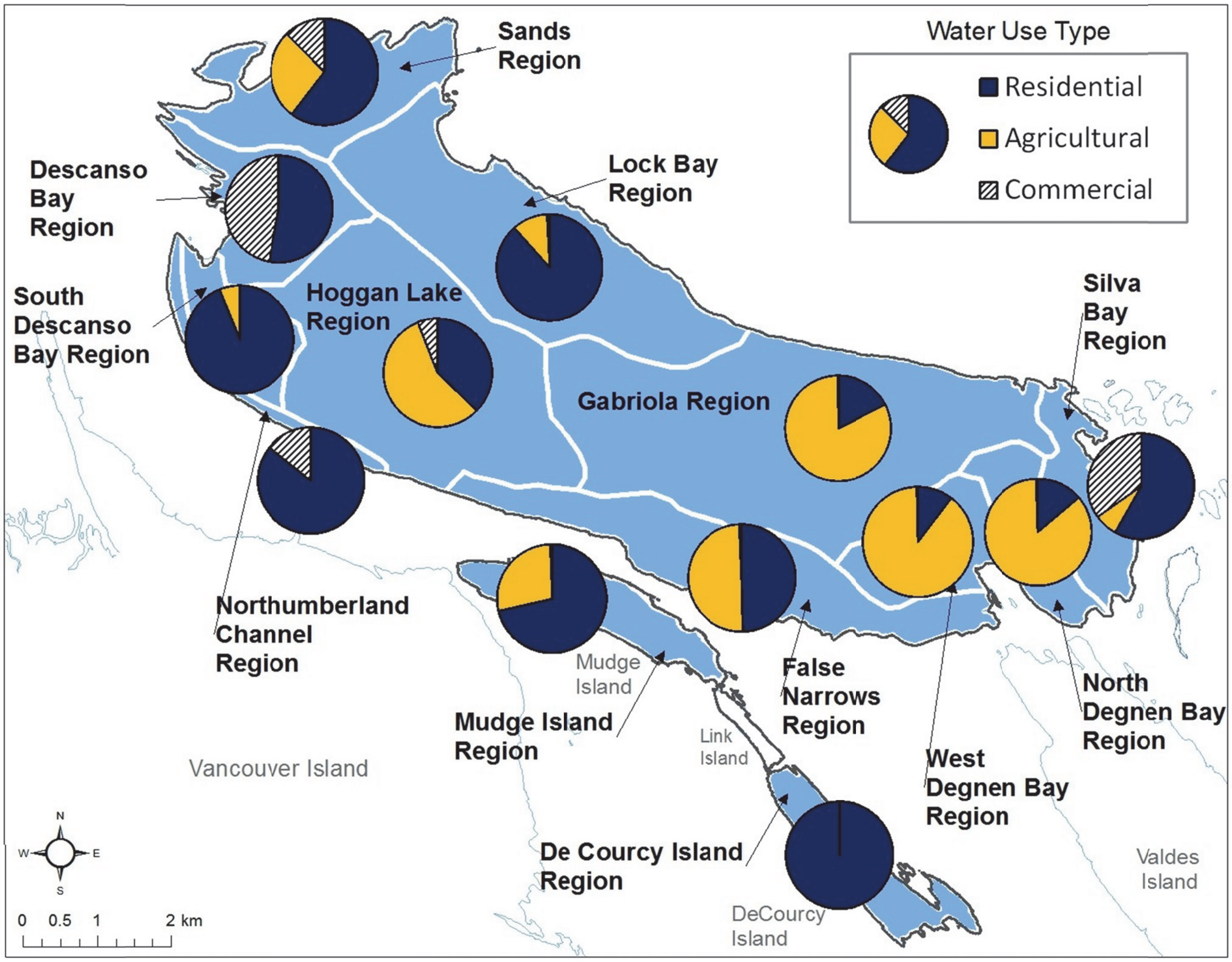


Figure 16: Water use type in sub-regions.

This study is designed as a simple accounting of groundwater recharge against residential, commercial, and agricultural demand. Total annual and monthly water demands are the sum of commercial, residential, and agricultural pumping withdrawals for each sub-region (see Figure 16). The water volumes and rates of use are not necessarily actual water use volumes, as they are not metered accurately or not at all, but they are estimated using the best data available. Many of the numbers used and calculations made require assumptions to simplify the process and to fill in data gaps. The estimated numbers are uncertain and are based on a sample of water users. In a preliminary assessment of the water budget, these estimates provide a reasonable approximation of the water demands and water stresses for each sub-region.

Appendix D contains more information about water budget data and calculations.

Commercial pumping

Commercial pumping withdrawal was calculated by summing the water use values provided by a survey given to commercial establishments. Commercial establishments include resorts, campgrounds, gas stations, restaurants, schools, churches, parks, shopping malls, multiple-unit retirement “villages”, greenhouses, offices, and other business establishments. For non-reporting establishments, water usage estimates were calculated using daily industrial water demands or were extrapolated from values provided by reporting establishments. The calculations made using daily water demands assumed that each establishment consistently used a maximum amount of water.

Residential pumping

Residences are defined here as detached houses on private properties, and include homes where owners live in or rental properties. Residential pumping withdrawal was calculated by summing the average monthly water use volumes for toilets, faucets, showers, dishwashers, clothes washers, and outdoor gardening. These monthly water use values are calculated from survey data. The responses of the 2012 survey are from 389 residential households on Gabriola Island, which represent 10.8% of the 3,590 households on the island (Figure 16). Residential water conservation practices described in this study were acquired from survey data, and may not reflect those in practice by the entire Gabriola population. The number of completed questionnaires returned from regions of Mudge Island, West Degnen, and Northumberland Channel is particularly low.

Agricultural pumping

Agricultural pumping was assessed from farm type and water licence information. Farms are classified by three output types: crops, livestock, and mixed (crops and livestock). For farms that produce only crops, water demands are calculated from irrigation data. Water use estimates for livestock and mixed-output farms are extrapolated from survey data.

3.3 Water Demand Results

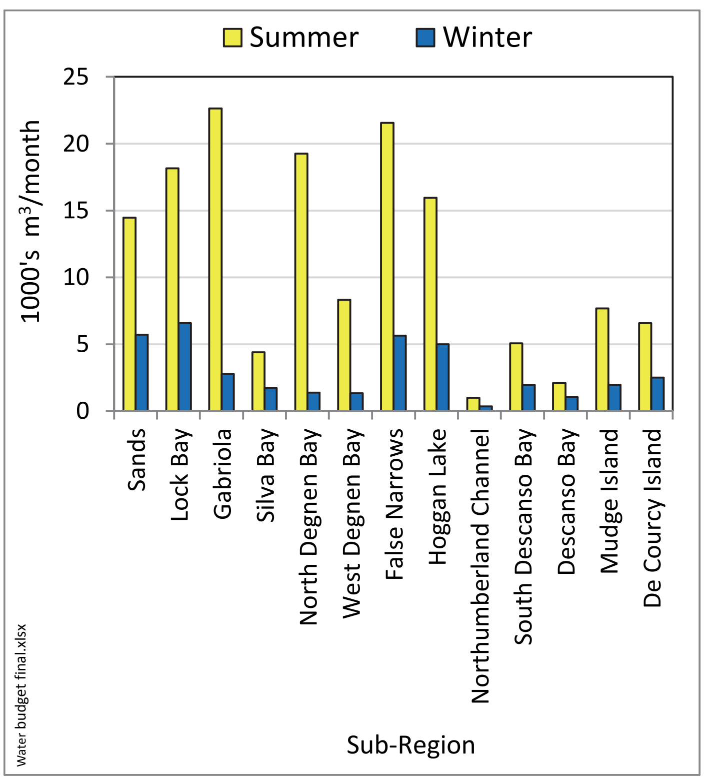


Figure 17: Monthly summer and winter pumping water demand for sub-regions.

The water demand for each sub-region varies depending on the number of commercial establishments, residential households, and farms. In this water budget, the residential and farm water demand account for most of the total water demand, and commercial water demand is the smallest component.

All three land-use types show seasonal variation in water demand consistent with groundwater users in the RDN. Figure 17 shows monthly water demand estimates by water sub-region for residential, commercial, and farming water consumers. During the summer, water demands increases the most for residential water use and agricultural use, and in some sub-regions there is an increase in commercial water use. Commercial establishments have the lowest water demand. Residential demand is between the two, and farms have the highest demand.

Gabriola Island has a year-round population of 4,050, increasing to 6,000 in the summer months because of tourists and seasonal residents. Gabriola residents who spend the entire year on the island are very water conscious and employ practices to minimize their draw on groundwater. Residential water demand increases during the summer because of the influx of tourists and summer residents. Commercial water use increases during the summer months because many businesses are seasonal and focussed on serving the tourists and summer residents and do not operate at as high a capacity in the fall to spring months.

Monthly water demands are described in detail in Appendix D.

The quantities presented are in cubic metres of water. One cubic metre of water is a cube one metre wide holding 1,000 litres, which weighs about one tonne.

3.3.1 Residential

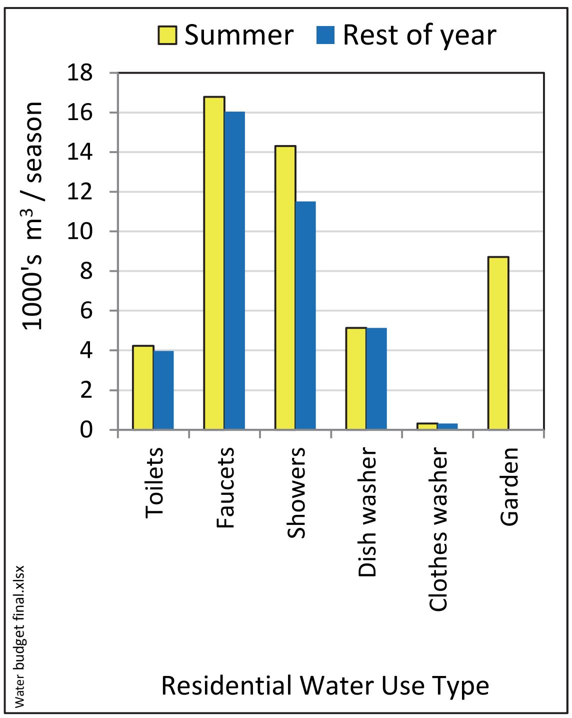


Figure 18: Residential pumping water use by use type of fixture and outdoor garden, comparing summer season and rest of year.

The total annual residential water use in the whole water budget region (all sub-regions on Gabriola, Mudge, DeCourcy islands) is approximately 447,000 cubic metres. Residential water use is the most strongly seasonal type of water use (Figure 18). The average monthly residential water demand is typically three times greater in a summer month than during other months, partly because of population increase by 50% during the summer compared to winter, and partly as result of greater demand for outdoor gardening. The total monthly summer residential water use is 212,000 cubic metres (during 3 months) and the total monthly winter residential water use is 235,000 cubic metres (during 9 months). Almost as much water is used during the summer months as during the rest of the year.

In all residential responses, of the total water use the average proportion of well water use was 69%. Rainwater was used on average for 30% of water use (some rainwater use was reported by 45% of respondents), and only 1% of residential water use on average came from water delivery. The proportion of well water over rain-water used per household by sub-region varies between 35% and 100%, and 15% of respondents report that they only use rain-water and no well water. 10% of the survey respondents receive water deliveries at least once every twelve years, and 82% of those who get water deliveries receive them at least once a year, the median volume of water delivered being 18.2 cubic meters.

Figure 18 displays an estimate of residential water use during the summer (June to August), and during the rest of the year (September to May). The highest usage percentages during the summer are from gardening, faucets and showers. During the rest of the year, garden watering is not needed and most of the water is used for showers and faucets. The average respondent used most of water for faucets and showers and most responses were near the mean values shown. About 60% of the residential households reported the use of dishwashers.

The mean overall residential water use is about 176 cubic metres per year per household, but there is a wide distribution of responses (some people use very little water, other households use more). Depending on how the water survey results are calculated (averaged by sub-region or for whole electoral area) and what assumptions are made for under-reported water uses, the annual water usage for a residential household on Gabriola Island is estimated to be between 176 and 210 cubic metres per year. This falls roughly in the upper middle range of residential water usage on the southern Gulf Islands. An average residential household uses 15.0 cubic metres per month in the winter and 19.3 cubic metres per month in the summer. An average residential household uses 129% more water per month in the summer compared to the winter. This falls outside the range of summer water use increase of 145 to 215%, estimated for other Gulf Islands.

Gabriola Island residential water use can be compared to other regions. In the southern Gulf Islands, in the Capital Regional District and the North Saltspring Water District, the fulltime residential households are estimated to use between 116 cubic metres per year for a rainwater dependant household with water saving features, and 273 cubic metres per year for an average household.

3.3.2 Commercial

Commercial establishments have the lowest water demand. The total annual water demand for commercial establishments is approximately 46,000 cubic metres. The total monthly summer commercial water use is 15,000 cubic metres, and the total monthly winter commercial water use is 31,000 cubic metres.

Commercial demand is only slightly seasonal, on average, although in some regions such as Silva Bay and Descanso Bay there is more summer demand than during the rest of the year. In the Descanso Bay sub-region, the Folk Life Village Mall has seasonal variation in demand from tourism and summer-related population influxes. There are several retirement villages, which report to draw consistent volumes of water year-round. A summer camp operating in the Sands sub-region draws a significant amount of water during July and August, but only a nominal amount the rest of the year. There are few parcels classified with industry land-use types, and for this study, industrial establishments are grouped within the commercial category.

There are no estimates of bulk water import from Nanaimo, although there are sightings of water delivery trucks on BC Ferries ships travelling between Nanaimo and Gabriola Island. Summer Rain Water Delivery pumps a known volume of groundwater from two sub-regions (GW Solutions, 2007), but it is unknown how much of this water is transferred to other areas. Other water delivery businesses are present on the Island, but the 2012 survey did not indicate pumping demand quantities or locations of those suppliers.

3.3.3 Agricultural

The total annual agricultural water use on Gabriola Island is approximately 469,000 cubic metres. There are three seasons of agricultural water use in this analysis: spring (April to May), summer (June to September), and the rest of the year. Agriculture has the highest seasonal water fluctuation of all three land-use types in this study. A large proportion of water use in Agriculture is for irrigation, which is not required during the rainy season. Agricultural water demand outside the irrigation season comes from farms tending to livestock. The total monthly spring season agricultural water use is 134,000 cubic metres. The total summer agricultural water use is the highest at approximately 214,000 cubic metres, and the total monthly agricultural winter water use is lower, at approximately 121,000 cubic metres.

There is greater agricultural water use in the Gabriola and North Degnen sub-regions because of the large area of land zoned for farming. Some sub-regions did not have any zoned agricultural land use, resulting in no agricultural water demand. For farms which produce only crops, water demands are calculated from water license for farming which allows for 3,046 cubic metres of water per hectare for irrigation during the licensed irrigation period (April 1st to September 30th). This can result in quite large estimates of water demand which may not be occurring such as at North Degnen Bay sub-region. Water use estimates for livestock and mixed farms were based on water survey results.

3.3.4 Total Pumping Demand

The water pumping demand for each sub-region varies depending on number of commercial establishments, residential households, and farms. All three land-use types show seasonal variation in water demand. Commercial establishments have the lowest water demand (300 to 400 cubic metres per month). The highest demand occurs in residential households (5,400 cubic metres per month during the summer and 2,000 cubic metres per month during the rest of year) and farms (5,500 cubic metres per month during the summer and 600 cubic metres per month during the rest of year).

The total monthly pumping demand during the summer is 148,000 cubic metres per month and during winter months it is approximately 37,000 cubic metres per month. The annual demand is approximately 962,000 cubic metres per year. The largest total demand is in Gabriola and False Narrows sub-regions and smallest total demand is in Northumberland Channel sub-region. The largest sub-regions tend to have the largest total demand. The greatest pumping demand per square kilometre of area occurs in North Degnen Bay Region because of agricultural pumping demand estimates, and the lowest pumping demand per unit area occurs in Descanso Bay Region.

3.4 Water Stress

Water stress for an aquifer is a relative measure which compares the total demand of groundwater to the amount of natural recharge to the aquifer. In this assessment, water stress was calculated as the ratio of volumes of total pumping demand to the total recharge, as a percentage value. Values were calculated for monthly totals for each sub-region. This methodology was used to match similar approach in the RDN's Vancouver Island water budget study, which is presently being undertaken by others.

$$\text{water stress} = \text{total demand volume} / \text{total recharge volume} * 100\%$$

Where there is large surplus of groundwater recharge, the stress on the groundwater resource is low, and where there is low surplus, the stress is moderate. Where demand exceeds recharge in some months, the stress on water resource is highest because groundwater is taken out of storage in the short term.

The categories of water stress were:

- Lower stress : demand < 50% of recharge (large excess of recharge)
- Moderate stress: demand > 50% of recharge
- Higher stress: recharge deficit where demand > recharge

The calculation was done for two annual groundwater recharge values representing the high (25%) and low (10%) recharge scenarios of a reasonable range of recharge as percentage of mean annual precipitation.

On annual basis, the water stress is low in both high and low recharge scenarios. In the high recharge scenario the surplus of water for an average year is approximately 11,500,000 cubic metres per year. In the low recharge scenario the surplus of water is approximately 4,000,000 cubic metres per year. On the annual time scale, there is no deficit of water and the overall annual water stress is considered to be low because there is enough recharge to supply the demand.

On a monthly time scale, in the summer months the total groundwater demand may exceed the recharge in some regions in the low recharge scenario, but not in the high recharge scenario. Monthly water surplus and water stress is presented in Table 1 and is also shown graphically for all sub-regions in Figure 19.

The water sub-regions which have higher water stress during some summer months are Sands, Lock Bay, North Degnen Bay, West Degnen Bay, False Narrows, South Descanso Bay, Mudge Island and DeCourcy Island. The Northumberland Channel region has a moderate water stress for almost the entire year. However, the water in this region is extracted from the Northumberland Formation, a large aquifer which has a large recharge area. North Degnen Bay, West Degnen Bay, South Descanso, and Mudge Island are all classified as moderate water stress because of irrigation demands from April to September.

In reality, the different watershed regions are connected and water demand in one region can be supplied by groundwater flow from storage (and recharge) in adjacent regions. Groundwater flow does not observe these land use boundaries. This is especially true for the relatively small and narrow sub-regions that are adjacent to large central sub-regions. Overall, there is a large amount of groundwater available in storage that sustains pumping demand during high use dry months and that is recharged quickly at the beginning of wet season in autumn.

With a low ("conservative") recharge estimate (10% of mean annual precipitation), the most populated regions show an increase in water demand stress during the dry seasons. With a high recharge estimate, which may be occurring but is not proven at this time, the level of stress is very small during dry seasons. The actual recharge rate is most likely somewhere between the low and high recharge estimates used for these calculations.

Table 1: Monthly water stress by water sub-region on Gabriola, Mudge, and DeCourcy Islands for low and high recharge scenarios.

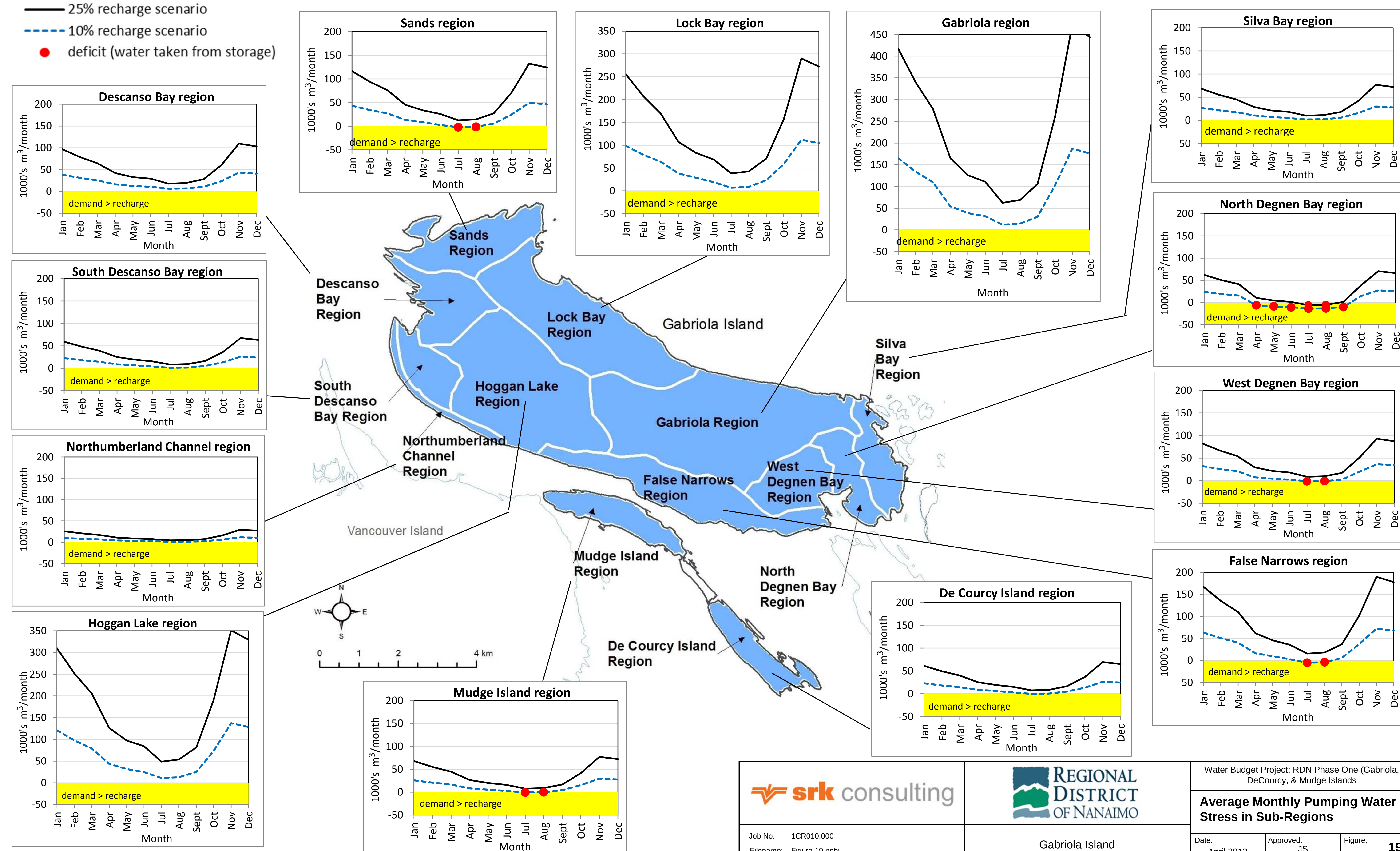
	Sub-regions	Monthly Pumping Water Stress (Groundwater Demand / Recharge) %												Annual (%)
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
10% recharge scenario	Sands	11	14	17	37	50	82	121	112	63	19	10	10	27
	Lock Bay	6	8	9	16	21	42	67	62	25	10	6	6	14
	Gabriola	2	2	2	26	33	41	64	60	40	3	1	2	12
	Silva Bay Region	4	5	6	13	28	43	67	62	33	9	5	5	13
	North Degnen Bay	5	7	8	154	197	231	364	338	230	9	5	5	64
	West Degnen Bay	4	5	6	49	62	77	121	112	78	6	4	4	23
	False Narrows	8	10	12	45	58	86	136	126	71	13	7	8	27
	Hoggan Lake	4	5	6	21	27	38	56	52	33	6	3	4	12
	Northumberland Channel	3	4	4	7	13	23	37	34	14	5	3	3	7
	South Descanso Bay	8	10	12	18	23	49	78	72	28	13	7	7	17
	Descanso Bay	2	3	4	6	10	15	23	21	11	4	2	2	5
	Mudge Island	7	8	10	33	43	70	110	102	49	11	6	7	21
	DeCourcy Island	10	12	15	22	28	61	97	90	33	16	9	9	21
25% recharge scenario	Sands	5	5	7	15	20	33	48	45	25	7	4	4	11
	Lock Bay	2	3	4	7	8	17	27	25	10	4	2	2	6
	Gabriola	1	1	1	11	13	16	26	24	16	1	1	1	5
	Silva Bay Region	2	2	3	5	11	17	27	25	13	4	2	2	5
	North Degnen Bay	2	3	3	62	79	92	146	135	92	3	2	2	26
	West Degnen Bay	2	2	2	20	25	31	48	45	31	3	1	2	9
	False Narrows	3	4	5	18	23	34	54	50	29	5	3	3	11
	Hoggan Lake	2	2	2	8	11	15	22	21	13	3	1	1	5
	Northumberland Channel	1	1	2	3	5	9	15	14	6	2	1	1	3
	South Descanso Bay	3	4	5	7	9	20	31	29	11	5	3	3	7
	Descanso Bay	1	1	1	2	4	6	9	9	4	2	1	1	2
	Mudge Island	3	3	4	13	17	28	44	41	20	4	2	3	9
	DeCourcy Island	4	5	6	9	11	24	39	36	13	6	3	4	8

Water budget final.xlsx [Water Balance]

Colour legend: water stress value (recharge – demand)

white	low stress (demand < 50% of recharge)
l.green	moderate stress (demand > 50% of recharge)
yellow	higher stress (demand > recharge, water taken out of storage and recharged later)

Average Monthly Water Surplus and Water Stress in Sub-regions (1000s m³/month)



srk consulting

REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands

Average Monthly Pumping Water Stress in Sub-Regions

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Gabriola Island

Date: April 2013 | Approved: JS | Figure: 19

4 Data Gaps and Recommended Data Collection

The following discussion addresses the most important data gaps in the conceptual model and presents a prioritized listing of data collection that could be used for future assessments. This recommended data would improve the hydrogeological conceptual model as well as water budget accuracy. The costs of collecting data vary and, as a result, some of the suggestions may be prohibitive depending on budget availability; others can be done at relatively low cost and provide good value. A summary of prioritized data collection suggestions is provided at the end of this section (Table 2).

4.1 Properties of Hydrogeological Units

Pumping tests of new test wells are needed to obtain additional hydrogeological unit properties. However, the cost would depend on the type of testing selected because of the drilling and equipment required.

For example, long-duration pumping tests are preferable because they impose a larger stress on the aquifer and provide a better estimate of hydraulic parameters, but these tests are also more expensive. In contrast, short-duration pumping or injection tests are less expensive and obtain results that can be scaled up and that show the relative differences of transmissivity between different locations and hydrogeological units. In this case, a number of smaller tests in multiple locations would prove more useful than one or two large tests that would not be representative of the whole island and would not, therefore, add significantly to the existing model.

Tidal analysis can be done but it requires a second test to determine storativity property of fractured rocks, before a reliable transmissivity value can be estimated. A different test can be done in the same well (pumping test, slug test) to estimate transmissivity and the tidal analysis can then be used to estimate the storativity value.

All methods of testing have limitations and there is some uncertainty in the calculated values of hydraulic parameters.

4.2 Water Levels

On Mudge and DeCourcy Islands, more static water level measurements are needed from wells. These wells should be surveyed or their locations matched closely to nearest topographic contour to obtain the needed measurements.

On Gabriola Island, a large number of static water levels (of varying accuracy) have been measured near the ground surface, however, there are no hydraulic head measurements at large depth and below the Spray mudstone layer. New observation wells could be installed with screens below and above this unit to determine groundwater conditions below the unit.

Additional observation wells would also be useful in areas with high water demand in the western part of Gabriola Island, south of Descanso Bay and in eastern part of the island. Unused residential wells could be used in place of dedicated observation wells. Monitoring could be done as short-term, frequent measurements to observe the effects of local drawdowns and recharge after rain events to improve understanding of the different regions.

Also on Gabriola Island, some residents are concerned about effects on their wells by commercial water users. If commercial extraction continues in the future, some additional effort should be made to monitor the largest commercial water users using nearby residential wells or new observation wells. If there is any effect, the drawdown could be detected in residential wells that are closest to the commercial pumping wells. The monitoring would need to be done over a long period of time—at least one year—to observe the seasonal effects of water table variation.

4.3 Salt Water Intrusion and Depth of Freshwater

Salt water intrusion should be monitored in many residential wells near ocean shores and should be compiled from reports containing well water quality measurements. More long-term observation wells may not detect salt water intrusion because it may be localized near pumping wells in the form of "up-coning" salt water. The fresh-saltwater interface is very steep, and the mixing zone is very narrow. Therefore, observation wells away from shorelines would not detect salt water intrusion occurring near shores.

The saltwater intrusion may be focused along discrete fractures rather than across the aquifer. Near-shore wells will be connected differently to the ocean and some wells may draw in salt water long time before nearby wells experience any change in salinity.

To determine the amount of useful water storage, some effort could be made to verify the depth of fresh water under the islands and water quality variation with depth.

4.4 Water Budget

Water balance estimates are described using the best available data, but there are data gaps for each land-use type that would have to be addressed to improve the estimates. The following are the uncertainties and assumptions that affect the reliability of the study:

- The number of survey respondents from West Degnen Bay, Northumberland, and Mudge Island is very low. To acquire more representative information for these sub-regions, further work needs to be done with a greater number of respondents.
- Water usages for many commercial and farming establishments are unknown and are only estimated. Further study needs to be undertaken to target specific commercial and farming establishments to acquire reasonable water use estimates.
- There is insufficient data to calculate the amount of drainage from surface runoff and groundwater discharge. The volume of groundwater recharge to the bedrock aquifers from surface water needs to be quantified because current estimates are uncertain. Small streams do not have any monitoring devices or any recent observations. Some spot measurements and gauges would be very useful for understanding surface-groundwater interactions.

Table 2: Recommended data collection.

Priority	Data Type	Purpose	Difficulty and Timing
1	Water use surveys in all regions	To improve the water demand component of water budget and water stress assessment in sub-regions.	This can be on-going annual surveys or more focussed surveys as needed. More volunteer participation is required. Water metering is also an option.
2	Long-term observation wells in commercial & residential areas	To monitor drawdown because of water demand and natural water level variation and to monitor water salinity trends	1 – 5 years. There is high cost of drilling of new wells and installation of monitoring equipment.
3	Drawdown in residential wells around large production wells	To assess impacts of large water users on residential wells	Immediate to 1 year. Easily done with small sensors. Require volunteers.
4	Short-duration monitoring of water levels in residential wells	To perform tidal analysis for aquifer properties and effects of pumping on aquifer, relative to fracture connectivity	Immediate to 1 year. Easily done with small sensors. Require volunteers.
5	Survey and measurements of surface water flows	To improve the runoff component of water balance.	1 – 5 years. A proper hydrologic study of surface water and groundwater interactions.
6	Additional hydraulic tests in representative locations in different hydrogeological units	To improve the hydrogeological conceptual model	1 – 5 years. Design a test plan for testing different hydrogeological units in appropriate test wells. Some appropriate existing wells can be used.
7	Improved geological map along island steep slopes/cliffs	To improve the geological model	1 year. There are inconsistencies between different maps. This is a desk study with some field surveying checks.
8	Data quality control of existing wells database.	To improve data quality of existing well logs, water levels, screen positions, collar locations, etc.	1 year. This needs to be done before any numerical modeling is started.
9	Deep water levels and water quality	To assess groundwater resource in deep portion of Gabriola Island below Spray mudstone	> 5 years. High cost of drilling a deep test well. Deep water is likely not needed for water supply in near future.

5 Conclusions

5.1 Hydrogeological Conceptual Model Assessment

The hydrogeological system has been reviewed and data gaps identified.

The most important observations coming out of the updated conceptual model that improve understanding of the groundwater flow system include:

- The residents and businesses use a shared groundwater resource that flows easily across property boundaries.
- Natural recharge from precipitation is estimated to be within a range of 10 to 25% of mean annual precipitation, although recharge remains uncertain and is likely spatially variable.
- Observations of water levels show a relatively quick but small rise in water level after each rainy period, and accumulating about 2 to 4 metres during the rainy season, followed by a slower decline during the dry season.
- Water levels do not appear to be declining from year to year; the aquifer(s) are generally fully recharged during the winter wet seasons.
- Total groundwater storage volume is large; being the greatest on Gabriola Island relative to surface area of the island and less (due to lower topography), but still significant, on Mudge and DeCourcy Islands.
- The stored groundwater provides a large reservoir of fresh water that is used to satisfy current pumping demand by residents during the dry season.

Comparison of water use and other observation data with the updated hydrogeological conceptual model has allowed some general conclusions to be made about how the groundwater system appears to be responding to extraction over time:

- On Gabriola, pumping of groundwater does not appear to drain the aquifer storage significantly.
- Locally on Gabriola, extraction can cause large drawdowns of the water table that can affect nearby wells, but these effects typically disappear quickly when pumps are turned off, showing no lasting negative effect. However, many residents use water storage tanks which are filled from groundwater wells. There is some interference between nearby wells and the more shallow wells may experience decreased water availability.
- Areas of dense residential development often occur on peninsulas and along shorelines; areas likely to be most sensitive to groundwater use because the area available for groundwater recharge is limited.
- In areas where pumping wells are in close proximity to shorelines within narrow points of land around small bays, the local geologic conditions and shallow depth of fresh water increases the chances of saltwater intrusion .

5.2 Water Budget Assessment

A water budget has been completed that provides an indication of water stress for each sub-region, and suggest the following results:

- On an annual time scale, it does not appear that any sub-regions are under significant stress. This is because the annual recharge appears to be sufficient to meet annual demand.
- On a monthly time scale, certain regions are probably under relatively higher stress or, in other words, in some months certain regions extract more groundwater from storage than is recharged.

Results of the water budget should be considered indicative of the hydrogeological setting, not absolute. Water budget calculations require a number of assumptions, such as recharge or actual demand. Recharge can only be estimated, not accurately measured. How much we really don't know about demand should not be underestimated, because:

- Recent water use surveys provide an indication of total pumping demand, but they represent only a small number of users; perhaps only those who are most interested in understanding the water resource situation. Therefore, assuming the same demand for all other users may not provide an accurate estimation of pumping demand.
- Water metering does not exist in most residential or commercial wells; thus, there are few actual hard numbers on which to base estimates.

Prediction of future water stress will not necessarily be a simple task. The current positive situation could change due to population or water use growth and/or climate change, if it results in less groundwater recharge. That being said, past population growth does not seem to have had a significant impact on water levels in the aquifer as a whole; water supply problems are localized or seasonal. The seasonal cycle of aquifer recharge and discharge has not changed in a long time.

5.3 Gaining a Better Understanding for the Future

There are things that can be done to provide a better ability to plan for the future. While it may be difficult to completely overcome uncertainty regarding certain features of the groundwater system that control how much groundwater can be extracted (e.g., recharge and storage quantities) some useful monitoring or testing can be done to narrow the range and allow on-going observation of how the aquifer is responding to use. Such methods were presented for consideration in Section 4.4. In addition, tools such as groundwater numerical models can provide a way to evaluate water-use scenarios or sensitivity to various assumptions, but these models will always be limited by available data, particularly at a local scale.

Finally, water quality was not in the scope of this study on groundwater availability. There has been an increase of seawater intrusion in some near-shore areas (but not all). In general, more awareness of the occurrence of saltwater intrusion should be made available to residents. Doing so would help avoid the costs of drilling new wells in the affected areas and also avoid drawing in additional sea water, which would worsen saltwater intrusion in existing wells.

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All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.

7 Glossary of Terms

Aquifer: A geological formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquitard: A geological formation, or part of a formation, through which virtually no water moves.

Brackish water: Slightly salty. In this study, defined as water with a chloride concentration of greater than 250 mg/L (EC greater than 1,000 μS/cm) and less that of seawater (~19,000 mg/L).

Datalogger: Submersible electronic device that records characteristic data collected from groundwater such as level, temperature, electrical conductivity, etc.

Drawdown: The distance between the non-pumping water level and the surface of the cone of depression.

Fresh water: As defined in this study, water with chloride concentration below the CDWQG value of 250 mg/L (EC of less than ~1,000 μS/cm).

Freshwater lens: In this study, the static body of groundwater (does not include transient recharge mounding) that floats above the denser, saline water below.

Geological unit: A volume of rock with similar lighology or other geologic properties.

Geological formation: A geological unit or group of units with similar age or type of depositional history, and other geological similarities on larger regional scale.

Hydraulic conductivity: The rate of flow of a unit volume of water a prevailing density and viscosity passes through one square unit of porous medium under a unit hydraulic gradient (meters/second).

Hydrogeological unit: A volume of rock or sediment which has similar hydraulic properties for groundwater flow.

Litholog: For this study; a record (log) of the rock types encountered during drilling. The Ministry of Environment well database contains summary lithologic units made by drillers.

Numerical modelling: A method of describing groundwater flow by mathematical approximations with specified values for boundary conditions.

Precipitation: Rainfall and snowfall, expressed as depth of water equivalent which accumulates on land or water, measured with rain gauges. Not all precipitation infiltrates to the aquifer.

Recharge: Water from precipitation and surface waters which infiltrates down to the water table and adds to water storage in the aquifer.

Salt water: As defined in this study, water with chloride concentration above the CDWQG value of 250 mg/L (EC of greater than ~1,000 μS/cm).

Saltwater intrusion: The migration, either lateral or vertical, of saltwater into freshwater aquifers under the influence of groundwater development such as pumping of freshwater near a source of saltwater.

Static: Characterized by a fixed or stationary condition.

Steady-state: A condition that does not change over time, or in which any one change is continually balanced by another, such as the stable condition of a system in equilibrium.

Storativity: The volume of water released from, or taken into, storage by a confined aquifer per unit surface area of aquifer per unit change in hydraulic head.

Transmissivity: The rate at which water of a prevailing density and viscosity is transmitted through a unit width of porous medium under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the unit and is the product of hydraulic conductivity and the saturated thickness of the aquifer ($metres^2$/second).

Upconing: In this study, the process in which dense salt water is vertically transported through less dense freshwater by means of a pressure gradient established by pumping. The process is named for the inverted cone shape of saline water that may form at the interface below a pumped well.

Water level: A measurement of depth to water in a well or an elevation of water in a water body or a well. It is made with water level tape or other sensor. Water level accuracy depends on how well the well collar is surveyed and other considerations.

Appendices

Appendix A: Geological Review

Appendix A - Table of Contents

Appendix A - Figures

Appendix A - Tables

1 Geology of Gabriola, Mudge, and DeCourcy Islands

1.1 Bedrock Geology

The bedrock geology maps for the Gulf Islands have changed significantly over time in level of detail and interpretation. The earliest map found was by Halstead (1963), followed by maps by Muller and Jeletzky (1970) and England (1989). The geology of Gabriola Island is very similar to that of Hornby Island, which has recently been described in some detail by Katnick and Mustard (2003). The depositional environments and definition of the sedimentary rocks of the Nanaimo Group are described in more detail in Mustard (1994) and a summary is presented in Table A- 1. Journeay (2004) produced the most recent and detailed map of Gulf Islands bedrock geology, which is available in digital format in GIS (GSC, 2004) and was used in aquifer vulnerability mapping by Denny et al (2006). The surficial geology map of Gabriola and Mudge Island and nearby sea floor is included in Figure A-1 from Natural Resources Canada & Fisheries And Oceans Canada (Picard, 2010) and annotated by authors of this report and from a surficial geology map previously presented on the Gabriola Island community profile, and identical to the digital map used in this report.

Table A- 1 Descriptions of the Nanaimo Group formations on Gabriola, Mudge, DeCourcy Islands (summary from Mustard 1994, Muller and Jeletzky, 1970, and Hodge, 1978)

Formation Name	Dominant Lithological Units	Less Dominant Units	Thickness (vertical)
Gabriola	thick bedded sandstone	rare laminated silty mudstone interbeds	40 to 120m (eroded)
Spray	shale and siltstone sequences	sandstone interbeds (variable)	20 to 40m
Geoffrey	thick bedded sandstone and coarse conglomerate	prominent interbeds of shale	60 to 80m
Northumberland	silty shale (upper Northumberland) – with some clay alteration in layers, sandstone and conglomerate (lower Northumberland)	thin interbeds of sandstone and siltstone, minor thick beds of sandstone	200 to 300m in False Narrows between Gabriola and Mudge Islands
DeCourcy	thick bedded sandstone	siltstone and mudstone interbeds	N/A
Cedar District	thin bedded silty shale, siltstone and sandstone		N/A

1.2 Structural Geology of Nanaimo Group Sedimentary Rocks

Tectonic events caused uplifting and folding of sedimentary strata, resulting in faulting and fracturing. Isostatic rebound after the ice age may have also contributed to fracturing along bedding planes. Structural geological work has been done by many academic researchers and a good reference list is provided in Mustard (1994) and Mackie (2002). These were very rigorous scientific investigations at the regional scale.

Local geological and hydrogeological observations, and some interpretations, were recently written by Doe and Peirce (2010) in a journal of a local historical society. Although not reviewed and formally presented, there is a wealth of local observations and good interpretations in several articles in that journal. The most recent and most detailed geological discussion of Gabriola Island is in Doe (2009a, 2009b) and one map is shown in compilation Figure A-1.

On Gabriola Island the dominant structure is a syncline fold called the Gabriola Syncline (England 1989). The syncline axis runs along the middle of Gabriola Island. The stratigraphic units are bent by the syncline and dip at 10 to 15 degrees toward the syncline axis. An idealized cross-section is shown in Figure A-1 which was presented in a previous local article by Earle and Krogh (2004).

The syncline structure is of different shape on the north-west side of the Gabriola Fault; a large fault which extends from Lock Bay south to Northumberland Channel. Along Cox Bay (Leboeuf Bay), the rock strata dip very gently to the north and north-west away from the Gabriola Fault. Doe (2009a, 2009b, 2012) discuss the possible structural origins of north-west and south-east parts of Gabriola Island.

The largest faults on Gabriola Island are shown on Figure A-1. The three largest faults are:

- a) Gabriola Fault
    - this fault extends from Leboeuf Bay to Cox's Bay in north end of Gabriola Island
    - Doe (2009a) suggests that this fault may be a continuation of the Chase River Fault on Vancouver Island, and that there may be surficial expression of the fault on the sea floor as well based on bathymetric charts. Coal mines traced this fault as continuing across the Northumberland Channel
- b) fault in south end of Gabriola Island
    - this fault extends along Maples-Dragon's Lane in south end of Gabriola Island (this fault does not have an official name)
    - there is small geomorphic expression at the shoreline in the north, and a topographic low along the fault, which affects the surface drainage pattern
    - it may run along the break between Mudge and Link Islands
    - there is a permanent spring at the south end of the fault and a permanent groundwater fed lake at the end of Dorby Road
- c) Flat Top Islands Fault
    - runs mostly along the sea bed as seen on bathymetric maps

There are other possible structures, which may be expressed in ground topography and many fault zones are visible on island shores. Many "fault-like" features are most likely erosional features resulting from lithologic differences. The early maps produced by Brown and Erdman (1975) appear to associate too many topographic features with faults as pointed out by Doe (2009a). The latest map of major faults on Gabriola and other Gulf Islands is by Journeay (2004), provided by Simon Fraser University in digital format for this report.

Fractures occur predominantly in zones of intense deformation associated with larger structural features such as large faults. Secondary fractures are structurally caused but are not as continuous as primary fractures and faults. Smaller fractures or joints also connect larger fractures. Large fractures associated with fold-related tensile and compressive stresses on Gabriola Island are either parallel to the fold axis and are caused by tensile stress (longitudinal fold fractures) or are perpendicular to the fold and are caused by compressive stress (lateral fold fractures). There are also x-shaped conjugate fractures visible on beaches in sandstone.

Vertical joints also form locally where sandstone strata become unevenly supported by underlying mudstone due to weathering. Joint spacing in this case depends on thickness of sandstone layer (or "bed" in geology) – thicker beds have more widely spaced vertical joints. Vertical joints are important for allowing groundwater to infiltrate downward acrossand/or through sandstone beds. Joint aperture (size of joint space in rock) varies greatly from <1 mm to >50cm. Most are a few mm in size where seen on beaches (these have a larger aperture at surface than at depth because of effects of erosion).

1.3 Overburden Geology

Land topography on Gulf Islands is mostly coincident with bedrock topography, except where overburden sediments fill depressions. Overburden units are present in some places on top of bedrock. These are generally above the water table and are of minor importance for groundwater quantity, although overburden can locally control groundwater recharge. Hodge (1978) reported that only a few productive wells were completed in overburden deposits and these are typically dry and well drained. There is a good surficial geology map showing occurrence of Quaternary sediments on Gabriola Island in the Island Trust (2007) Gabriola Island Community Profile, provided by Natural Resources Canada.

The EBA (2011) report on geo-hazards on Gabriola Island includes is a good summary of soils, terrain, and overburden properties and reviews existing geotechnical reports dating from 1992 to 2009. Soils are sparse and thin (~2m), and are formed from bedrock weathering and from deposited glacial till and small pockets of glacial outwash. Overburden deposits on Gabriola Island are predominantly glaciomarine sediments. The thickest overburden deposits are in the SE corner of Gabriola Island (up to 25m of coarse gravel/boulder till deposits) west of Degnen Bay.

The shape of Gabriola Island and its ground topography are a result of its geology and erosional processes; a good summary is given in Gabriola Island Community Profile document (2007). The article by Doe (2000) explains the erosional and other processes which likely shaped the islands and produced bench-like topography in some places. Earle (2002) discusses the effect of past sea level changes on Gabriola Island surficial sediments and landforms.

1.4 Mining Activities in Nanaimo Bay Near Gabriola Island

Coal has been mined in the past under Nanaimo Bay but the old mine workings do not extend to Gabriola Island. EBA (2011) reviewed the Coal Mine Underground Workings Atlas to determine whether coal had been mined on Gabriola, and determined that there were no underground coalmine workings under the Island. National Resources Canada (2012) has a map of underground workings near Nanaimo.

2 Preliminary 3D Geological Model of Gabriola Island

As part of this project, a preliminary geological model was constructed for Gabriola, Mudge, and DeCourcy islands. The purpose of this model is to combine previously drawn cross sections, surficial geology maps, and well logs (well lithology database) to produce a digital product which can be used in Phase 2 assessment and for estimating volumes fractured rock aquifer in this report.

2.1 Methods

The data used were mainly from geological outcrops taken from a surficial bedrock geology map by Journeay (2004), provided by Simon Fraser University in GIS format. These data were draped onto a digital elevation model created from detailed ground topographic contours provided by the RDN. Previously documented geological descriptions, especially of structural geology of Gabriola Island, were used to guide the interpretation. The boundaries between geological formations were represented by surfaces, and solid volumes filled between these to calculate unit volume. The surfaces were tied in, where it was possible, with the available water well lithologs.

The Province of British Columbia maintains a water well database (WELLS), in which information obtained by the driller at the time of well construction is stored. Such information includes, for example, well depth, water depth at the end of drilling, construction method, an estimate of well yield, and a lithology log. Lithology data for the Gulf Islands had been previously extracted and standardized for use in vulnerability mapping for the Gulf Islands. Standardization is based on a set of rules that allow dominant material types to be identified based on first appearance of the term or by other qualifiers (e.g., silty sand means “sand” is the dominant material type with “silt” as the secondary material). Grain size and colour, as well as fracturing, are descriptors.

For the purpose of constructing the Gabriola Island geological model, the well lithologs were simplified and standardized by SRK again. The dominant units considered were: sandstone, sandstone & shale interlayering, shale, conglomerate, and clay from shale alteration. Well logs do not contain more specific descriptions in most wells.

All available water well lithologs were viewed in 3D software to help guide construction of the geologic layer surfaces. The data set contains mostly low quality simple geologicallogs where only major types of rocks are logged by drillers from rock cuttings. Very few logs were logged by geologists or hydrogeologists on site. The test well logs done by Piteau (1993) are some of the best documented and these were used exactly as shown in cross-sections in report by Piteau Associates.

2.2 Results

There is large uncertainty as to the boundaries of the geologicalformations inside of Gabriola Island and the model is preliminary and is the best current fit to a large (and often low quality) data set. The 3D model was constructed mostly from surficial geologicaloutcrops and from clusters of well lithologs. The well logs are generally of unknown quality and often show conflicting lithologic information. The test holes by Piteau (1993) are of good quality and were used as control points.

Results of the model "layers" are shown in 3D profile view in Figure A-2 and the figure is annotated with additional comments.

There is not enough information at this time to construct a three-dimensional model of Mudge and DeCourcy islands, although the rock strata are known to dip down toward the east. The well logs do not contain sufficient detail to differentiate the Cedar District and DeCourcy Formations by lithology alone.

A series of figures from Figure A- 3 to Figure A-8 shows close-up views of the geological model for various parts of Gabriola Island. The goal is to provide good overview of Gabriola Island geology in a visual manner to the island community and the Nanaimo Regional District staff.

The following observations were made:

- Figure A- 3: North shore east from Lock Bay has a high and low terrace-like steps in ground surface, which are associated with outcrops of shale that were preferentially eroded. This area has a large number of water wells and well lithologs in MOE database. Many wells near shore are completed in the Northumberland Formation, a shale unit with many clay intervals. The shale is permeable enough to produce water and the clay interbeds may act as effective confining units.
- Figure A-4: In Silva Bay area there are clusters of residences with water wells. Only two well logs were found on the smaller islands off Silva Bay. The higher ground is composed of sandstone of Gabriola Formation south of the bay and Geoffrey Formation north of the bay. The Spray Formation shale has been eroded more to form a valley and it likely underlies Silva Bay, which is part of this valley.
- Figure A-5: The area around Degnen Bay has similar geology to Silva Bay in that the Spray shale has been eroded more to form a valley which forms Degnen Bay. The land topography reflects the erosional processes and the geological units. Shale layers are easily eroded and form valleys. Sandstones stand out as cliffs and ridges. The well lithologs show variable geology and some clay layers within the shale at depth.
- Figure A-6: Along the south shore of Gabriola Island near False Narrows channel, the geology is similar to the north shore of the island, although the land surface is steeper and high cliffs of sandstone outcrops are present. The Spray Formation shale is located higher up the slope and forms a land bench (as usual, it has been eroded preferentially). Many of the upper water wells drilled in upper slopes are completed in sandstone and partly in the Spray Shale. On the lower land terrace along the shore, the wells are completed in the Northumberland Formation, a shale with clay interbeds similar to the north shore.
- Figure A-7: The area south of Descanso Bay (Descanso Valley) is composed of a head-land of Geoffrey Formation sandstone, which forms high cliffs along the shore, and a valley

eroded into Spray shale, and very high cliffs of Gabriola Formation sandstones. Wells are completed to various depths and in various units. Wells drilled from the top of cliffs are necessarily deeper to access the water table. Wells drilled in the valley in Spray shale have clay intervals.

- Figure A-8: The north-western shores of Gabriola Island, to the west of Gabriola Fault, which runs from Lock Bay to Descanso Bay, has a different orientation of the geologicalstrata and different thicknesses than on main part of Gabriola Island. Three layers of shale of an unidentified geologicalformation lie between relatively thin sandstone units, and dip to the west and north-west away from land. This is a different situation from the other shores of Gabriola Island. This area has large density of water wells, showing various lithologic units which are difficult to interpret. The interpretation was done mainly from surficial outcrops and land shape and clusters of well logs showing consistent lithologies. The dipping boundaries of the shale and sandstone units were extrapolated and projected down as almost planar surfaces and are shown in a section and profile views on this figure. Groundwater flow is away from land and well drawdowns often produce water levels at or below sea level along the shores. This area has a history of sea water intrusion along the shore. The shale layers are relatively thin and clay intervals are only present at larger depth, so there is less “geologic” protection from sea water intrusion in this area.

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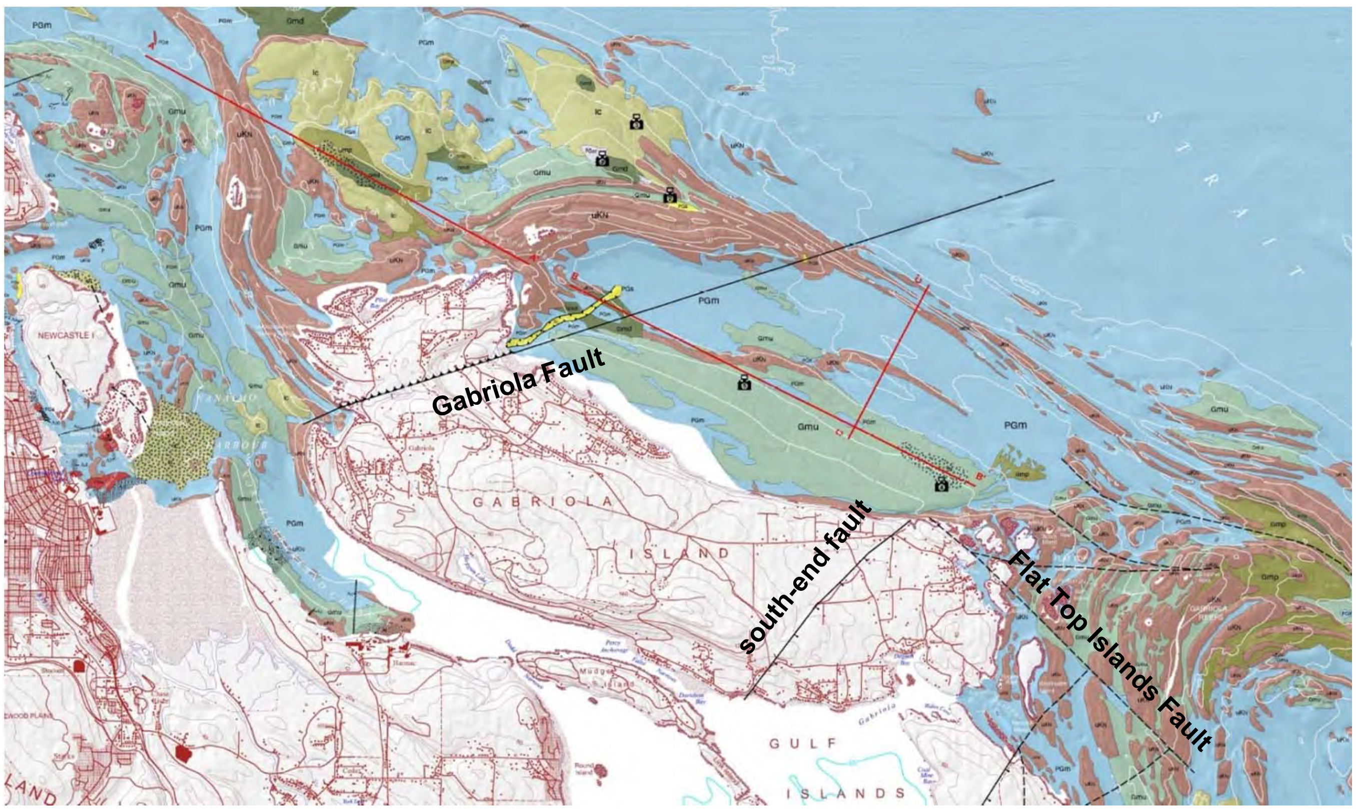
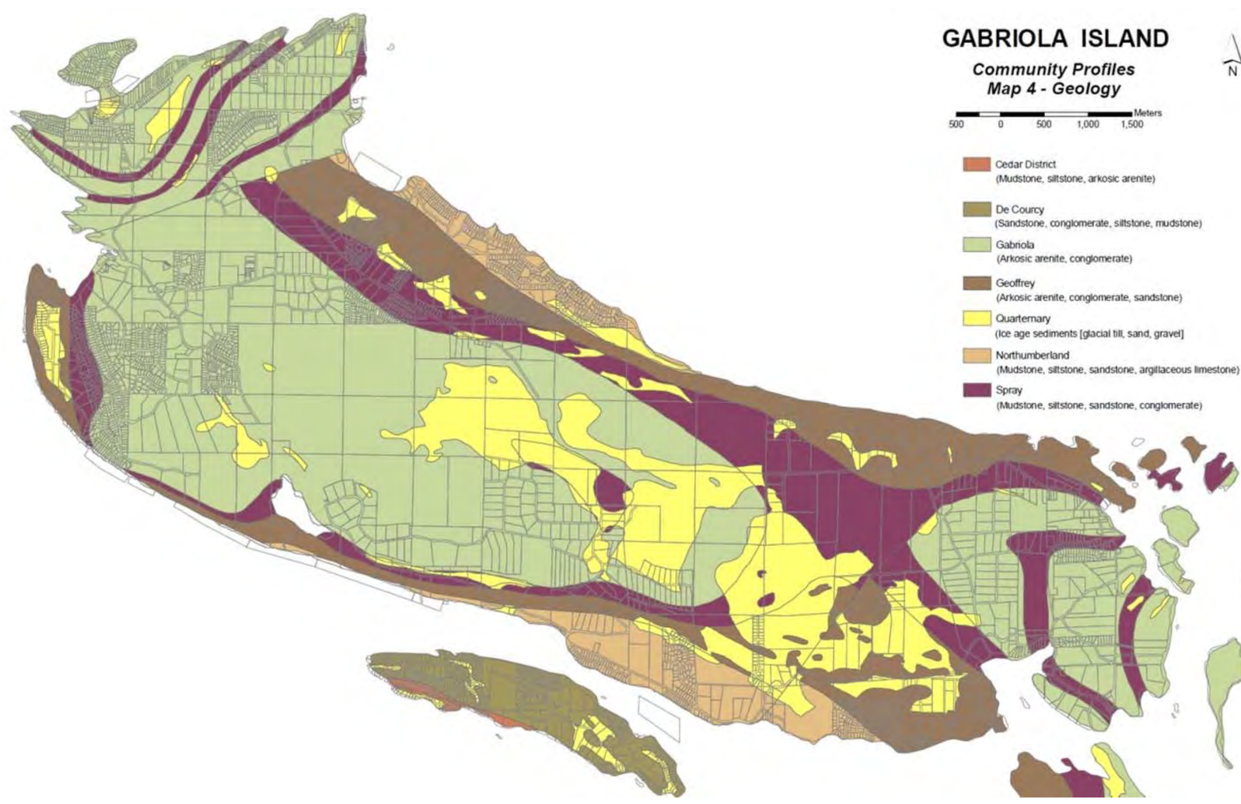


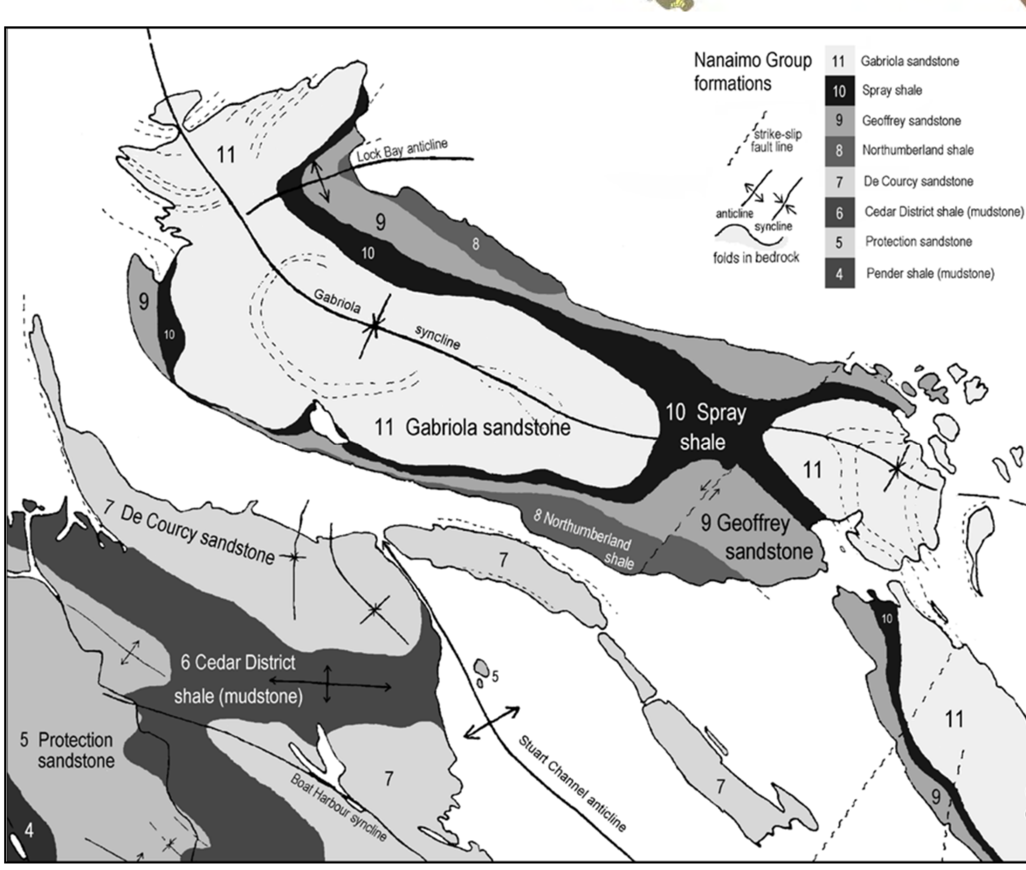
Surficial Geology and Shaded Seafloor Relief, Nanaimo, BC, Geology by Picard 2004-2008, Map 2118A – Gabriola Island area selected from original map by Natural Resources Canada & Fisheries And Oceans Canada (2010).

Labels of large fault lines were added on this map by author (after Doe, 1999) comments.

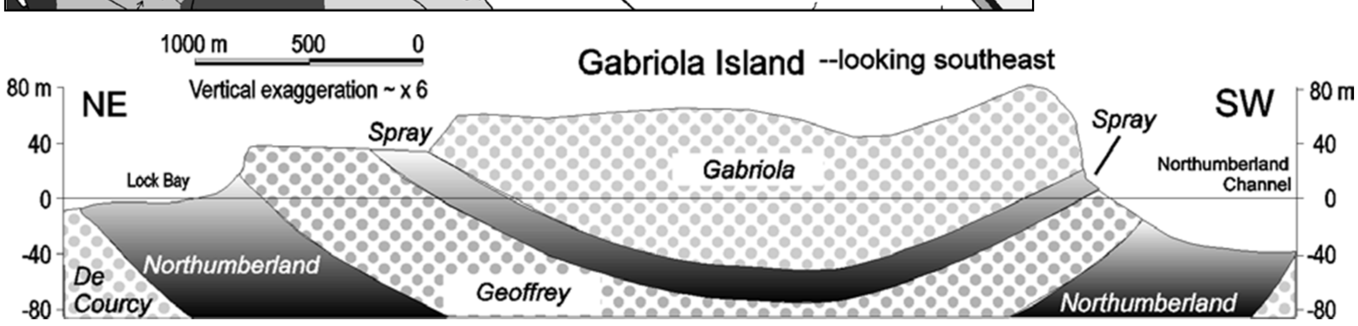
uKn = bedrock
Gmd, Gmp, Gmu = glaciomarine sediments
Ic = ice contact deposits
PG... = post glacial sediments
m – mud, s = sand, sr = sponge reefs, a = anthropogenic



Surficial Geology of Gabriola Island, from Gabriola Island Community Profile (November 2009), data from Natural Resources Canada



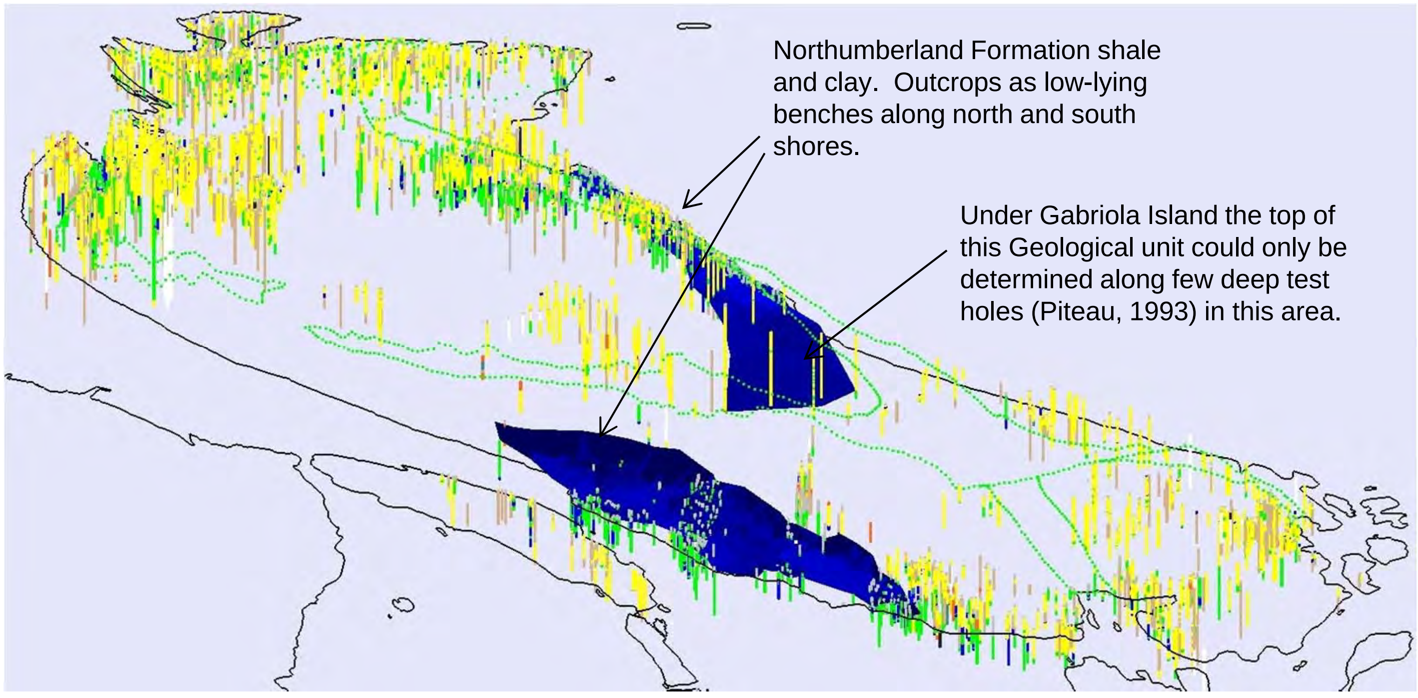
Bedrock geology of Gabriola and its surroundings, from *SHALE* No.1 November 2000, adapted from England (1989) by Doe (2000)



Cross-section of Gabriola Island (from Earle and Krogh, 2004), from Lock Bay to the Northumberland Channel.

srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Compilation of Geological maps of Gabriola and Mudge Islands from previous reports
Job No: 1CR010.000 Filename: Figure A1 to A8 - geology.pptx	Gabriola Island	Date: April 2013 · Approved: JS · Figure: **A-1**

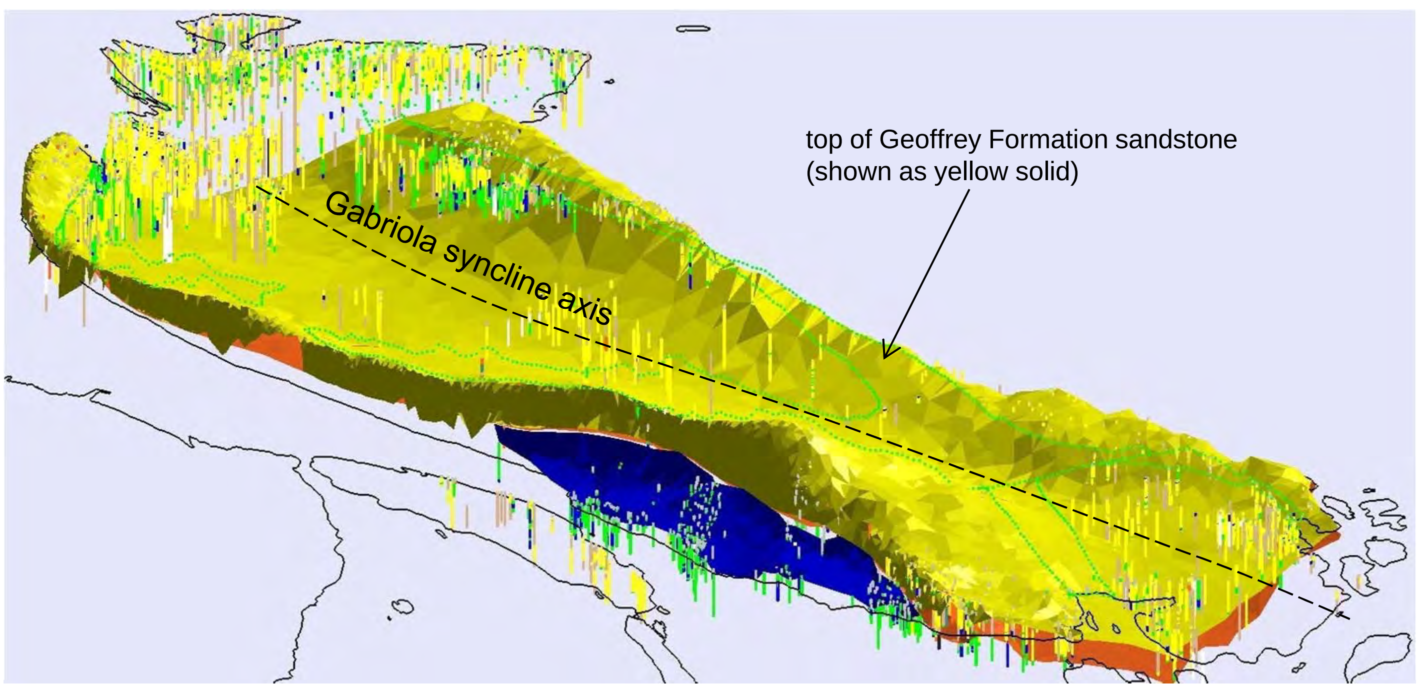
Northumberland Formation (shale and clay)



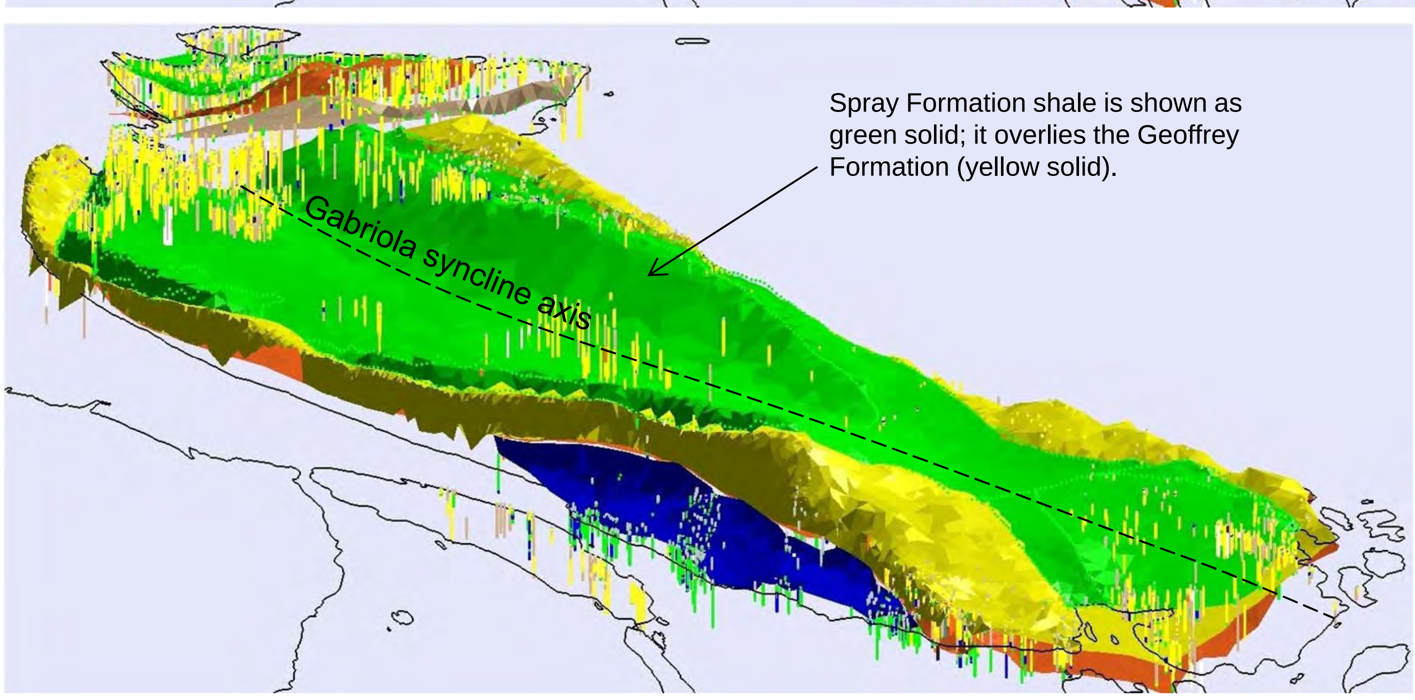
Well lithologs legend:

Materials
- Overburden
- Sandstone
- Clay
- Shale
- Conglomerate
- Sandstone & Shale
- Sandstone & Conglomerate
- Unknown
- Other rock (granite etc)
- Conglomerate & Shale
- watertable

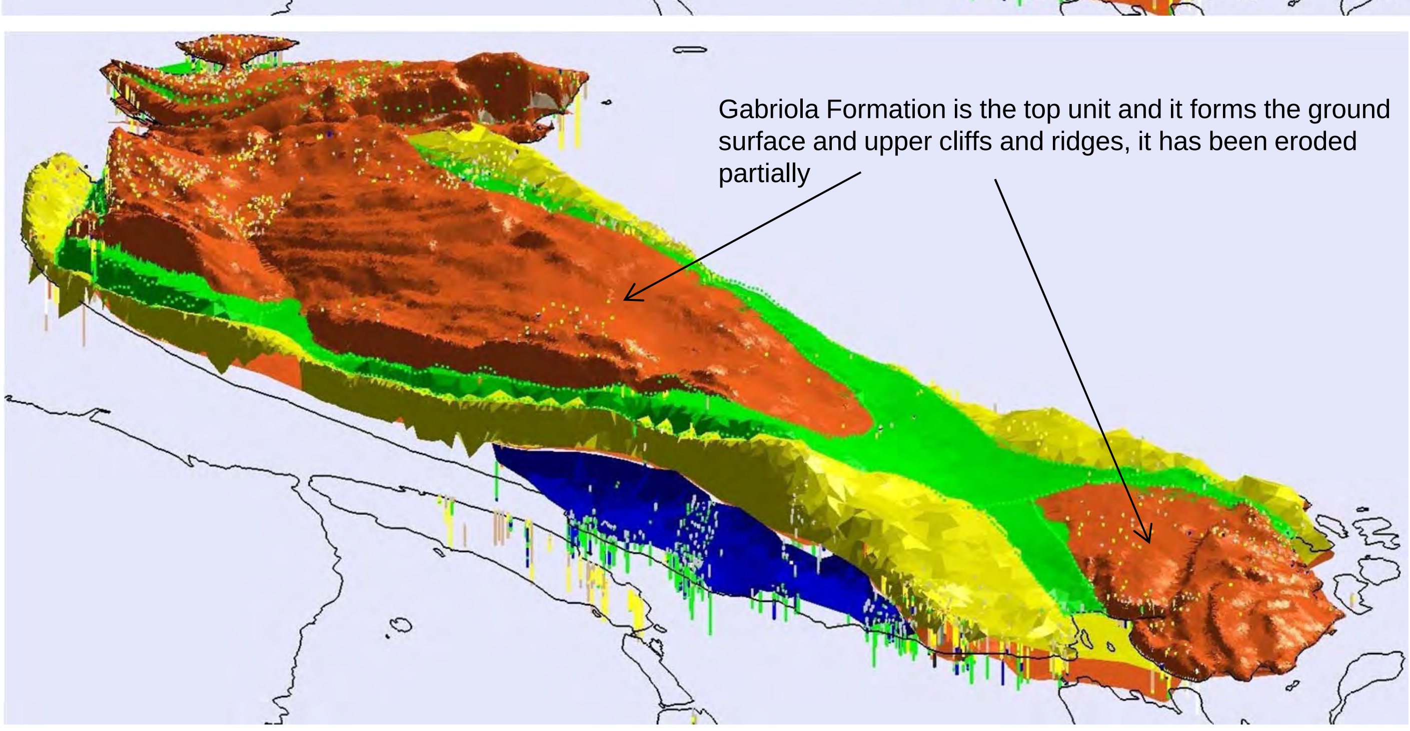
Geoffrey Formation (sandstone)



Spray Formation (shale)

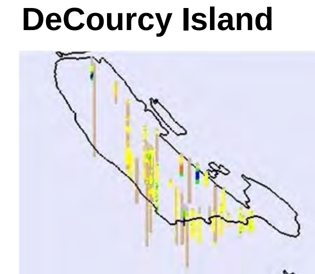


Gabriola Formation and other units on Gabriola Island

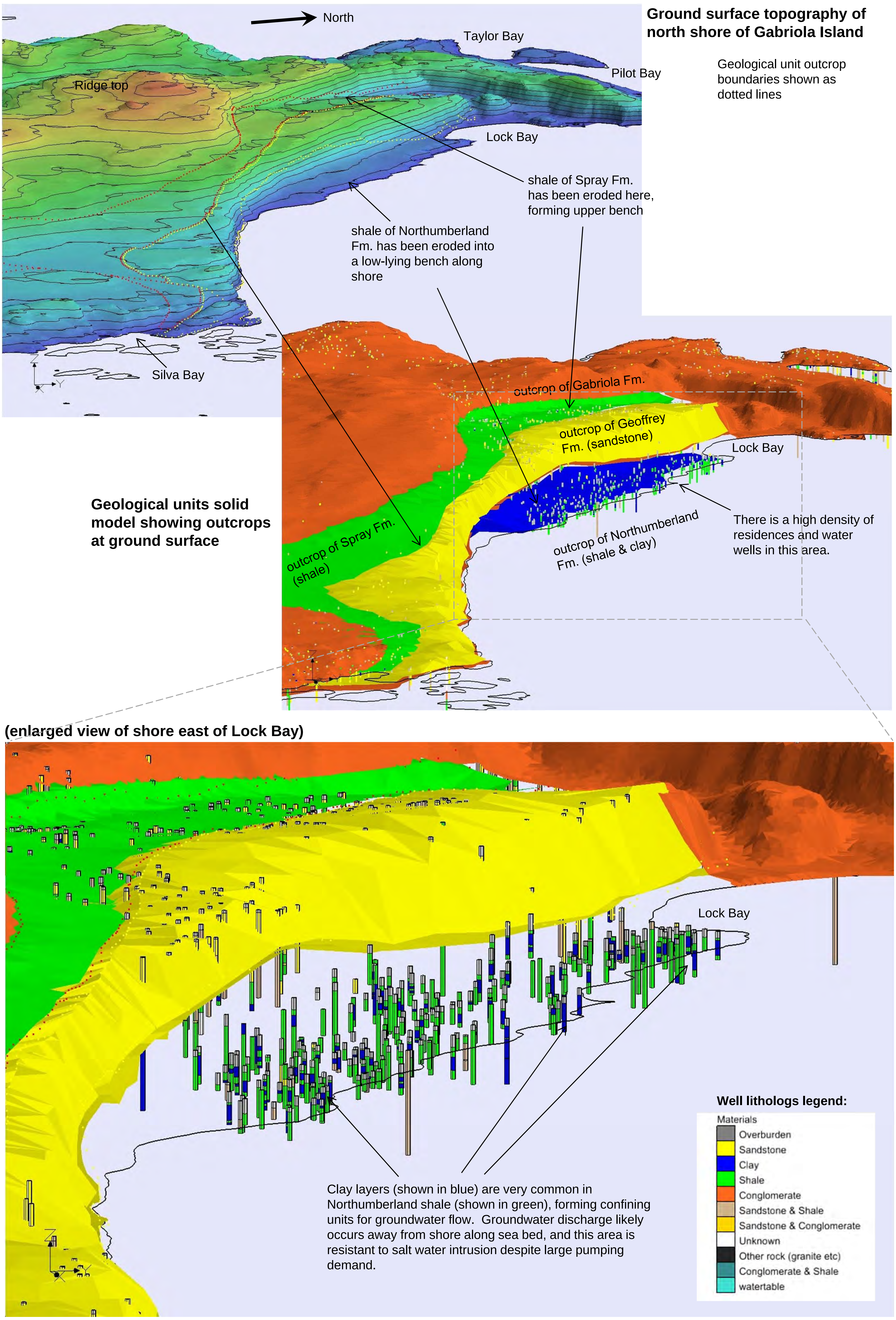


There is little information on Mudge and DeCourcy except surficial geology map; a 3D model is not available at this time from the small number of well lithologs because most logs show a mix of sandstone and shale

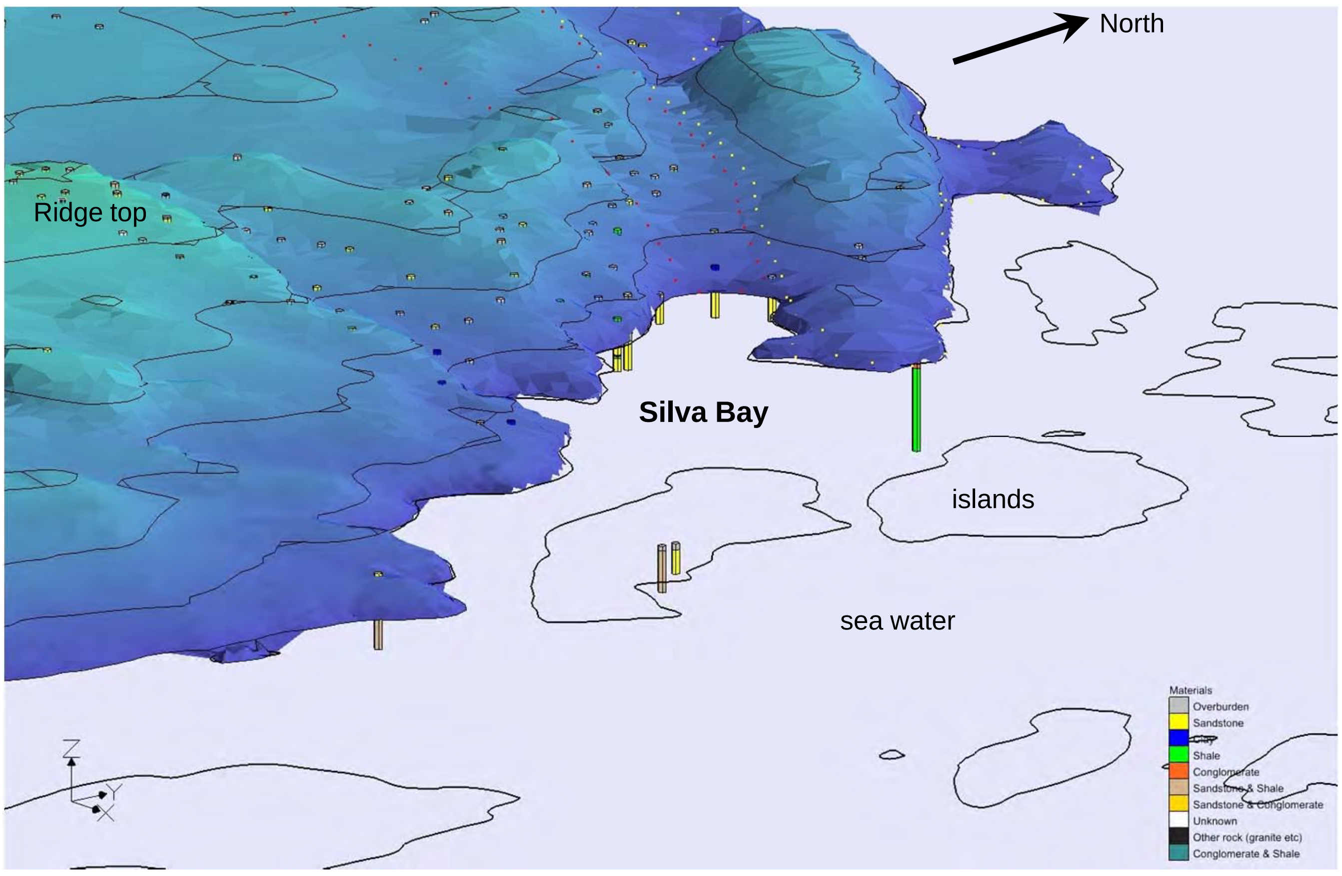
DeCourcy Island



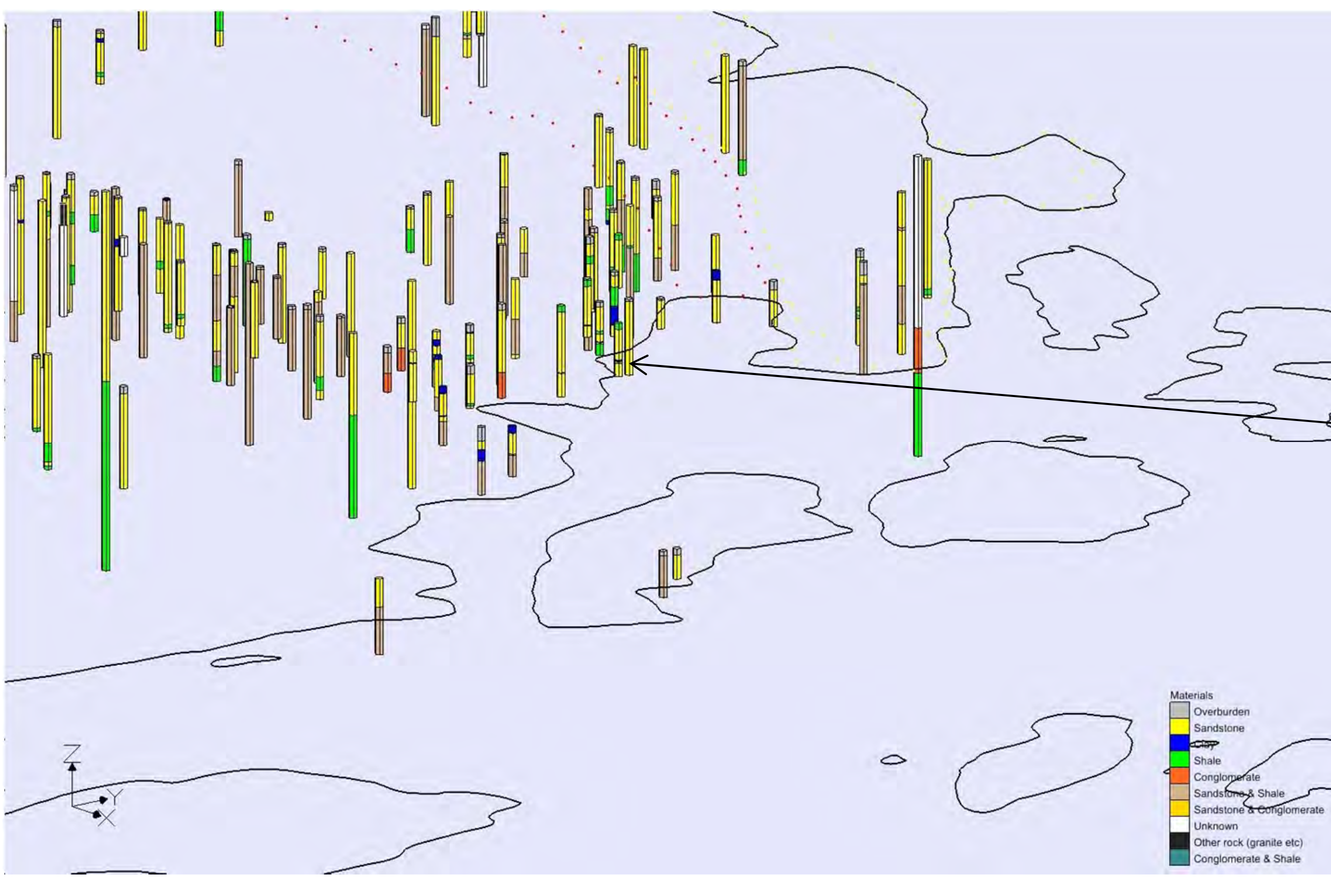
srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
Job No: 1CR010.000	Gabriola Island	**Geological 3D model of Gabriola Island and well lithologs from MOE wells database**
Filename: Figure A1 to A8 - geology.pptx		Date: April 2013 · Approved: JS · Figure: **A-2**



srk consulting	Regional District of Nanaimo	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)		
		North shore of Gabriola Island – topography, geological units, and well lithologs		
Job No: 1CR010.000 Filename: Figure A1 to A8 - geology.pptx	Gabriola Island	Date: April 2013	Approved: JS	Figure: **A-3**

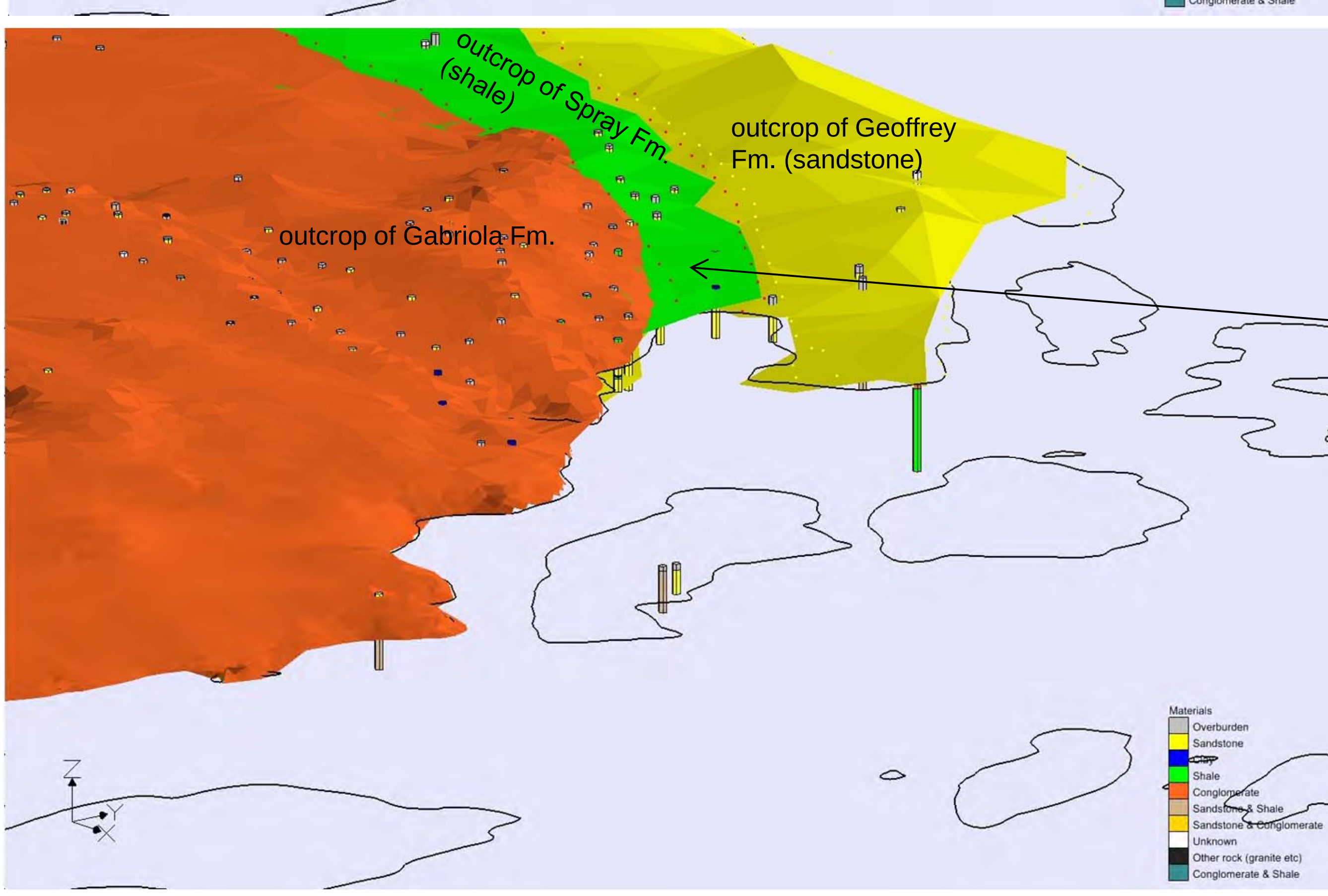


Ground surface topography of Silva Bay area of Gabriola Island



Water well lithologs and shore outlines

There is a high density of residences and water wells in this area. There is history of salt water intrusion to some wells near shore.



Geological units solid model showing outcrops at ground surface

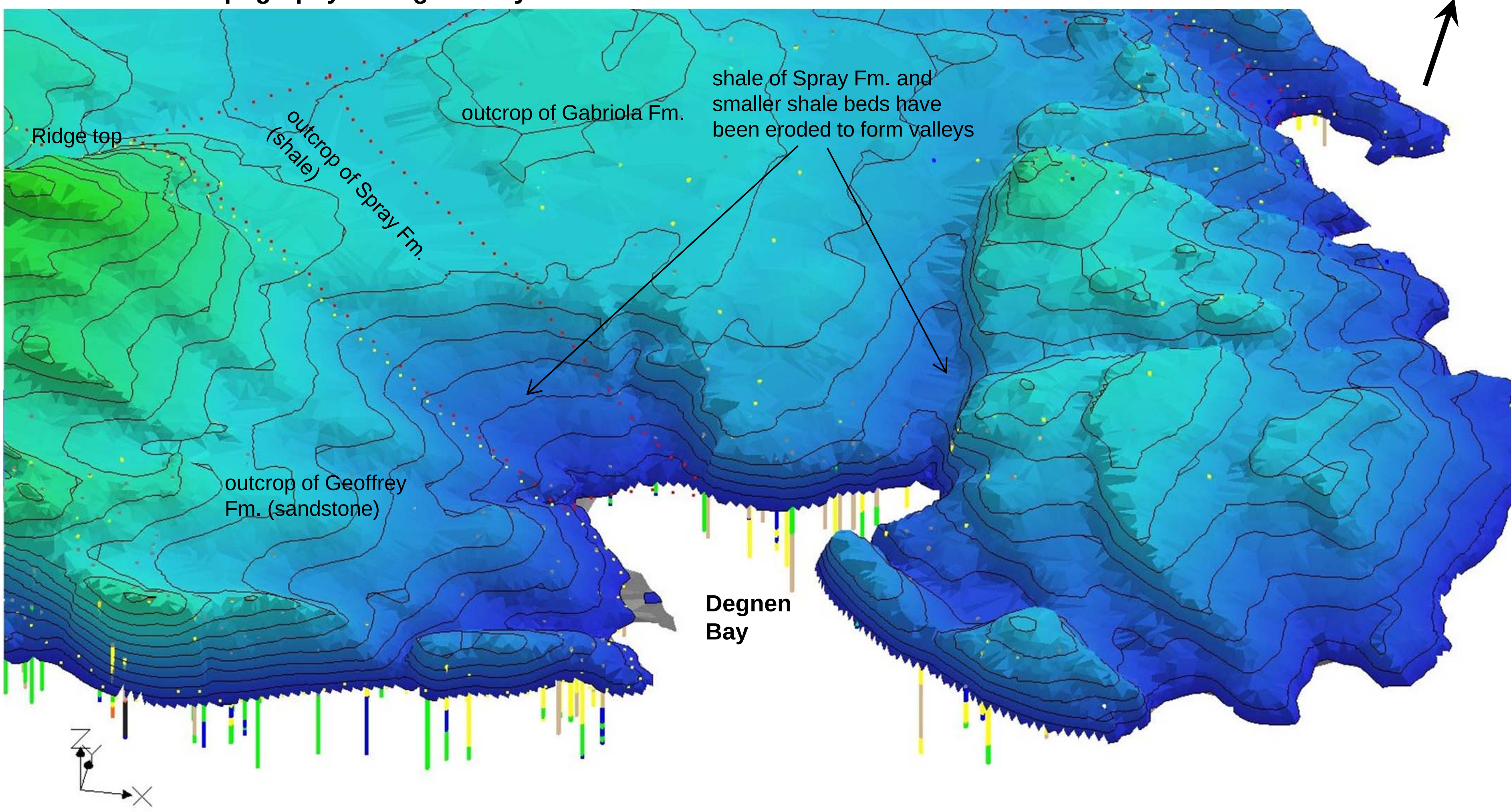
shale of Spray Fm. has been eroded to form a valley

Well lithologs legend:

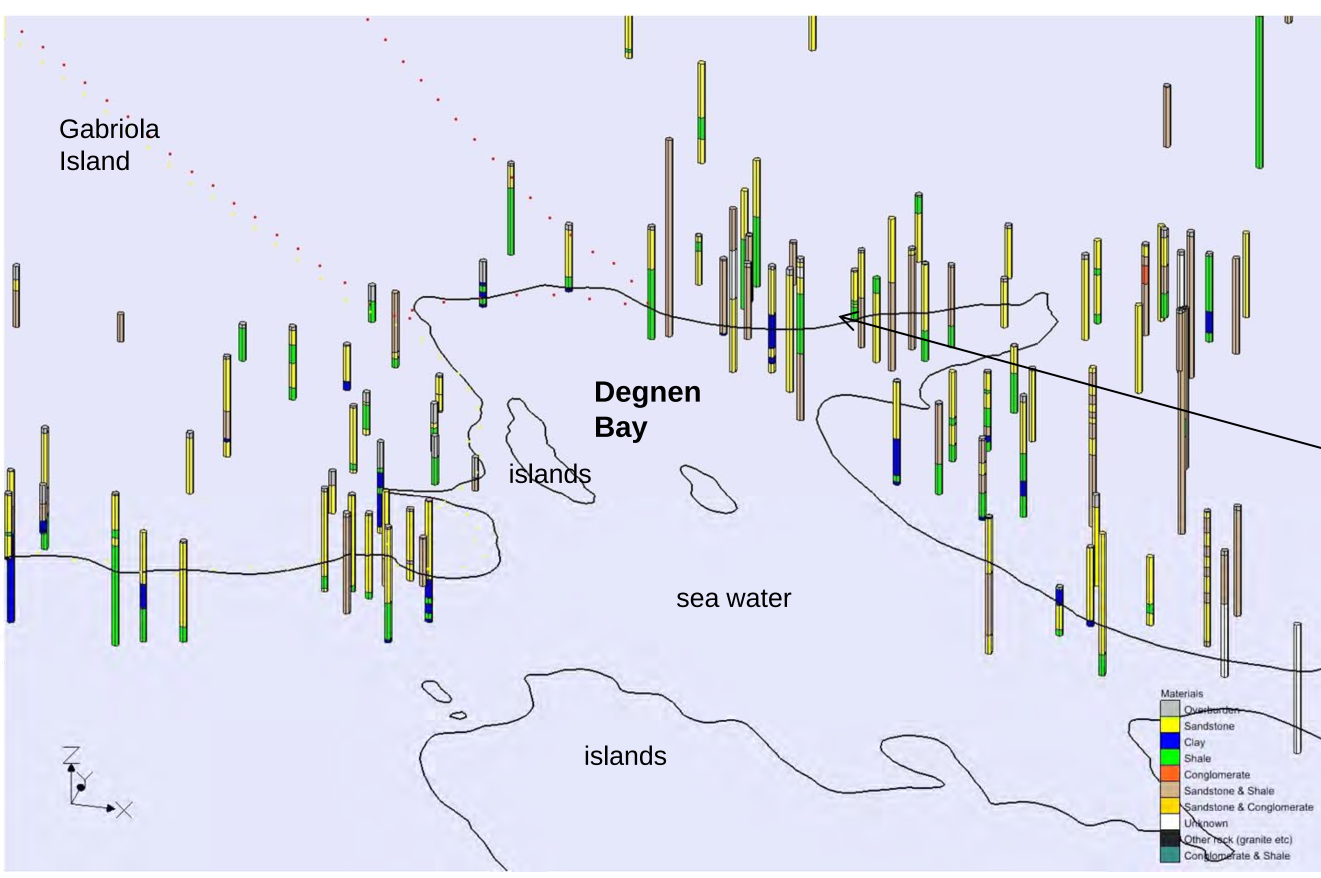
srk consulting	Regional District of Nanaimo	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Silva Bay area of Gabriola Island – topography, geological units and well lithologs
Job No: 1CR010.000 Filename: Figure A1 to A8 - geology.pptx	Gabriola Island	Date: April 2013 · Approved: JS · Figure: **A-4**

Ground surface topography of Degnen Bay area of Gabriola Island

North

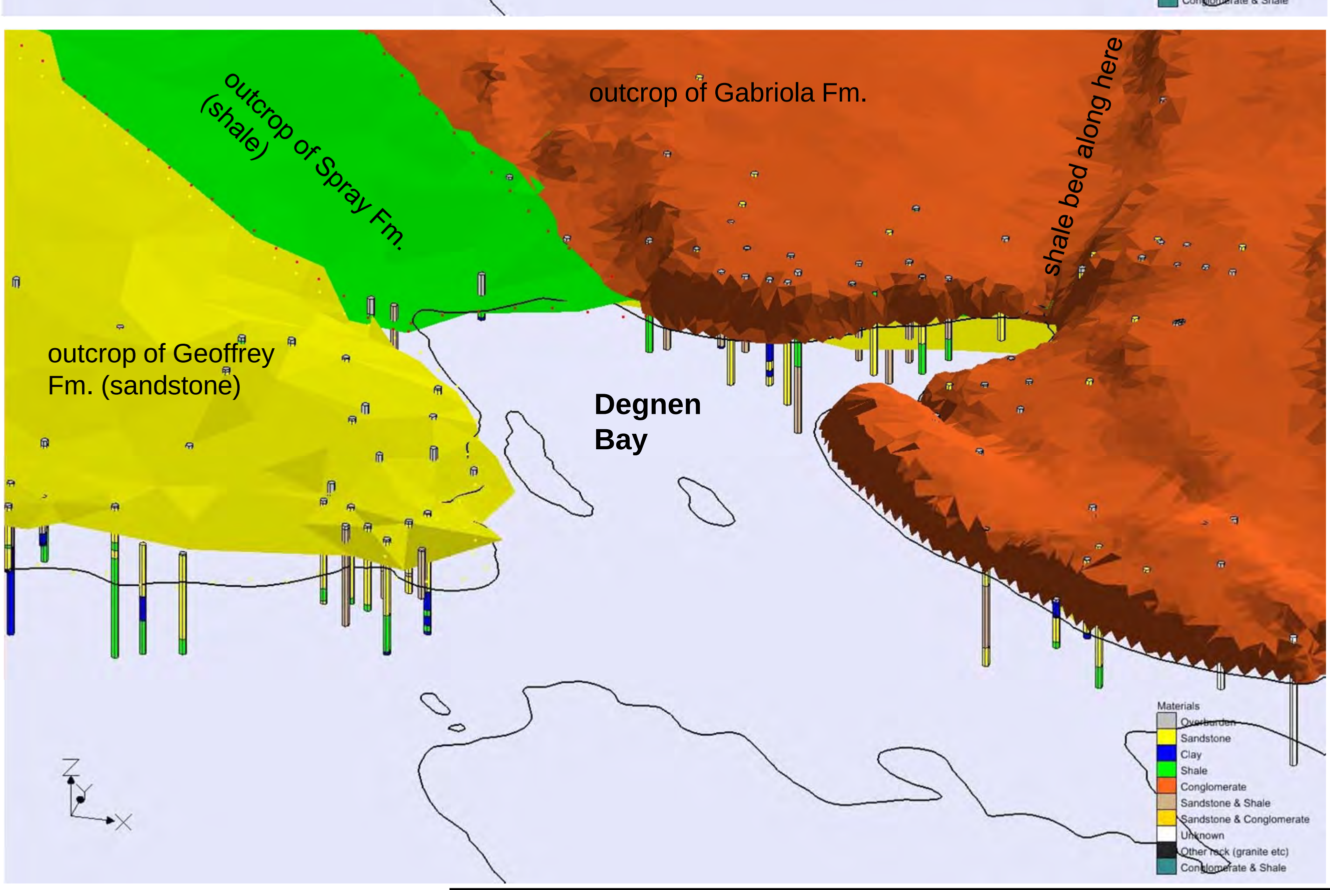


Water well lithologs and shore outlines



There is a high density of residences and water wells in this area. There is history of salt water intrusion to some wells near shore.

Geological units solid model showing outcrops at ground surface

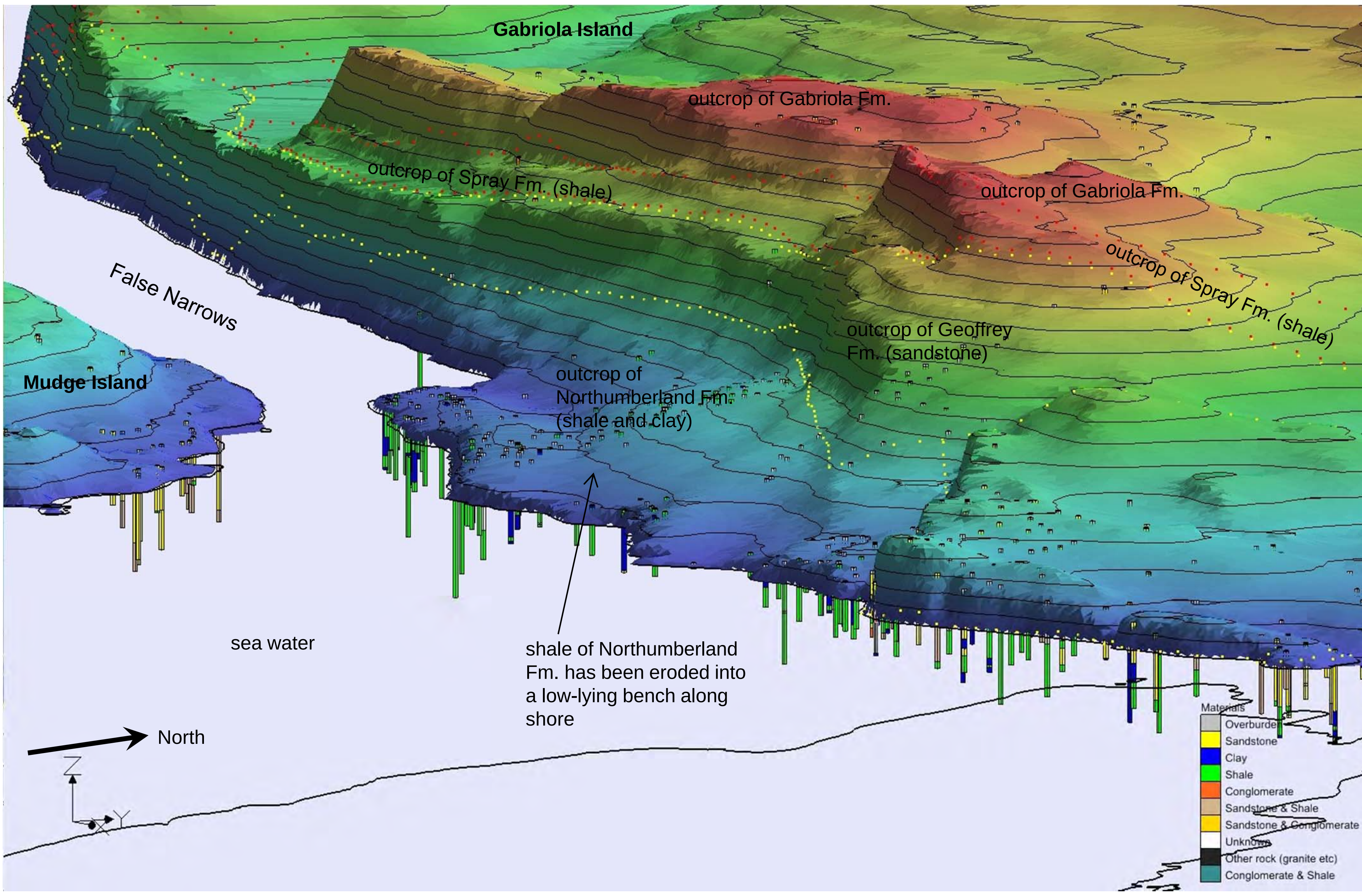


Well lithologs legend:

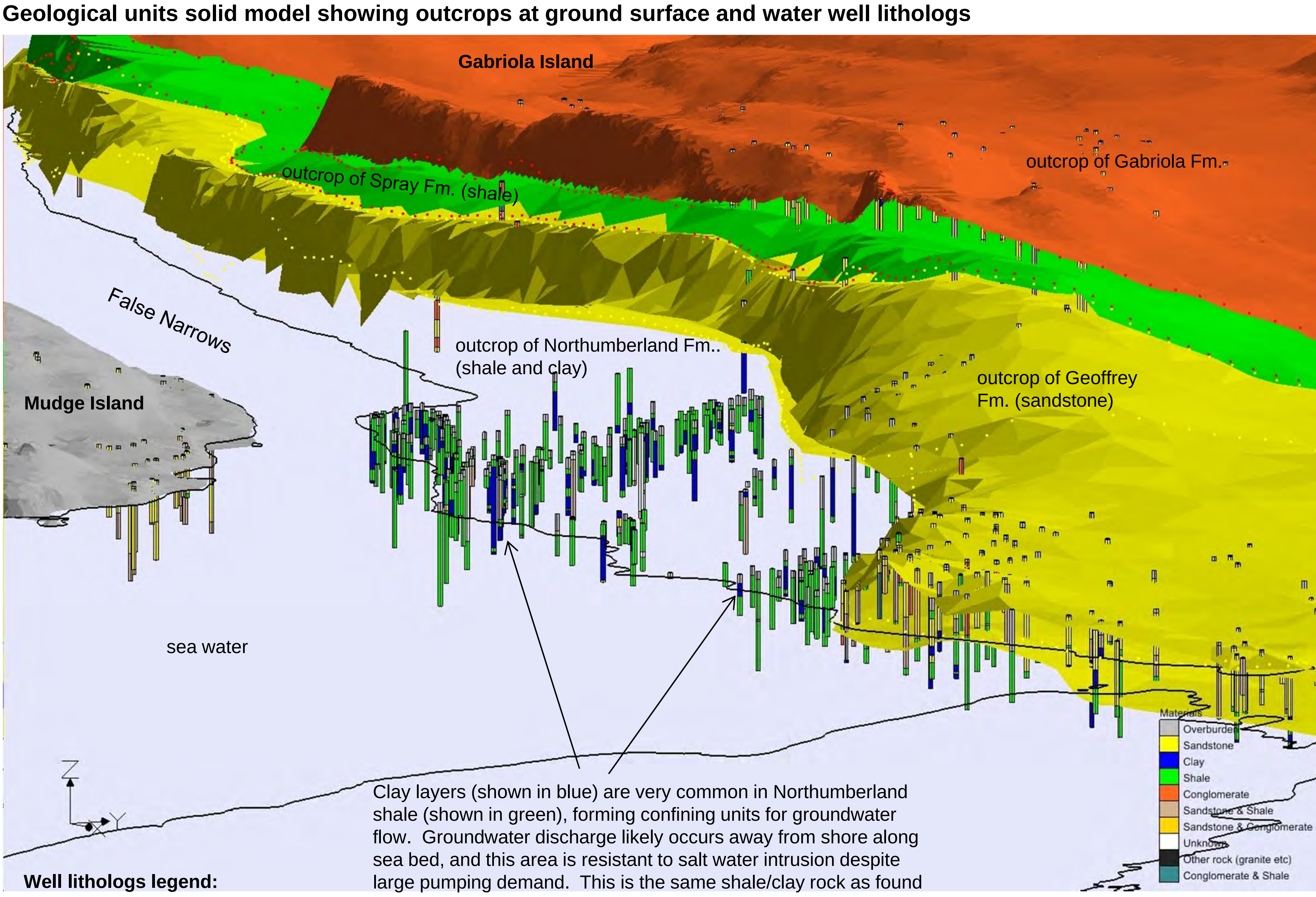
Materials
- Overburden
- Sandstone
- Clay
- Shale
- Conglomerate
- Sandstone & Shale
- Sandstone & Conglomerate
- Unknown
- Other rock (granite etc)
- Conglomerate & Shale
- watertable

srk consulting	Regional District of Nanaimo	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Degnen Bay area of Gabriola Island – topography, geological units and well lithologs
Job No: 1CR010.000	Gabriola Island	Date: April 2013
Filename: Figure A1 to A8 - geology.pptx		Approved: JS
		Figure: **A-5**

Ground surface topography of south shore of Gabriola Island along False Narrows



Geological units solid model showing outcrops at ground surface and water well lithologs

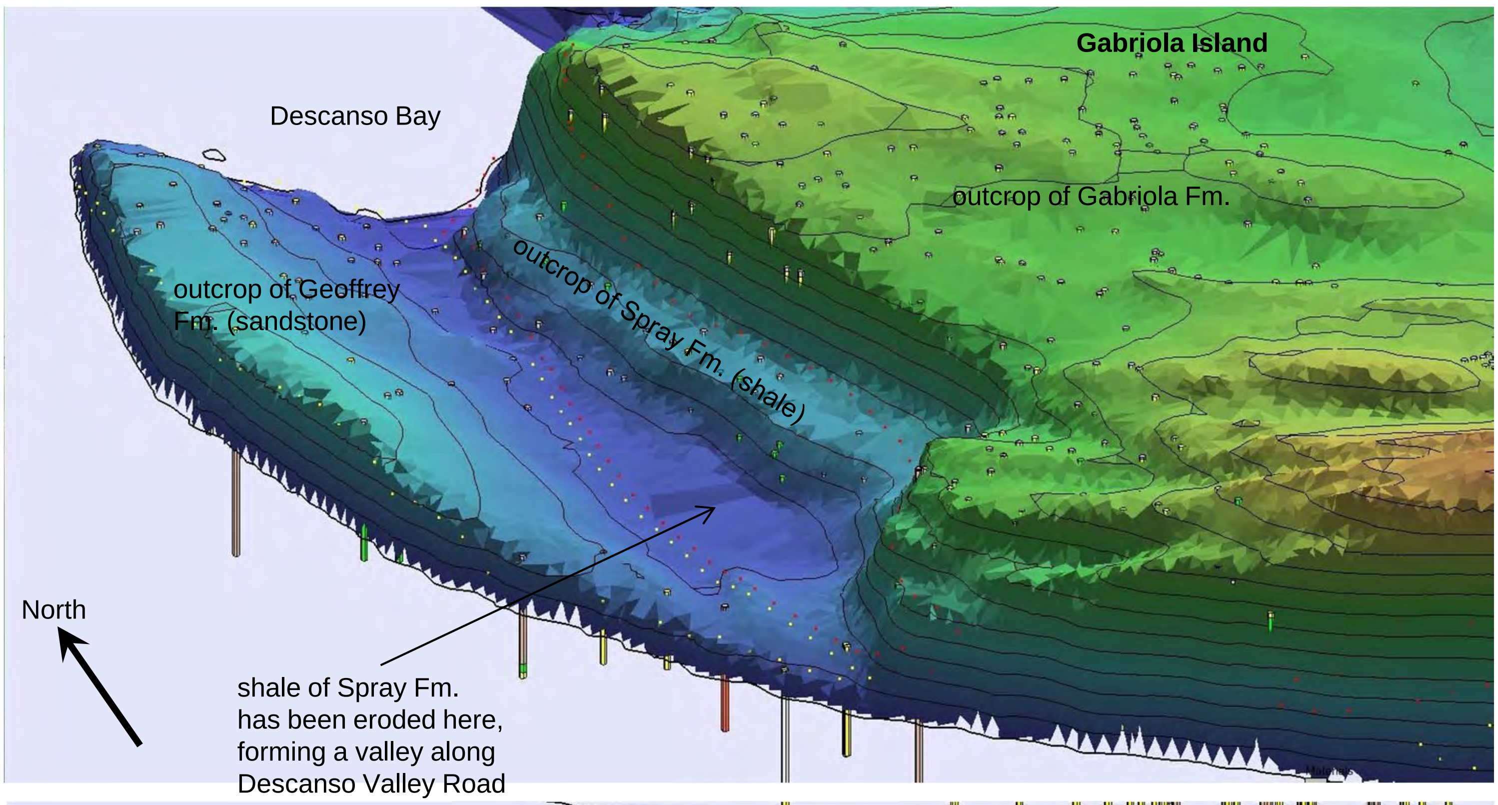


Clay layers (shown in blue) are very common in Northumberland shale (shown in green), forming confining units for groundwater flow. Groundwater discharge likely occurs away from shore along sea bed, and this area is resistant to salt water intrusion despite large pumping demand. This is the same shale/clay rock as found east of Lock Bay on north shore of island.

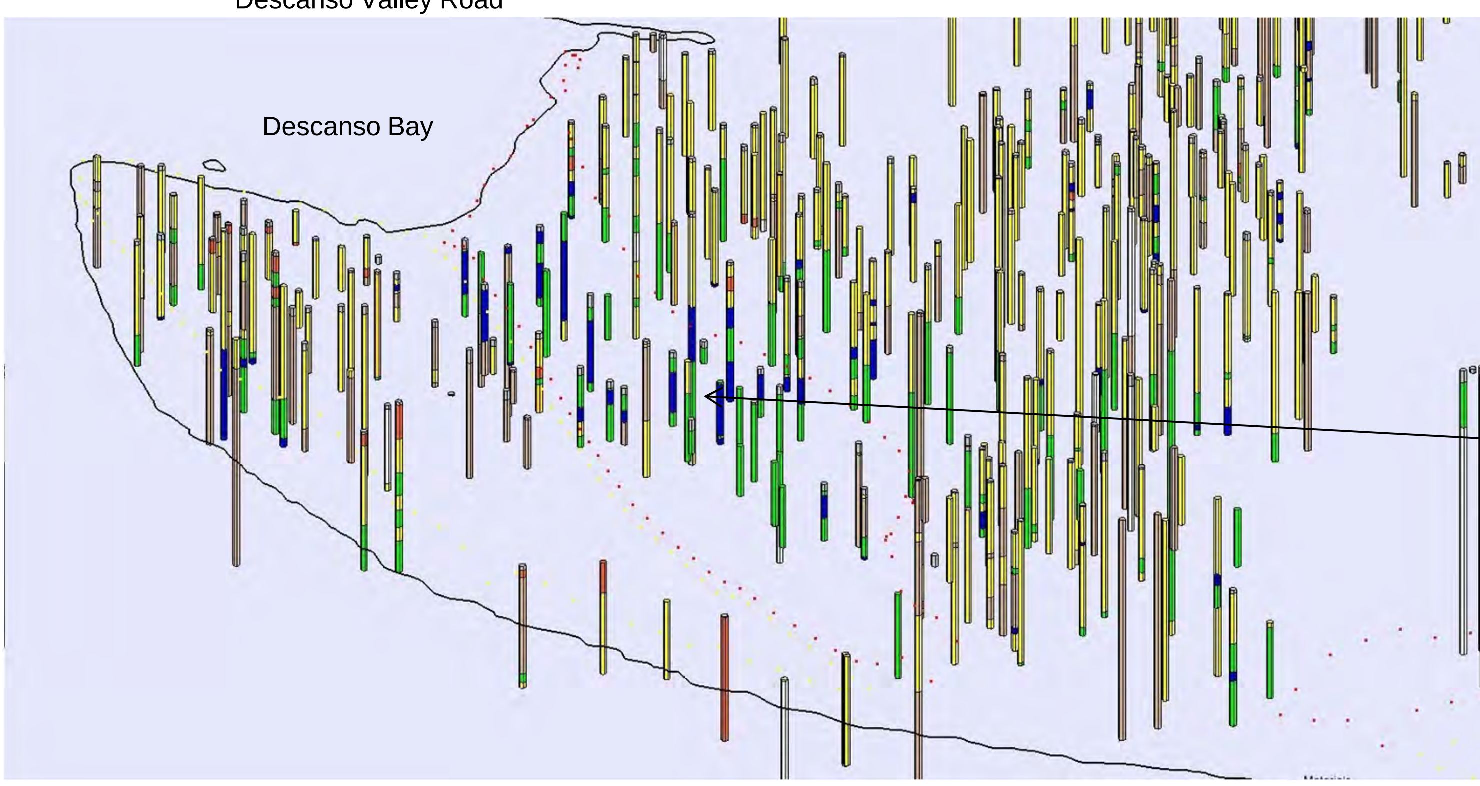
Well lithologs legend:

Materials
- Overburden
- Sandstone
- Clay
- Shale
- Conglomerate
- Sandstone & Shale
- Sandstone & Conglomerate
- Unknown
- Other rock (granite etc)
- Conglomerate & Shale
- watertable

srk consulting	Regional District of Nanaimo	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
Job No: 1CR010.000	Gabriola Island	**False Narrows area of Gabriola Island – topography, geological units and well lithologs**
Filename: Figure A1 to A8 - geology.pptx		Date: April 2013 / Approved: JS / Figure: **A-6**



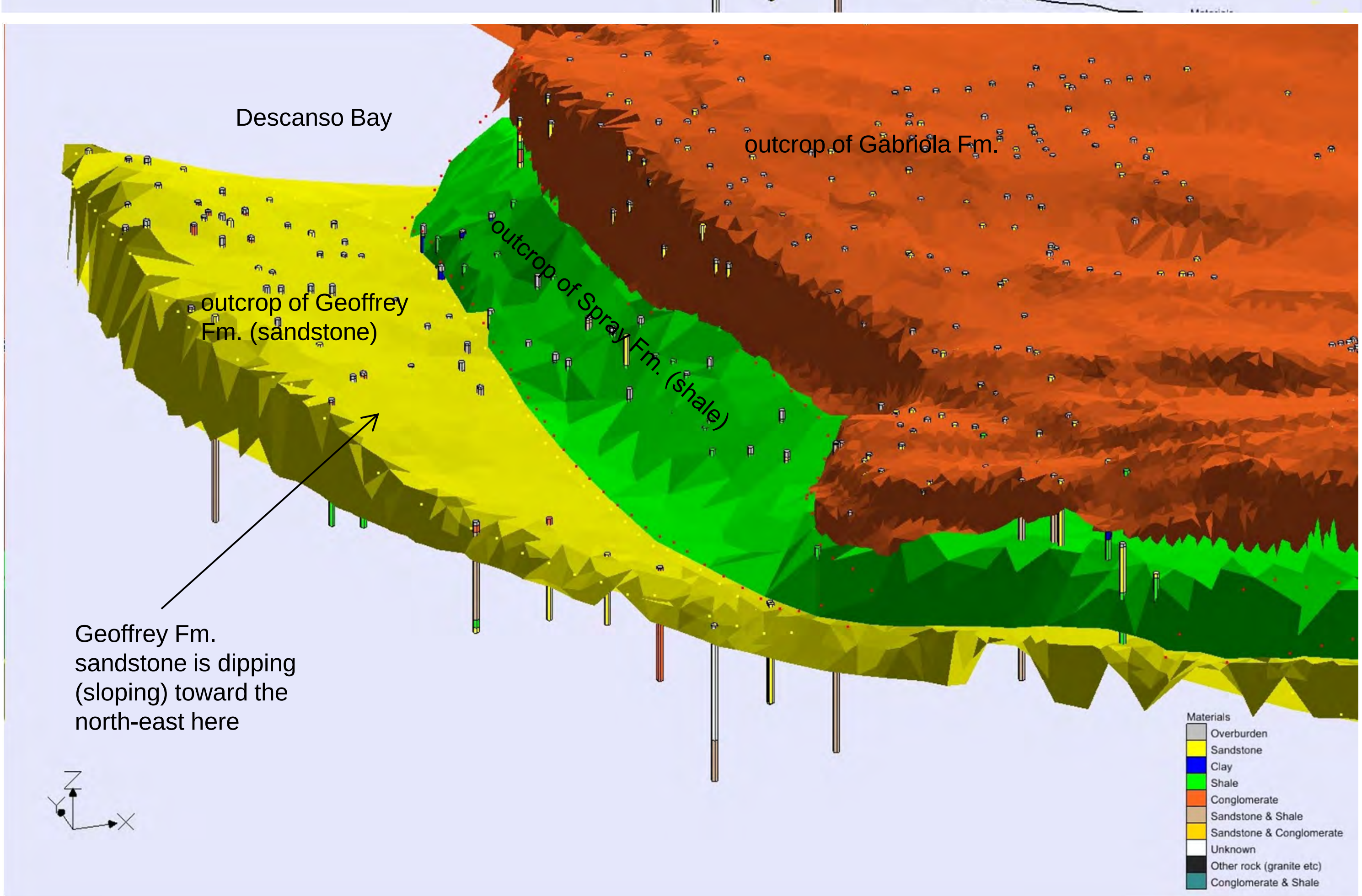
Ground surface topography of south-west shore of Gabriola Island, and Descanso valley, south of Descanso Bay



Water well lithologs and shore outlines

well lithologs show very variable lithology of rocks, mostly sandstone and shale

well lithologs show dominant shale and clay in Spray Fm.



Geological units solid model showing outcrops at ground surface and water well lithologs

Well lithologs legend:

Materials
- Overburden
- Sandstone
- Clay
- Shale
- Conglomerate
- Sandstone & Shale
- Sandstone & Conglomerate
- Unknown
- Other rock (granite etc)
- Conglomerate & Shale
- watertable

srk consulting

Regional District of Nanaimo

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

South of Descanso Bay on Gabriola Island – topography, geological units and well lithologs

Job No: 1CR010.000

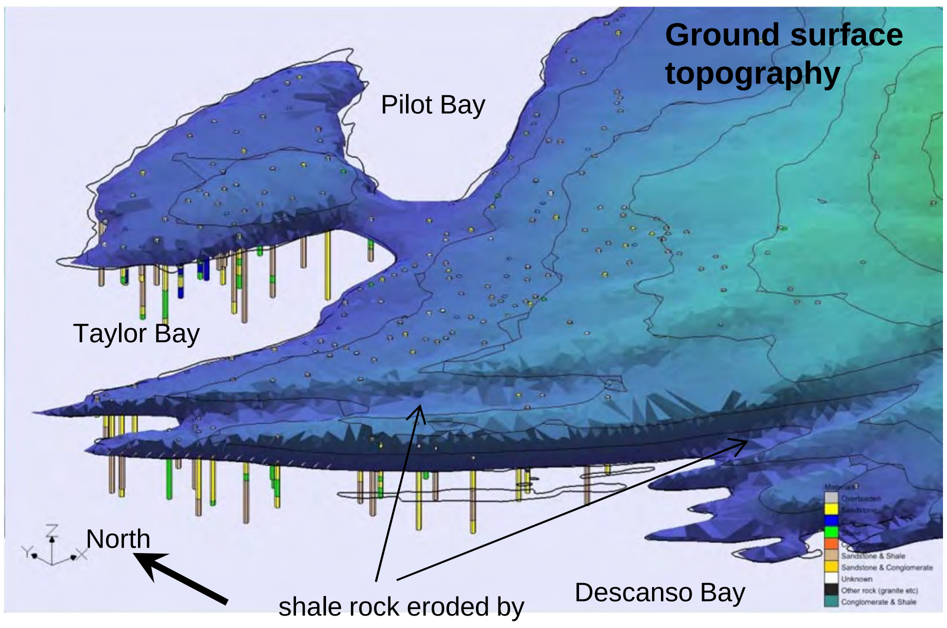
Filename: Figure A1 to A8 - geology.pptx

Gabriola Island

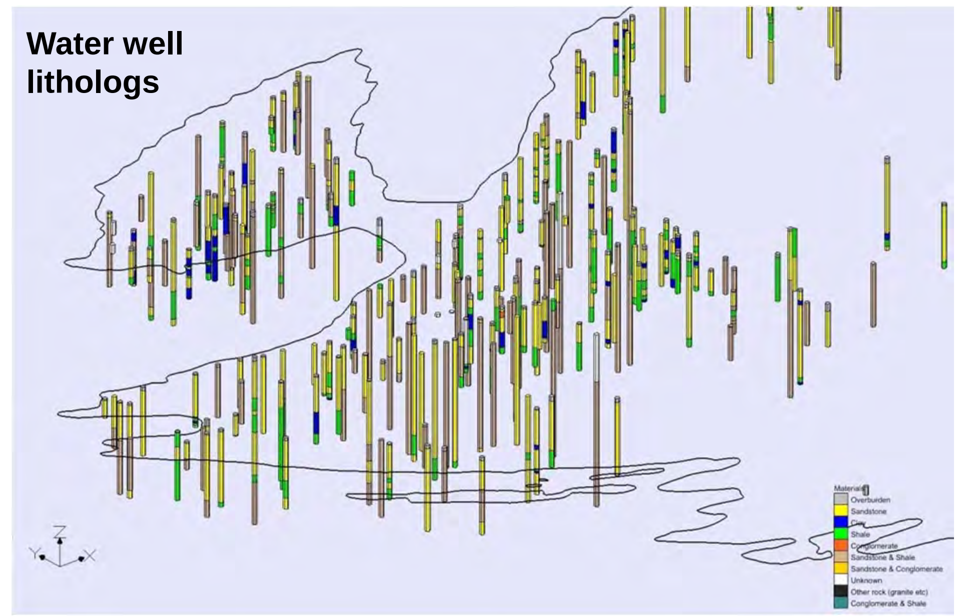
Date: April 2013

Approved: JS

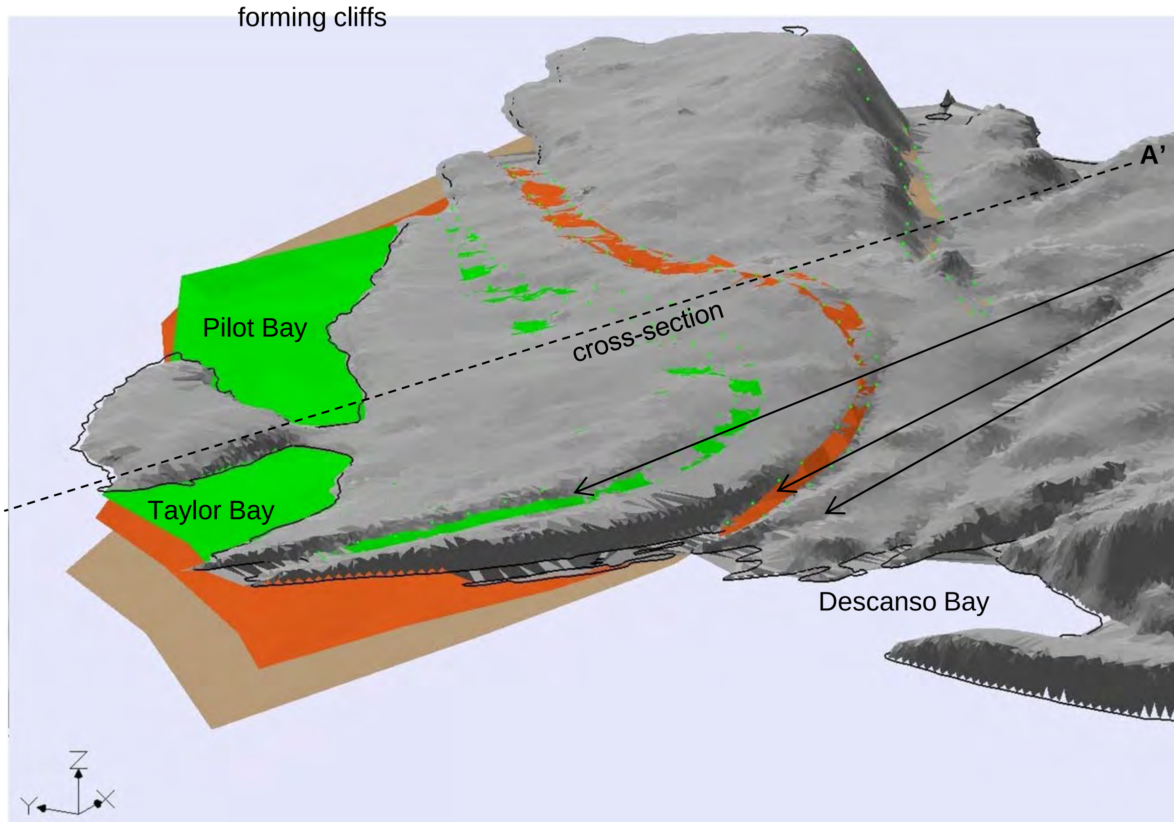
Figure: **A-7**



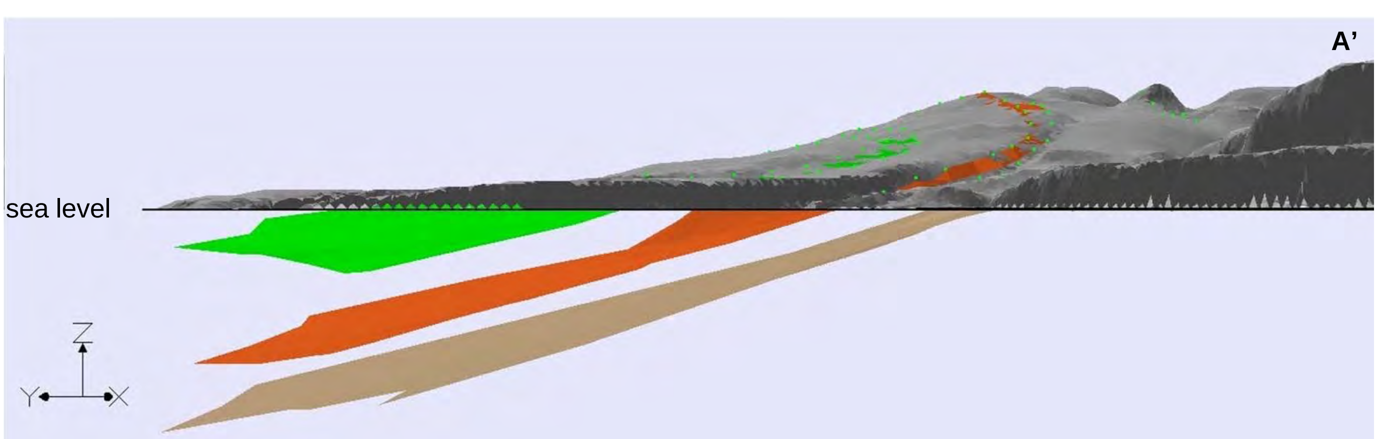
shale rock eroded by waves, sandstone forming cliffs



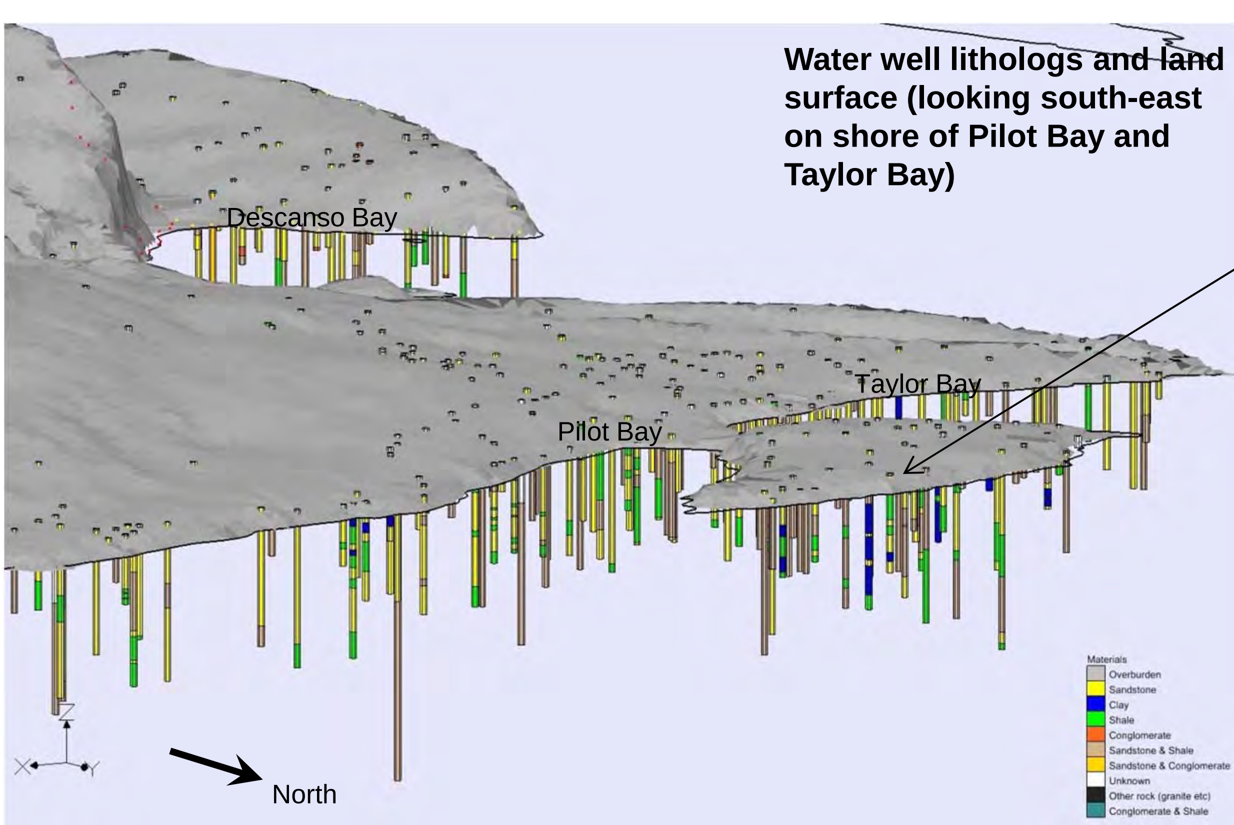
Shale rock layers in west part of Gabriola Island



dipping to the west are shale layers which outcrop as bands of shale on ground surface, and are represented in model as dipping surfaces for visualization (see below for cross-section view along West-East)



cross-section view along West-East line (looking north) of dipping layers of shale in western part of Gabriola Island under Pilot Bay and Taylor Bay



There is a high density of residences and water wells in this area. There is history of salt water intrusion to some wells near shore.

Well lithologs legend:

Materials

- Overburden
- Sandstone
- Clay
- Shale
- Conglomerate
- Sandstone & Shale
- Sandstone & Conglomerate
- Unknown
- Other rock (granite etc)
- Conglomerate & Shale
- watertable

srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Pilot Bay, Taylor Bay, Descanso Bay – topography, geological units and well lithologs
Job No: 1CR010.000 Filename: Figure A1 to A8 - geology.pptx	Gabriola Island	Date: April 2013 / Approved: JS / Figure: **A-8**

Appendix B: Hydrogeological Conceptual Model

Appendix B - Table of Contents

Appendix B – Figures

Appendix B - Tables

1 Summary of Hydrogeological Investigations and Data Available

1.1 History of Hydrogeological Investigations

There have been hydrogeological (groundwater) investigations on The Gulf Islands since the 1970's. On Gabriola Island, groundwater testing started in 1971 under the direction of the British Columbia Ministry of Environment (B.C. MOE). Several test wells were drilled in 1972 and water level recorders installed in observation wells 72-1 and 72-4. Brown and Dakin (1972) and Brown and Erdman (1975) wrote reports on Gabriola Island groundwater conditions. There was a survey of residents on water use in 1973-1974, followed by a report by Hodge (1978), summarizing hydrogeological conditions known at the time from 850 well records. Another report by Moen (1979) reviewed water availability on Gabriola Island, although more from a hydrological (surface water) perspective, and provided some flow measurements on streams and outflow from Hoggan Lake.

Well drilling continued as the number of residences increased but no formal groundwater investigations were done (or were not published) in the 1980's. BC MOE installed and tested two more observation wells in early 1990's, and in 1993 by Piteau Associates tested wells on a planned subdivision owned by Weldwood of Canada Ltd. in north-central part of the island. Much of the pumping test data on Gabriola comes from this work.

From 2001 to 2008, there were academic studies done on the southern Gulf Island hydrogeology of fractured rock aquifers by Simon Fraser University (SFU) and the Geological Survey of Canada (GSC). The groundwater conditions and geochemical evolution of groundwater on Saturna Island was done by Allen and Suchy (2001), Allen (2004), Allen et al (2002) and Liteanu and Allen (2008). Gabriola Island was not specifically studied, but there were fracture orientation measurements taken by Mackie et al (2001) and Mackie (2002) during a combined geological-hydrogeological study. There is also a larger report for the MOE by Allen et al (2003) on this subject. One Master's thesis (Appiah-Adjei, 2006) dealt with climate change and recharge dynamics on the Gulf Islands. A regional hydrostructural study of the Gulf Islands was done by Surrette (2006), Surrette et al (2008), Surrette and Allen (2008)

Aquifer vulnerability mapping was done by Denny et al. (2007) and also by Liggett and Gilchrist (2010). The BC MOE database has two bedrock aquifers on Gabriola Island, #706 and #709, and both are classified as high-vulnerability to contamination and either high or moderate demand. In the same year, a report was written by Groundwater Solutions (2007) about groundwater conditions on Gabriola Island with respect to the Summer Rain Water Delivery (SRWD) production well on the island.

Separately, the Geology and Chemistry departments at Malaspina University-College (now Vancouver Island University) have been engaged in a study of the geochemistry of the groundwater used by residents of eastern Vancouver Island and the Gulf Islands (Earle and Krogh, 2004). Local geological and hydrogeological observations, and some interpretations, were written by Doe and Windecker (2005), and, although not reviewed externally, there is a wealth of local observations and good interpretations in several articles in that journal. A recent very good introduction to Gabriola Island hydrogeology was written by Peirce and Doe (2010).

All of the available reports, maps, and data were reviewed in detail during this Phase 1 assessment for water budget.

1.2 Aquifers in Fractured Rocks

The Gulf Islands are considered to be comprised of fractured rock aquifers that provide for local groundwater use. For groundwater assessments (i.e.: numerical modelling studies), the fractured rocks are usually considered to be a form of equivalent porous media for groundwater flow because it is impractical to try and represent the complicated fracture networks at the large scale of whole islands and because there are not enough measurements available to determine this complex fracture network. In previous reports, whole islands were considered to be groundwater aquifers, but there is variability between geological units and the style and density of fractures which transmit most of groundwater flow. Geological units which have similar hydraulic properties can be grouped into hydrogeological units. The more permeable ones are aquifers and the less permeable ones are aquitards (i.e.: these units retard groundwater movement). These terms are relative to each other, and some islands as a whole are better aquifers than other islands in the region.

Another way of looking at the hydrogeological units is to consider the structural geology and the occurrence of fracture zones, as well as the style of fracturing within different geological units. Zones of similarly fractured rock with similar hydraulic properties have been defined recently as hydro-structural domains. The work of Mackie (2002) on the structural geology and hydrogeology of the Gulf Islands resulted in definition of three hydro-structural domains as:

- highly fractured interbedded mudstone (shale) and sandstone with small fracture spacing (<10cm)
- less fractured sandstone with larger fracture spacing (>1m)
- fault and fracture zones with small fracture spacing (<5cm)

An illustration of a typical cross-section in the Nanaimo Group rocks was presented by Denny et al (2007). More work on hydrostructural domains was done by Surrette and Allen (2008). The conceptual model has been used by various recent reports on the Gulf Islands and is shown in Figure B-1. The most permeable zones (k_1) are near large faults because fracture density increases near structural faults. The fault plane itself might not be very permeable if it contains any infill such as clay gouge, but the fracture zone will be more permeable than the surrounding rock. This effect can be often seen in test wells and residential water wells during drilling, whereby water inflow increases when a large fracture zone is drilled through. However, not all fault zones are equally permeable and this concept is a generalization of a very complicated hydrogeological system. There are also differences between sandstone and mudstone (shale) rock layers because of their different style of fracturing.

Surrette et al (2008) summarized and mapped pumping test data on The Gulf Islands up to that year. Gabriola Island was not part of this regional study. The study presented an example of application of a methodology for modeling fracture sets, permeability distributions, and linking it to pumping test data and discrete fracture modeling results. Some practical comments emerged from this work:

- there is a bias in the tested wells because drillers preferentially located large wells in known fault or large fracture zones

- most tests (27 of 29) were completed in wells drilled in sandstone-dominant rock formations, and only 2 tests in mudstone-dominant rock formations, so the average transmissivity was very uncertain for mudstones (shales)

1.3 Preferential Flow Paths and Barriers to Flow

1.3.1 Bedding Planes

Groundwater flows in any connected fractures in any orientation. There are likely preferential flow directions along weathered bedding planes (enlarged fractures), usually at the contact of sandstone and mudstone, but also through sub-vertical or vertical large fractures in sandstone. Water is expected to flow faster through large fractures in sandstone than through highly fractured mudstone where fracture apertures are very small.

Peirce and Doe (2010) described observations where groundwater flows easily through large fractures in sandstone and backs-up in the sandstone fractures at the sandstone-mudstone (shale) interface. For example, the contact between the Gabriola and Spray Formations and the Geoffrey and Northumberland Formations may be zones of preferential groundwater flow, often associated with springs and groundwater seepage along cliffs around the island shores.

1.3.2 Confining Units

Confining units are those hydrogeological units which transmit groundwater slower than other adjacent units. The differences are due to different lithology and types of fractures present in the rock and the fracture properties such as fill or alteration of the rock. Groundwater may be “perched” and flow on top of confining units (with unsaturated conditions below the confining unit), or flow laterally along such units rather than vertically through them. Confining units may also prevent groundwater discharge or slow it down such that water pressures are greater under such units than above. Sometimes flowing artesian pressures may develop where groundwater flows out of drilled wells or from springs tapping fractures through confining units.

Confining units may also be present on top of bedrock and reduce recharge to groundwater from rainfall. Clayey sediments are present in glacial till in some areas of Gabriola Island. It has relatively low permeability compared to fractured rock. There are only pockets of clayey till on Gabriola Island because most of it has been eroded and only bedrock remains.

1.3.3 Faults

Faults may be either very conductive to groundwater flow along the fault or act as barriers to flow across the fault plane. In the latter case, the fault zone may be very conductive to flow parallel to the fault but not across the clay-gouge filled fault. On the Gulf Islands, the fault properties are only known at outcrops and the drilling methods usually employed produce rock chips and no complete core, so the properties of faults are largely unknown. In the mining industry, the testing of faults involves expensive test methods (i.e.: drilling and injection packer testing, large scale pumping tests, multi-level observation well installations).

1.4 Hydraulic Properties of Fractured Rocks

The bulk properties of fractured rock in this report assume that the hydraulic tests are conducted in an equivalent porous medium. This means that the fractures and unfractured rock are considered together (an ensemble) and the fractured medium has equivalent set of hydraulic properties. Pumping tests yield values of transmissivity and storativity for tests done in confined aquifers, and transmissivity and specific yield for tests done in unconfined aquifers. Hydraulic conductivity can be determined from transmissivity if the effective aquifer thickness (or test zone thickness which is being tested) is known. Similarly, the storativity value can be converted to a specific storage value if the effective aquifer thickness is known. The most common parameters are listed in Table B-1.

In the published reports, most results show transmissivity values and a few results show hydraulic conductivity, and others only report specific capacity values. Specific capacity is a measure of how much drawdown there is at a particular pumping rate. Values of the properties come from local and regional sources:

- regional summaries of hydraulic tests on all of the Gulf Islands used in various reports (these include pumping tests done on MOE observation wells)
- discrete fracture models of other Gulf Islands with similar fractured rocks to Gabriola Island
- pumping tests in test holes on Gabriola Island for a proposed residential subdivision (Piteau, 1993)
- tidal analysis in residential wells along ocean shores on Gabriola and Mudge Islands (SRK, 2012 – this report)

Table B-1 Hydraulic parameters measured in hydraulic tests

Symbol	Parameter Name	Description
k	intrinsic permeability	the most basic property of rock's ability to transmit fluid of a given viscosity, such as water; it is based on Darcy's Law for flow of fluids through porous media and in this form it is usually measured in research projects or where different fluids may be flowing
K	hydraulic conductivity	the most useful measure of rock's ability to transmit water, per unit thickness of hydrogeological unit (K = T / aquifer thickness); it is a proportionality constant for flow of water through porous media (it is derived from intrinsic permeability value but for water only)
T	transmissivity	the usual result of pumping tests and other analyses, the ability of rock unit to transmit water over its entire thickness (e.g. aquifer thickness)
S	storativity	the storage property of aquifer, calculated from drawdown in observation wells around pumping well
Ss	specific storage	the storage property of aquifer per unit thickness of hydrogeological unit (Ss = S / aquifer thickness)
Sy	specific yield	how much water can be drained from unconfined aquifer when it dewaters by a unit metre of water level; this parameter is needed for estimating recharge using the water table fluctuation method
SC	specific capacity	determined during step tests and a useful measure of what pumping rate can be maintained in a well
	long term water yield	a useful indicator of productivity of aquifer, and indirectly, its permeability

1.4.1 Hydrogeological Assessments of the Gulf Islands

One of the first detailed groundwater studies was by Dakin et al (1983) on Mayne Island, which has similar geology to Gabriola Island. The hydraulic conductivities of the fractured bedrock were considered to be affected by presence of secondary mineralization encountered in fractures and by the presence of shale interbeds found in most sandstone units. This suggests that shale interbeds were seen as aquitards in that case. The report quoted results of tests for porosity and intrinsic permeability of Nanaimo Basin sandstone sediments from earlier investigations and other unpublished reports. Based on these data, the hydraulic conductivities of sandstone ranged between $1x10^{-7}$ m/s and $3x10^{-6}$ m/s and the average porosity was about 6%. Data from pumping tests in wells gave apparent hydraulic conductivities in the range $1x10^{-7}$ to $1x10^{-6}$ m/s. To put these values into more practical terms, the upper range of these values suggests a typical “moderately” productive fractured rocks aquifer (good for residential wells but not high enough for large industrial pumping wells or city water supplies). The lower range of those values indicates a poorly productive aquifer that can be pumped, but only at low pumping rates, and it may need more time to recharge between pumping cycles. The storativity coefficient was assumed to be $1x10^{-4}$ which was used previously for similar study on Mayne Island.

Hydrogeological studies on The Gulf Islands by Simon Fraser University produced summaries of hydraulic parameters for The Gulf Islands. The summary from a report to MOE by Allen et al (2003) is reproduced here. The transmissivity values for various geological formations (not for individual islands) and types of tests are shown in Table B-2 and the storativity values are in Table B-3. The data show that there is large variability in results, as is typical for fractured rock aquifers, but most transmissivity average values are near $1x10^{-5}$ m^2/s. Hydraulic conductivity values may be similar or may be lower, depending on the assumed aquifer thickness, which was influenced by the test. SFU also conducted discrete fracture network modeling using the measured properties of fractures on several of the Gulf Islands. Typical hydraulic conductivity were in range from $3x10^{-6}$ to $1x10^{-7}$ m/s, which is similar to the averages calculated from tables by Allen et al (2003).

Table B-2 Transmissivity (m^2/s) values from pump tests on all of the Gulf Islands, with summary statistics by geological formation (from Allen et al, 2003).

Geological Formation:		Gabriola	Geoffrey	Spray	DeCourcy	Cedar District
Long Duration Tests (Drawdown)	# tests	12	13	3	4	2
	Geomean	**2x10-5**	**5x10-5**	**1x10-5**	**5x10-5**	**3x10-5**
	Range	$2x10^{-6}$ to $6x10^{-4}$	$5x10^{-5}$ to $8x10^{-4}$	$3x10^{-6}$ to $5x10^{-5}$	$4x10^{-5}$ to $7x10^{-5}$	$1x10^{-5}$ to $6x10^{-5}$
Short Duration Tests (Drawdown)	# tests	61	9	5		
	Averages	**6x10-6**	**1x10-5**	**5x10-6**		
	Range	$3x10^{-7}$ to $5x10^{-2}$	$1x10^{-6}$ to $7x10^{-5}$	$8x10^{-7}$ to $4x10^{-5}$		

Table B-3 Storativity values from pump tests on all of the Gulf Islands, with summary statistics by geological formation (from Allen et al, 2003).

Geological Formation:		Gabriola	Geoffrey	Spray	DeCourcy	Cedar District
Long Duration Tests	Geomean	**$3x10^{-2}$**	**$1x10^{-4}$**		**$4x10^{-4}$**	
	Range	$2x10^{-2}$ to $4x10^{-2}$	$4x10^{-5}$ to $4x10^{-4}$		$3x10^{-4}$ to $6x10^{-4}$	
Short Duration Tests	Geomean	**$2x10^{-5}$**	**$1x10^{-4}$**			
	Range	$2x10^{-7}$ to $4x10^{-2}$	$9x10^{-5}$ to $3x10^{-4}$			

The lack of significant differences between the averages for different geological formations was unexpected and does not agree with some observations of groundwater seepage, or the shape of water table on Gabriola Island. However, Allen et al (2003) reported that many of the well tests had been done in wells that were strategically drilled near fracture zones, so that the results may be biased to yield higher transmissivity values that might be measured away from fracture zones. Wells were assigned to various geological formations based on surficial geology maps and recorded lithology in the well record. It is likely that the average transmissivities for rocks on Gabriola Island are of the same order of magnitude (not exactly the same values).

1.4.2 Test Wells by Piteau Associates (1993) on Gabriola Island

The largest testing program on Gabriola Island was done in 1993 by Piteau Associates. Tests were done in 6 wells in a planned subdivision owned by Weldwood of Canada Ltd. in north-central part of the island. Eleven exploration boreholes were eventually drilled and a brief geological and geophysical survey was done to locate largest fracture zones. All boreholes which intersected the regional fracture zone had relatively high initial yields (over 1.4 L/s), but after conducting detailed hydraulic analyses, the sustainable yields were determined to be about half of these values. This drop in yield was a consequence of the fracture zone being only moderately permeable and there being a high degree of mutual interference between wells located along the regional fracture zone, although pumping within the fracture zone does not seem to affect wells further away from this zone. There was also an unsuccessful attempt to hydro fracture wells TH-9 and -10 to increase yield. Well lithologs and cross-sections were produced and these data were used in updating the three-dimensional geological model in this report. Data from this testing program are somewhat biased toward the more permeable fracture zones and not a random sample of Gabriola Island rocks. The water producing fractures in these wells are in the Geoffrey Formation.

Results of this test program are shown in Table B- 4. The transmissivity values are in the same range as the summary tables by Allen et al (2003) although the regional summary was done by geological formation and not by the whole island.

Table B- 4 Transmissivity (T) and Specific Capacity Values from Pumping Tests on Gabriola Island (Piteau, 1993).

Test Hole	Pumping Rate (L/s)	Transmissivity (m^2/s)		Specific Capacity (L/s/m)
		Pumping	Recovery	
TH-1	0.5	$2x10^{-6}$	$3x10^{-6}$	~0.01
TH-2	1.2	$7x10^{-6}$	$1x10^{-5}$	~0.04
TH-3	1.2	$2x10^{-5}$	$2x10^{-5}$	~0.01 (pumping at 0.4 l/s)
TH-9	0.35	$4x10^{-6}$	$3x10^{-6}$	N/A
TH-11	0.35	$8x10^{-6}$	$8x10^{-6}$	N/A
TH-5 when TH-3 pumped	1.4	$6x10^{-6}$	$1x10^{-4}$	N/A

1.4.3 Tidal Analysis by SRK (2012)

SRK monitored water levels in 10 residential wells in August 2012, and one well on Mudge Island in October 2012, to determine tidal fluctuation in the aquifers and to calculate aquifer hydraulic diffusivity (T/S) from tidal analysis. The methodology and results are described in Appendix C.

The results showed that the diffusivity of aquifer has a large variation on Gabriola Island. Tables of results are provided in Appendix C. The largest diffusivity and transmissivity are near large fracture zones in sandstone. The smallest values are in sandstone or shale.

Transmissivity (as an indicator of permeability) was estimated by assuming a reasonable value of storativity of $1x10^{-5}$ for Geoffrey Formation sandstone. This value is the upper range of storativity calculated for four wells on Gabriola Island, by solving from hydraulic diffusivity ratio and transmissivity, where the transmissivity value was previously calculated from pump tests. The estimated storativity values range from $1x10^{-6}$ to $1x10^{-4}$ (see Appendix C for details). This is consistent with expected storativity magnitude for this fractured rock, and $1x10^{-4}$ to $1x10^{-5}$ values are typical of Geoffrey Formation on the other Gulf Islands (Table B-3). However, these values may not represent the whole of Gabriola Island.

A map of all available tidal analysis points and pumping test locations in wells and resulting diffusivity and transmissivity values are shown on Figure B-2. Compared to averages for all The Gulf Islands, Gabriola has slightly lower transmissivity at the pumping test locations, but this difference may not be significant and it is unknown how representative the Piteau (1993) tests are for the whole of Gabriola Island. Test results will also vary depending on what unit was tested (depth of well) and proximity to large structures. Given that Piteau test holes were targeting the most permeable structures in that area, the true average of all rock formations on Gabriola Island is likely smaller by an order of magnitude (around $1x10^{-6}$ m^2/s transmissivity and less than $1x10^{-7}$ m/s hydraulic conductivity). Large fracture zones will have properties perhaps similar to those reported by Piteau.

Most of these wells are completed in the Geoffrey Formation or in the Northumberland Formation. The wells are not screened except for shallow surface casing. Wells are typically drilled until significant water source is found, although water can enter the well from all fractures along its length.

1.4.4 Aquifer Vulnerability Mapping by the GSC and SFU

Denny et al (2007) (GSC and SFU) mapped aquifer vulnerability in this region using a modified DRASTIC method (DRASTIC FM – to account for fractured media). The same data summaries were used as in previous SFU studies and no new wells had since been tested. However, it is important to mention these reports because regional averages by geological formation were used in calculations of aquifer vulnerability. There was also good conceptual model review work done during those studies. The hydraulic conductivity values were in range of $5x10^{-7}$ to $5x10^{-5}$ m/s.

1.4.5 Unconfined Aquifer Properties

The groundwater flow process through the unsaturated zone of an aquifer has additional considerations which were not covered in this report. The recharge percolation seems to be relatively rapid through sandstone units because of large sub-vertical fractures. In mudstones, vertical flow is likely much slower as suggested by the shape of water table and many perched ponds and lakes on top of mudstone outcrops.

One very important parameter for recharge estimation is the specific yield, which is a storage parameter of an unconfined aquifer. This value is difficult to determine for Gabriola Island, and indeed for all the other islands, and values are likely somewhere between 0.05 and 0.01, but locally Sy can be much lower where blocks of rock are not highly fractured. Sy represents the volume of groundwater which can drain or fill one cubic meter of fractured rock in this aquifer. The volume of space in open fractures is very small in most rocks because the number of fractures is either small in sandstone or the more densely fractured shales have very small fracture aperture (very tight fractures). Most of the volume of rock is solid rock. Sandstones can have various degrees of cementation of the sand grains but this porosity drains much more slowly and is of less practical consideration than the larger and faster draining or filling fractures.

1.4.6 Water Yields in Wells

Water yields are a useful indirect measure of aquifer productivity. The values in MOE well database were extracted after many queries of different data sets. Some well yield information was located in different tables or as comments in well lithologs. Well yields are a useful indicator of aquifer productivity, but also may be too high in some wells because the initial ("blown yields") were recorded for many wells by drillers. It is normal to see much higher yield initially and then much lower yield later as the local fracture network dewaters or depressurizes and a steady-state flow is approached into well from a larger aquifer area. A long term well yield is the preferred estimate, not the initial yield.

Assuming the reported well yields are reasonable and comparable, the complete well yield data set was plotted in Figure B-3 on a surficial geology map. Wells with higher yields are clustered in some areas, but there is a high variability in well yields. The distribution of wells is very uneven. There is no clear correlation with the surficial geology map, and no relationship was expected given this type of fractured, layered, and folded geology. There is a suggestion of higher yields along large fault zones, but nothing definitive arose from the analysis of this noisy data set. Some correlation with fault zones was expected.

On Gabriola Island, the most productive areas appear to be in:

- north and south shore of Gabriola Island east of Lock Bay where the Northumberland Formation outcrops; this is a very productive hydrogeological unit
- fracture zones near intersections of major faults in some areas
- area east of Taylor Bay and south of Descanso Bay

As shown in Caine et al (1996), no correlation was found in a regional study between well yield and proximity to fracture zones in a regional study, even after the removal of wells with a low locational accuracy, and the separation of fractures in sedimentary and igneous or metamorphic rocks. Well yield information alone cannot explain the effects of faults on groundwater flow.

2 Groundwater Flow

2.1 Average Water Table

2.1.1 Data and Methods

In the MOE wells database there are hundreds of wells with “static” water levels, usually recorded as an observation during the drilling and testing process. A map of all these locations is shown in Figure B-4. The wells are clustered in more densely populated areas and are not evenly distributed across the islands. There are very few wells in the middle (uplands) of Gabriola Island.

There are numerous data quality problems with static water levels in MOE database. Many nearby wells show inconsistent results. The most common problems with these water levels are, in order of importance:

- well positional accuracy is usually poor, such that well locations were entered in MOE database from property mid-points and not actual well locations; this results in large error of well location and because well collar elevation was calculated based on well location and the digital elevation model, many well collar elevations have errors of <1m to >20m (especially where wells are near cliffs)
- very few well collars were surveyed
- water level was recorded either during drilling when the well intercepted water bearing fractures, or at the end of drilling, and is not a measured static water level
- water level may not have been given sufficient time to recover following drilling completion
- well water levels were recorded in the past in feet and recently in either feet or metres and there may be errors in unit conversions in the database
- well may be influenced by nearby pumping
- wells drilled in various seasons and water levels fluctuate seasonally by a few metres

The water table was shaped manually by a hydrogeologist using three-dimensional shaping software (AquaVeo, 2012) to make the surface while viewing all data and all geological units. The surface was shaped mostly from water levels in residential wells and the few observation and test wells present on Gabriola Island. Surface water bodies such as lakes can be assumed to be connected to groundwater table, or at least one such water table. Lake elevations were taken from the digital elevation model and were also added to the water table surface. The surface was also constrained to be below ground surface and be equal to zero elevation along ocean shores.

An average water table can be fitted to all observations by using an approach which uses the values of the majority of wells within a small area and rejecting wells with inconsistent levels in that area. Anomalous levels were considered carefully, and often the surface was shaped as an average of various measurements if there was no clear solution. Many iterations of manual shaping and adjustment were made, area by area across the island, and by considering the island as a whole. The hydrogeological units were also considered to make interpretations.

The amount of data on Mudge and DeCourcy Islands is much less than on Gabriola Island. Those islands have a few clusters of wells. The water table was shaped so that the island centre would have the highest water level, and generally follow land topography, guided by the few available water levels in wells.

2.1.2 Results

The average water table map is shown in Figure B-5 for the whole of Gabriola Island, and Mudge and DeCourcy Islands. There is more new detail in these maps than in previously available maps. The water table is consistent with most of the water levels, including latest observations, lake levels, and the most recent elevation models of the islands. Three other maps consider the same average water table but show more detail for parts of Gabriola Island. Figure B-6 shows the north-western part of Gabriola Island, Figure B-7 shows the eastern Gabriola Island, and Figure B-8 shows the south-central Gabriola, Mudge and DeCourcy Islands. The actual water levels are locally more complicated than shown and there may be locally perched water tables present, although these are not likely to be very extensive.

The water level generally follows the land topography on Gabriola Island. The highest water level was interpreted to be in the middle of Gabriola Island at elevation of just over 130m asl. The areas of land with many bays and peninsulas on western and eastern shores of Gabriola Island have water levels a few metres above sea level and some areas are close to sea level, despite 10 to 20m high cliffs present in some shores. Close to the ocean shores, the groundwater table surface shape does not follow land topography. Wells drilled on cliffs along ocean are necessarily deep to reach the water table (a seepage face may develop along these cliffs near the base).

There is apparently also a strong influence of geological units on groundwater levels. Perched water tables may occur where there are confining layers. For example, the water level on top of the Spray Formation shale is likely perched in some places, especially near cliffs. Hoggan Lake sits on top of the Spray Formation shale and does not drain to the sea completely. It may also be underlain by clay sediments which could slow down the leakage of water, although no cores have been taken in the lake to verify sediment type. The lake receives seepage and surface water from a small catchment and the inflow is sufficient to maintain the lake volume. The lake likely does loose some water as groundwater outflow through the shale rock below it, but it must be smaller than the inflow to lake. In sandstones, pockets of discontinuous fracture networks might be saturated but not drain easily and thus hold water above the average water level of a surrounding larger area.

Depth to water is useful to consider when planning to drill water wells and provides some insight into groundwater conditions. It was calculated by subtracting the average water table surface from the ground surface and results are shown in Figure B-9. At all well locations where there is information about depth to water, the depth to water value is colour-coded using the same colour scale as the depth distribution map to indicate data variability. At most locations the water table is 3 to 10m below ground. There are some locations along the edges of the Gabriola Syncline where depth to water is larger than 20m, and up to 50m in some locations. These are topographic highs (tops of cliffs), which have deep wells that show different, and lower, water levels than the shallower nearby wells. These areas near high cliffs are where there is a separation of water tables, a shallow one perched along the shale layer and a deeper one in underlying sandstone which has water level closer to sea level.

2.2 The Depth and Shape of Freshwater-Saltwater Interface

The density-dependent flow process and the formation of fresh-water lenses under islands and fresh-salt water interfaces along continental coasts are very important aspects of coastal hydrogeology. There have been many studies in many regions (e.g. Barlow, 2005), including some work done on the Gulf Islands in British Columbia (e.g. Allen et al, 2002; Allen and Liteanu, 2008, SRK & Thurber Engineering, 2008).

Over the last 5,000 to 12,000 years there have been large sea level changes on the coast of B.C. caused by glaciation and deglaciation and melt of ice. The combined effect of crustal adjustment to ice loading, global sea level change, and sea level change due to tectonism were the causes (Clague, 1983; Clague and James, 2002, Earle, 2002). These relative changes in sea level caused sea water to intrude and saturated the aquifer over a period of about 500 to 1,000 years (a relatively rapid process on geological time scale) according to simulations by Allen and Liteanu (2008).

This process has been shown to be generally consistent with the current chloride (an indicator of salinity) distribution with depth through the use of 3-D density-dependent numerical models by Allen and Liteanu (2008) in a case study of Saturna Island on the Gulf Islands. The simulation results showed that where the Gulf Islands coastlines were submerged by sea water after a sea level rise, it takes less than 1,000 years to “fully” saturate the aquifer with saltwater. This does not mean that the whole of large islands were submerged, but large parts at elevations less than ~200m were. Following isostatic land rebound and a drop in sea level, with the application of fresh recharge from rainfall to the island surface, the models predicted that steady-state conditions (the present hydrogeological system) were achieved within a period of about 1,000 years. Therefore, in the past few thousand years the hydrogeological system was most likely in close to steady state on time scale longer than annual, and only the cyclic seasonal and short term random variations of water levels occurred. While there is uncertainty in the timing of these submergence and re-emergence responses due to uncertainty in recharge and the aquifer properties used in the models, the history of salinization is realistic and explains the geochemical and isotopic composition observed on the Gulf Islands (Allen and Suchy, 2001; Allen, 2004; Earle and Krogh, 2004).

2.2.1 Steady-State Conditions

Under steady-state conditions (long-term equilibrium conditions), the position of the freshwater-saltwater interface is important for assessing the potential for saltwater upconing under pumping wells and lateral saltwater intrusion, as well as for estimating total groundwater storage. In theory, on oceanic islands the fresh water depresses and displaces the salt water beneath it forming a profile that has the appearance of a lens. In an unconfined aquifer, the theoretical freshwater lens geometry, depth to the freshwater saltwater interface (F) is related to the observed top of the freshwater lens through the Ghyben-Herzberg formula:

$$z = \rho_w / (\rho_s - \rho_w) * h$$

$$= 43.47 * h \quad \text{(if sea water density is 1.023 kg/m}^3\text{ near the Gulf Islands)}$$

where z is the depth to the saltwater interface below sea level at location (x,y), h is the elevation of the water table above sea level at point (x,y), ρ_w is the density of fresh water, and ρ_s is the density of salt water.

Where the calculated depth of fresh-salt water interface is very large, other effects take over. In deep fractured rocks there are very old groundwaters, usually brackish or briny. The groundwater flow system described in this report is a shallow one on the scale of hundreds of metres depth or less. In most rocks the hydraulic conductivity and fracture occurrence tends to decrease with depth in bedrock. At large depths the flow of groundwater is much slower and is influenced by density dependent flow and hydrothermal effects, and the assumptions of rock properties found near ground surface do now hold for very deep rocks.

The results of calculation are shown on Figure B-10. Only near shores is the depth to salt water relatively shallow, and the depth of freshwater lens increases rapidly away from shores. The theoretical depth of fresh water lens under Gabriola Island is very large, and for practical purposes there is no sea water under the middle of Gabriola Island. For example, a water table position of 25m above sea level results in a calculated depth of freshwater lens of hundreds of meters, however, this is a theoretical result and there will be mineralized and saline water at much shallower depth. Results are discussed further in main report section.

2.2.2 Salt Water Intrusion

One of the most common water quality issues on the islands is salt water intrusion. If the pump screen is connected to the ocean shore with large enough fractures, the salt water may be induced to flow toward the well to replace the pumped out fresh water. This flow occurs laterally through permeable zones in the bedrock. Saltwater intrusion, however, may also occur vertically by upconing, which draws salt water upwards as a result of lower hydraulic heads near the well. (i.e. a cone of depression). Thus, a group of wells may cause a larger displacement of freshwater by sea water, laterally and vertically. It is difficult to determine which process is occurring during salt water intrusion without many test wells and measurements. However, Allen et al (2002) observed direct connection to the ocean in a well via a single fracture. Once saltwater intrusion occurs, the natural flushing of salt water back out is a long process and may take years to hundreds of years, depending on the situation. In areas such as small peninsulas or areas with very limited natural recharge from precipitation (sometimes because of geological reasons), saltwater intrusion may be practically irreversible and worsen with continued pumping.

On Gabriola Island, where saltwater intrusion has occurred due to pumping near shores (shown on Figure B-10 from 1978 data by Hodge), the concentration of sodium and chloride is higher than normal, although the concentrations are usually much less than in sea water. It is not clear if there are any trends of salt water intrusion over the last 30 years, but there is some evidence from interviews of residents at tidal test well locations in 2012 by SRK that more wells near shores became salty in some areas.

In some sections of island shores, the local geology creates favourable hydrogeological conditions with strong hydraulic gradients towards the shore acting against saltwater intrusion during pumping, discharge of groundwater towards the shore, and semi-confining units present at depth which resist the upconing and lateral intrusion of seawater. Many shoreline pumping wells are productive and have good quality water (north-central shore of Gabriola Island).

2.3 Water Level Fluctuations with Time

2.3.1 Provincial Observation Wells on Gabriola Island

There are four active Provincial observation wells on Gabriola Island, and none on Mudge and DeCourcy islands (Table B- 5). There are also records from four de-activated observation wells on Gabriola Island. These wells provide frequent water level measurements done by chart recorders or other sensors.

Table B- 5 Provincial Observation Wells on Gabriola Island.

Obs. Well #	Status	Well Tag #	Old Obs. Well	Road	Elevation	Depth	UTM Easting	UTM Northing	Record Period	
					(masl)	(m)	(m)	(m)	From	To
196	Active	26709	72-1	Buttercup Rd.	~99	99.1	441325	5446840	Oct 1, 1973	present
197	Active	37811	72-4	North Rd.	~84	83.8	444207	5445122	Aug 1, 1973	present
385	Active	102208		Horseshoe Rd.	~57	43.4	439739	5447869	Jul 9, 2010	present
316	Active	7895		Oyster Way	~46	12.8	444003	5443150	Sep 2, 1992	present
194	Deactivated	26710	72-3	North Rd.	~80	76.2	438536	5447157	Aug 1, 1973	2007 (no reading after)
317	Deactivated	26350		Wild Cherry Terrace	~39	21.3	442403	5446900	Sep 2, 1992	Nov 17, 2011
	Deactivated		72-2		~37	83.8	447533	5444900	1972	1972
	Deactivated		72-5		N/A	99.1	N/A	N/A	1973	1977

The MOE site warns the user of the following caveats when using the data:

- "Some of the data you have selected has not been verified, and may be wrong."
- "It is not uncommon for individual monitors to give false readings due to temporary local conditions, and on occasion the readings can be grossly inaccurate."
- "To view the data you must accept all responsibility for its use and interpretation."

Water level records were downloaded from the MOE website in form of depth to water. Depth to water was converted to water level relative to local datum (usually taken as the minimum water level on the record for each well) to show only the magnitude of variation and to compare all records together. Each well is located at a different elevation and the water level is at some different depth below ground in each well. The water levels for each well were plotted as relative to local datum to enable comparison of all records together in Figure B-11.

2.3.2 Observed Water Levels

At all Provincial observation wells, the water levels have a dominant and cyclical variation each year, which is related to seasonal precipitation pattern. The lowest water levels occur at the end of summer and the highest water levels occur in autumn and winter when rainfall is abundant. The magnitude of seasonal variation of water level is relatively small, less than 4 metres from minimum to maximum. The smallest seasonal variation is in Provincial observation wells 194 and 317, where the range of variation is only 1.5m. Slightly larger seasonal water level variation occurs in Provincial observation wells 196, 197, 316 and 317.

Water level change is remarkably small compared to amount of precipitation falling on the island. There is lag time from the onset of autumn rain events to water level rise. The time lag is difficult to determine precisely without a time series analysis (not done in this report), but it is about 5 to 10 days when it can be seen with single rain events. Wells 194, 196, 316, 317 respond rapidly to large rain events (example is shown in year 2003), and well 197 has very small response to rain events and only very large ones.

The changes in water levels are closely related to precipitation at Gabriola weather station (Environment Canada, 2012) at approximately weekly time scale (weekly and monthly precipitation was plotted). This correlation of water level and precipitation is shown graphically in data from well 194 in Figure B-12. Daily precipitation has only clear correlation if the rain events are very large and is not shown here. The choice of weather station does not change the conclusions and the same pattern is observed if the Nanaimo weather station data are used or data from any other nearby weather station.

The water level records have some small inter-annual variation, but the average from year to year does not exceed 1m variation. The minimum or maximum levels in some years are lower or higher and there are some trends of slight change in the extreme water levels. The trends are inconsistent between the Provincial observation wells so there is no suggestion of any long term change on Gabriola Island as a whole, only some local temporary changes which may have various causes.

- Provincial observation well 194 has been deactivated since 2007. There are some random changes from year to year until 2002 when the recorder was changed from monthly to hourly measurements (Figure B-12). The maximum water levels did not change, but the minimum water levels are lower by 0.5 to 1m from 2002 to 2007 than in previous years. There is a commercial water supply well within 500m of this observation well which pumps about 30% of the total for all wells in that area according to Groundwater Solutions (2007). Without good pumping rate records and dates of installation it is not possible to determine any interaction with observation well 194. The record ends in 2007 or the data have not yet been published for later years.
- Provincial observation well 196 is active and has water level record since 1973. The water level variation has been slightly larger in some years but the recorder was also changed to allow for more frequent measurements after 2005, with small shift of measurement datum. There is no consistent trend over last 40 years (Figure B-13)
- Provincial observation well 197 is active and has a water level since 1973. There are shifts in the water level record for unknown reasons which are not related to changes in precipitation nor correspond to changes in other observation wells (Figure B-14). The shifts might be due to changes in data recorder or local pumping effects.
- Provincial observation well 316 is active and has a water level record since 1992 and it has a typical seasonal variation of 4m between minimum and maximum values each year (Figure B-15). There is no consistent trend in last 20 years.
- Provincial observation well 317 is deactivated and has a short and discontinuous record with relatively small seasonal variations (Figure B-16).
- Provincial observation well 385 is active and has only a recent record in last two years and about 4m seasonal variation in water level (Figure B-16).

2.4 Seasonal Change in the Volume of Stored Groundwater in an Aquifer

The seasonal change in groundwater volume was estimated by from the average seasonal water level variation, and an assumed range of specific yield values, and area of each island.

In this type of setting, the water level fluctuation is very rapid. Water infiltrating from precipitation does cause a groundwater level change but the aquifer drains very rapidly to ocean shores. The recharge rate can be estimated from the water level fluctuation, but it will certainly underestimate the actual recharge rate. Here, the water level fluctuation was used to estimate the low estimate of an unknown recharge rate. The actual recharge rate will be higher.

The fluctuation of groundwater level occurs much more rapidly during rain storms and also continues to drain and decrease the water level soon after each rain event. Therefore, the actual amount of precipitation required to raise and maintain the high water levels during winter is higher than 7% recharge rate. Next section discusses the recharge and discharge processes.

2.5 Groundwater Recharge and Discharge Processes

Total recharge rate from rain events has two “conceptual” components, which are useful for thinking about the water balance:

1) recharge, which is converted to change in groundwater storage as observed by a rise in water level following a rain event

2) recharge, which flows through the aquifer and maintains existing hydraulic gradient (and water levels) and does not cause an observed change in water level

The higher the hydraulic gradient in aquifer, the greater the recharge rate needed to maintain it at steady state. If recharge stops, the aquifer continues to drain and water levels begin to decrease (water leaves storage) until a new steady state is reached.

Recharge is variable in space and may be low in some areas and much higher in other areas. Higher than average precipitation may occur in the uplands in central Gabriola Island due to orographic effects, but the elevation difference is only 150m, so the effect is probably small. The regional precipitation gradient near Gabriola Island are described in Appendix D.

The most likely conceptual model is that of sandstone and mudstone aquifer, and some less transmissive mudstone layers forming aquitards, both shaped into a U-shaped syncline structure. The shale units may have some anisotropy as a whole if there are clay alteration “layers” present (as if seen in the Northumberland Formation). The present conceptual model of three-dimensional groundwater flow is not confirmed.

The aquifer fills and drains rapidly as observed. In its “drained state” at end of summer, the water table is not flat, it is very stepped and follows roughly the island topography, suggesting that water may be either perched in the unconfined aquifer or drain slower through underlying shale layers.

2.6 Surface Water Runoff

There is a significant amount of surface runoff during the rainy season on Gabriola Island. The most thorough description of surface streams and lakes and their flows is in a report by Welyk and Baldwin (1994), but local observations are also very important. The island is covered with small creeks which flow for a period of a week or two, and then dry up again until the next rainy period. Most larger streams do not flow during July and August of typical years. Many streams also stop flowing in June and from September to October period. Many small streams drain into the subsurface (few metres to 20m below ground), flow through fractures, and discharge again at lower elevation as a spring. Small springs feed the streams but most springs are ephemeral. The largest surface water body on Gabriola Island is Hoggan Lake (25.1 hectares). There are numerous smaller ponds present on the southern slopes of the island. Hoggan Lake was dammed in 1900's, forming a shallow lake over existing wetland. Lake depth was reported in 1978 as ~12m). The lake lies on the private property of Wildwood Estates. There was a flow gauge installed by Water Survey of Canada from 1972 to 1978 (08HB046), and a water level gauge data are also available from 1978 to 1979 (08HB053).

For the discharge gauge, the peak hydrograph was at approximately 0.35 m^3/s during the winter rainy season, followed by a recession of flow in spring, and a dry period with no flow from August to October (Welyk and Baldwyn, 1994). The mean annual discharge was 0.176 m^3/s with mean annual runoff of 531mm and drainage area of 6.48 km^2. This is the only catchment scale runoff estimate on Gabriola Island and it shows that runoff is about 60% of annual precipitation. With a large evaporation rate for the Gulf Islands region, the recharge rate is not expected to be very large on average. The next section discusses recharge quantities.

2.7 Methods of Estimating the Recharge from Precipitation

There are annual recharge rates estimated using different methods:

- Hydrological analysis at catchment scale from baseflow measurements in streams draining the catchment
- Water Table Fluctuation (WTF) Method of water fluctuation in observation wells and precipitation events (Appendix D in this report)
- Numerical models of water infiltration in one-dimensional soil column (regional estimates for the Gulf Islands, e.g. Appiah-Adjei, 2006)
- Recharge rates used in a calibrated 3-D numerical groundwater flow models on other Gulf Islands (Allen and Liteanu, 2008)
- Recharge rates estimated through water fluctuation and water balance for the Gulf Islands: James Island near Sydney, BC (SRK & Thurber Engineering ,2008)

2.7.1 Hydrological analysis

In many aquifers the hydrological analysis of baseflow discharge in streams and catchment water balance can provide a good estimate of recharge to aquifer. This method works in some regions but on the Gulf Islands there are very few streams and most groundwater seeps out to sea along shores and cannot be measured. Therefore, the most useful method of estimating recharge is not applicable on the Gulf Islands.

2.7.2 WTF method

The WTF method (see Healy, 2010) is useful in unconfined aquifers that have no other contribution to the water level and where the monitoring wells are in recharge areas. It may provide the only estimate of recharge in areas where there are no baseflow discharge data. This method is very good at estimating temporal changes in recharge or how much (relatively) recharge occurs and when, and how it is related to observed precipitation. However, the absolute value of recharge, its magnitude, depends on a realistic storage coefficient (e.g. specific yield) of the aquifer, which is very difficult to estimate for fractured rocks. On the Gulf Islands, this method will underestimate the actual recharge.

Water level records from selected Provincial observation wells on Gabriola Island were used in this analysis. The precipitation data were daily precipitation at Gabriola Island weather station (Environment Canada, 2012). Examples of selected rain events are shown in Figure B-17 and Figure B-18.

The water level fluctuation method (e.g. Healy, 2010) was used first used to estimate recharge to groundwater storage on Gabriola Island. The value of calculated recharge rate (R) in this method depends directly on the assumed value of specific yield (S_Y). It is also directly related to the observed change in water level or hydraulic head (Δh) over some time interval Δt of one precipitation (rainfall and/or snowmelt) “event”:

$$R = S_Y \Delta h/\Delta t$$

The analysis can be done for any rain event, but rain events that are too small do not result (visibly) in a rise in water table and the water level fluctuation cannot be calculated (the effect is smaller than other trends and “noise” already present in water level record). Therefore, the most distinct rain events and corresponding clear increases in water table were selected for this analysis.

2.7.3 Infiltration column models

Another method is to use a numerical model of a vertical soil infiltration column to simulate the water balance in that column and the percolation of water to the water table (e.g. Jyrkama et al, 2002). The required inputs are precipitation and other weather data (temperature, humidity, etc.), soil and aquifer properties, runoff coefficients at ground surface, vegetation parameters, and other assumptions. This method has been previously used to link climate change models to recharge models for the Abbotsford and Grand Forks aquifers (Scibek et al, 2007; Scibek and Allen, 2006), and later the Okanagan Valley.

An MSc thesis by Appiah-Adjei E.K. (2006) also used the recharge modeling of Scibek and Allen (2006) and applied it to the Gulf Islands. This study estimated a maximum recharge rate of 45% of mean annual precipitation (MAP) for the Gulf Islands, with 5% surface runoff and 50% evapotranspiration loss, although results were spatially variable.

However, there are many limitations of using the infiltration column models in the Gulf Islands.

- The HELP infiltration model was developed for landfills and soils, not fractured rocks. It has infiltration flow parameters which may not apply to fractured rocks. In particular, the runoff coefficient may be wrong in the uplands of Gabriola Island where there are shallow soils and bedrock outcrops. Shallow lateral subsurface flow through soil and weathered bedrock is not accounted for and may be important on the Gulf Islands.

- This methodology did not include layers which give rise to perched water tables, which exist in some places on Gabriola Island. It can be considered the maximum recharge of the recharge zone where there are no low permeability soil or geological units which may reduce infiltration.
- The effect of soil cover and thickness and type of surficial sediments on infiltration of water to underlying fractured rocks is uncertain.
- The author concluded that this method may overestimate recharge, although such high recharge rates are supported by some studies in Europe (Allen pers. comm.) and numerical flow models of the Gulf Islands.

2.7.4 3-D numerical models

A calibrated three-dimensional numerical flow model of a whole island can be constructed and calibrated to observations, and with some assumptions for the unknown parameters the recharge rate can be estimated during model calibration assuming the hydraulic properties are reasonably constrained. Numerical modeling has the same limitation of non-unique solution or solutions because it is sensitive to the storage parameters and the transmissivity parameters and aquifer geometry. A steady state solution will not be sensitive to storage parameters but it cannot simulate the seasonal variation of recharge, which is the dominant process here. Transient simulations are better but require more data to calibrate. Numerical 3-D flow models of the Gulf Islands are further complicated because of density-dependent flow processes and heterogeneous aquifers.

2.7.5 Regional studies based on regional precipitation and water balance

Denny et al (2007): Rates of net groundwater recharge were calculated using HELP model. Inputs into this model include climate data collected at the Victoria Airport meteorological station (800 mm/year) and the properties of surficial and bedrock geology sequences derived from the water well database. Results from the HELP model are non-spatial; therefore, model outputs were applied to soil polygons to create a spatially referenced recharge map (including Gabriola Island). Recharge rates in the region range from 102–533 mm/year (12% to 66% for different polygons).

Liggett and Gilchrist (2010): recharge to groundwater was estimated as in range of 103 to 178 mm/year based on regional modeled precipitation (from ClimateBC's PRISM data for 1961-1990 period), and assumptions about evapotranspiration using analytical formula. This represents recharge rate of about 10% to 20% of mean annual precipitation of 900mm/year. This study was done for the Regional District of Nanaimo, and Gabriola Island was only a small part of the coverage. The report compares the previous results of recharge distribution of Gabriola Island (Denny et al, 2007).

In other hydrogeological projects on the Gulf Islands, similar recharge values were determined (SRK & Thurber Engineering, 2008).

2.8 Results of WTF method for Gabriola Island

In this hydrogeological assessment, the WTF method was used to provide a minimum estimate of recharge from large rain events on Gabriola Island. The recharge value calculated in this method is directly proportional to the assumed value of specific yield; however, the representative value of specific yield is unknown for Gabriola Island as a whole. There will likely be zones of highly fractured rocks will have higher specific yield values and may receive more recharge. The overall representative average cannot be determined with this method on this island and the result can be considered the minimum recharge value of an uncertain range of recharge.

The analysis of water level fluctuations is useful in describing the response of groundwater levels to rain events. Following each rain event and spike in water levels, groundwater discharge rates increase and more groundwater seeps out to springs, surface streams, and ocean shores. Discharge to sea may be completely hidden from view, except where groundwater seeps from rock outcrops and onto shores.

During winter there is excess rainfall and this excess rainfall is not converted to higher and higher groundwater levels if rainfall increases. The seasonal maximum water level has a definite range of variation which is not related to how intense the rain storms are in autumn or winter. Wetter winters do not result in much more groundwater storage in the following summer, but only cause more runoff (discharge to streams/springs) and faster seepage to ocean because the infiltration rate to fractured rock has a definite limit.

Recharge is very low during the dry season because most of the rainfall evaporates from the soil and does not contribute significant recharge to aquifer. A late onset of autumn rains or a very long dry period does not result in significantly lower water levels in the aquifer because the natural drainage rate slows down as water levels decrease and the natural recharge and discharge is much larger than the pumping demand, except perhaps in some sensitive areas. All that is needed is a first large rain period and then enough rain events during winter to maintain the high water level (at 2 to 3m above the annual minimum during dry period).

Results show that during the first prolonged rainy period in autumn, the aquifer is recharged rapidly as a large proportion of the recharge is converted to replenishment of storage of aquifer (water levels recover). At most Provincial observation wells recharge value is between 1% and 20% for a range of specific yield between 0.01 and 0.001 (Figure B-19). For a specific yield value of 0.005, the recharge value is 10%. If only the larger estimates of specific yield are used, the resulting recharge at the monitoring wells is in the range of 10% to 20%, but it may be quite different in some parts of the island.

Another interesting finding is that calculated recharge rate depends on the absolute water level. This is shown in Figure B-20. Rainfall events seem to have greater effect on rising of water levels at the beginning of rainy season in autumn than during the middle of rainy season.

2.9 Recharge Range for Gabriola Island

Despite at least 15 years of studies of the Gulf Islands and the aim to determine the recharge rate, including some unpublished academic work (Allen pers. comm.), the uncertainty in the estimates for the recharge rate still remains. The potential range in hydraulic conductivity of fractured rocks is large, but groundwater flow models show that the recharge rate is much less sensitive and that it can be as high as 45% and the models still calibrate reasonably.

At this time the potential range of recharge on Gabriola and other the islands is between 10% and 45% of mean annual precipitation. Most evidence points to recharge of at least 20%.

The lower value of 10% is very conservative and it was estimated in some engineering studies on the Gulf Islands and on east coast of Vancouver Island in the rain shadow climatic zone. This value assumes a low specific yield, but this value is unknown and assumed.

A high recharge rate may exist but most of that water cannot be captured for storage and it drains quickly to the ocean shores. There are large fracture zones which may be preferentially collecting more water but also may drain quickly to the ocean.

2.10 Seasonal Change in Volume of Groundwater in Aquifer

The seasonal change in groundwater volume cannot be estimated reliably from the water level fluctuation method because the island aquifer continuously drains to the sea and the specific yield value is highly uncertain.

The annual recharge volume of groundwater can be calculated for a recharge rate (R) and an area of island (A):

$$\text{Volume of recharge} = R * A$$

This volume of recharge is large (Table B- 6), but most of it drains to the sea. The lower estimate of recharge volume is approximately $5x10^6$ m^3 (5 million m^3) for the lowest recharge rate of 10% of M.A.P.

The calculation for the upper estimate of volume of recharge was done for the upper limit of recharge estimates on the Gulf Islands (45%) to show the large volume of water which may be present (for water stress calculations a lower maximum recharge of 25% of MAP. was used). The maximum volume of recharge at the highest reasonable recharge rate is approximately $21x10^6$ (21 million m^3). Caution should be used for the maximum recharge estimate because the high recharge rate is unconfirmed.

The annual change in saturated volume (ΔS) of the aquifer is smaller than the annual recharge volume. The change in storage (as determined from water level fluctuation) is the product of specific yield (Sy), the average water level change (ΔH), and the island area (A):

$$\Delta S = Sy * \Delta H * A$$

Assuming that the average annual groundwater level change is 4m and the average specific yield is 0.01, the calculated annual storage volume fluctuation is $2x10^6$ m^3, or approximately one million cubic metres of water (Table B- 6). The volume for Mudge and DeCourcy Islands is approximately 90,000 m^3. The water fluctuation volumes underestimate the volume of groundwater available for pumping.

For water budget planning purposes, the conservative (low) recharge volume at 10% mean annual precipitation might be appropriate until the higher recharge rate can be confirmed.

Table B- 6 Annual groundwater storage volume fluctuation estimation for Gabriola, Mudge, DeCourcy Islands

Island	Area of Island (m^2)	Recharge Volume (thousands m^3/year)		Change is Groundwater Storage (thousands m^3/year)
	A	R min (10%)	R max (45%)	ΔS min
Gabriola	$5x10^7$	4,700	21,000	2,100
Mudge	$2x10^6$	200	900	90
DeCourcy	$2x10^6$	180	800	80

Storage change – annual.xlsx

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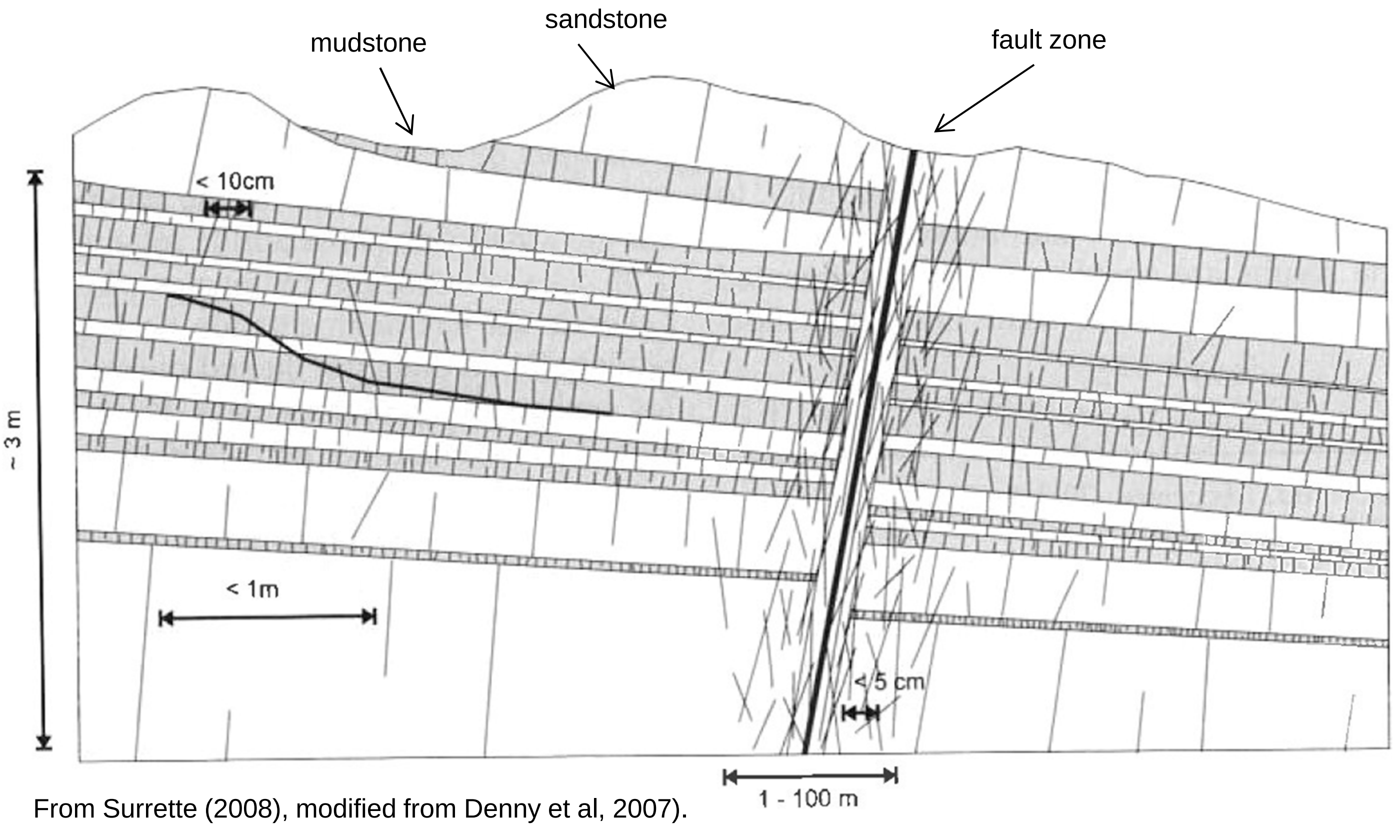


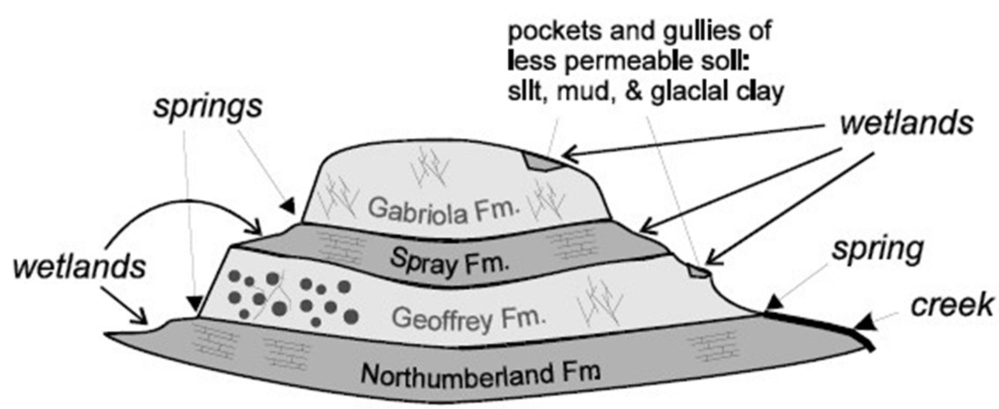
From Surrette (2008), modified from Denny et al, 2007).

k1 — Fracture Zone Domain (FZ)

k2 — Highly Fractured Interbedded Mudstone and Sandstone Domain (IBMS-SS)

k3 — Less Fractured Sandstone Domain (LFSS)

$k_1 > k_2 > k_3$



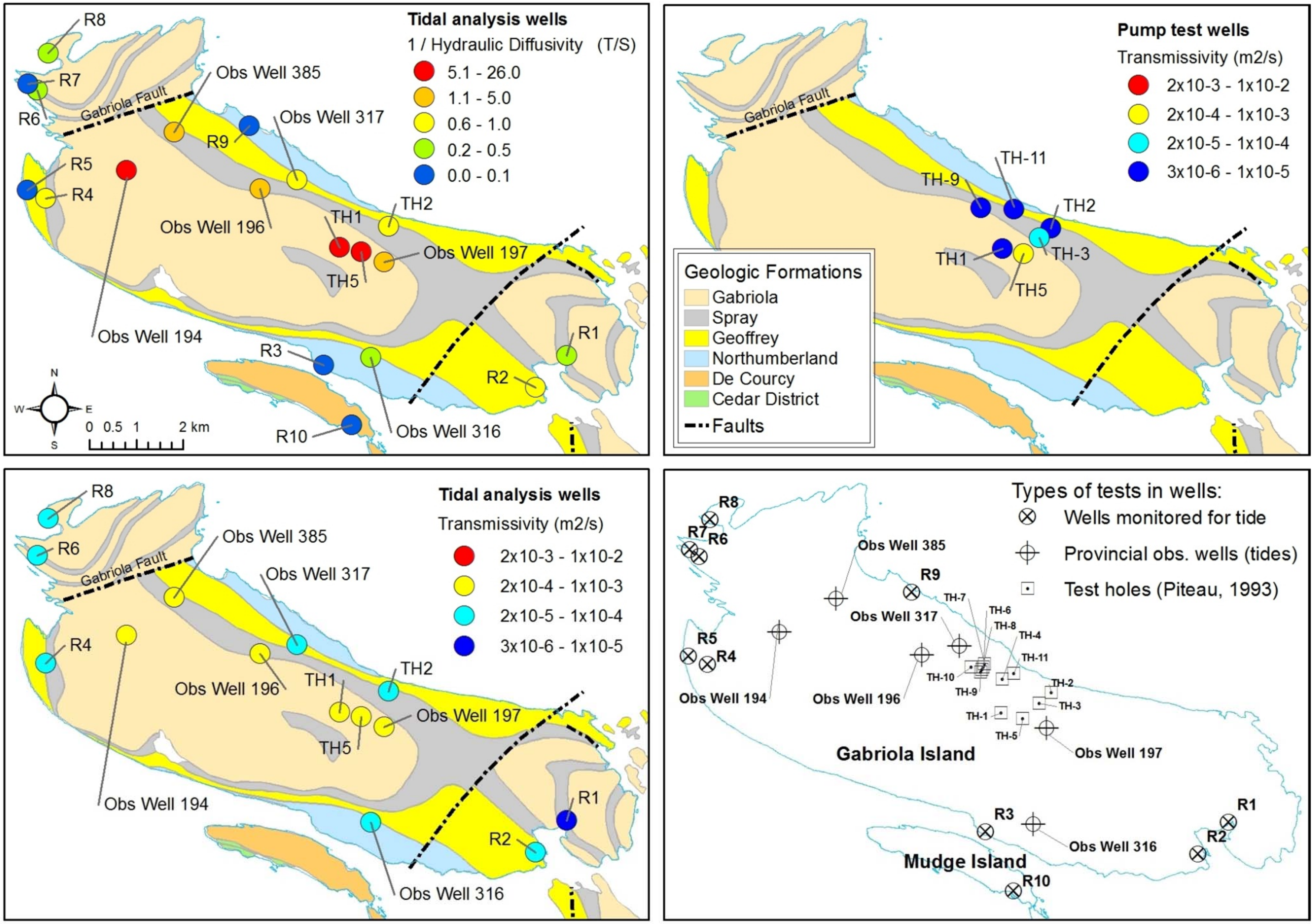
Conceptual section showing the effect of confining units and occurence of springs and wetlans (Peirce and Doe, 2010)

fractured sandstone well-drained & droughty in summer

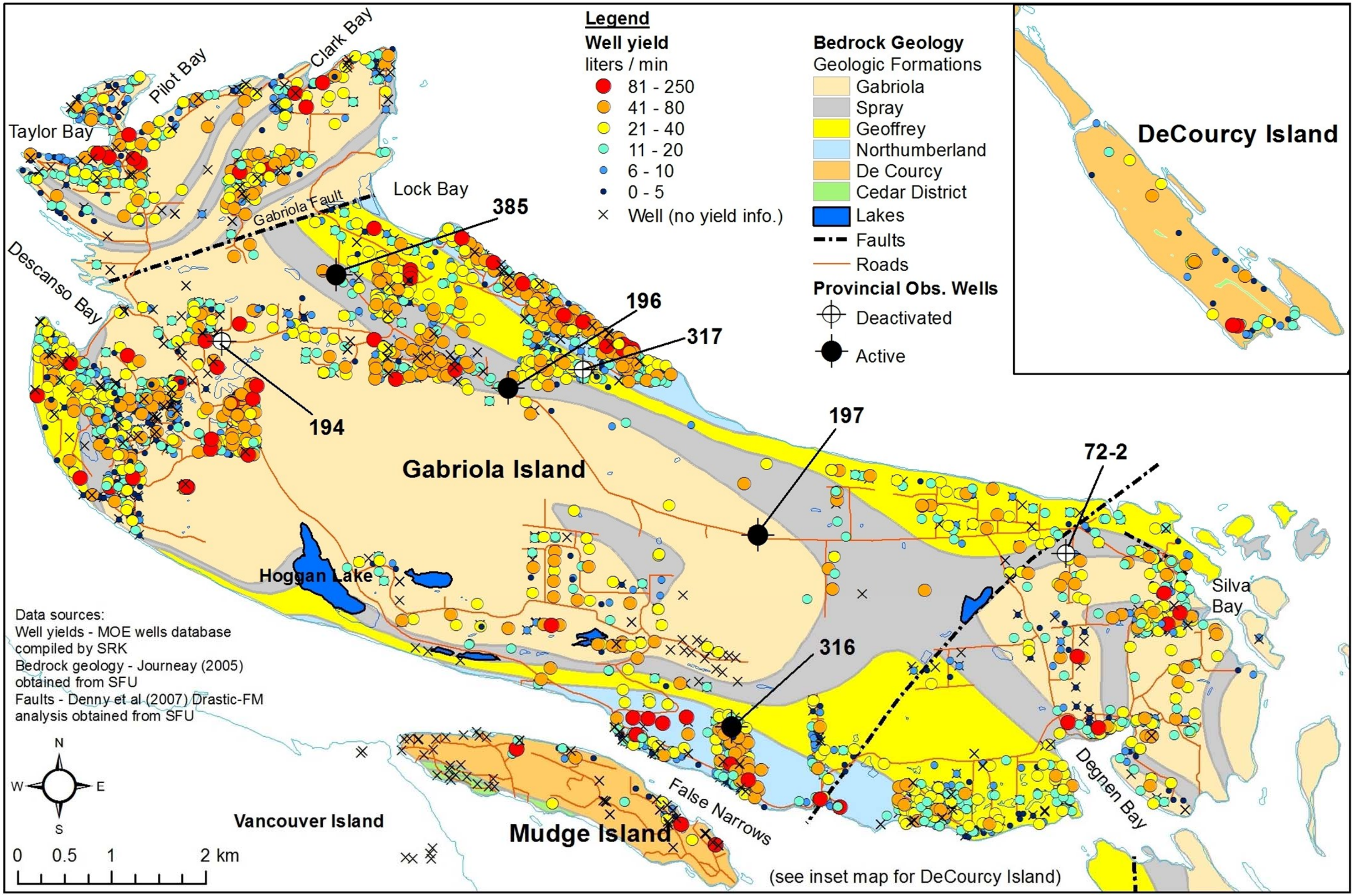
poorly drained mudrock (shale)

fractured conglomerate

srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)
		Example of the hydrostructural domain concept on the Gulf Islands
Job No: 1CR010.000 Filename: B-1.pptx	Gabriola Island	Date: April 2013 / Approved: JS / Figure: **B-1**



srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)
		Results of hydraulic tests on Gabriola Island
Job No: 1CR010.000 Filename: Figures B-2 to B-10.pptx	Gabriola Island	Date: April 2013 — Approved: JS — Figure: **B-2**



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Well yields, bedrock geology, and Provincial observation wells

Job No: 1CR010.000	Gabriola Island	Date: April 2013	Approved: JS	Figure: B-3
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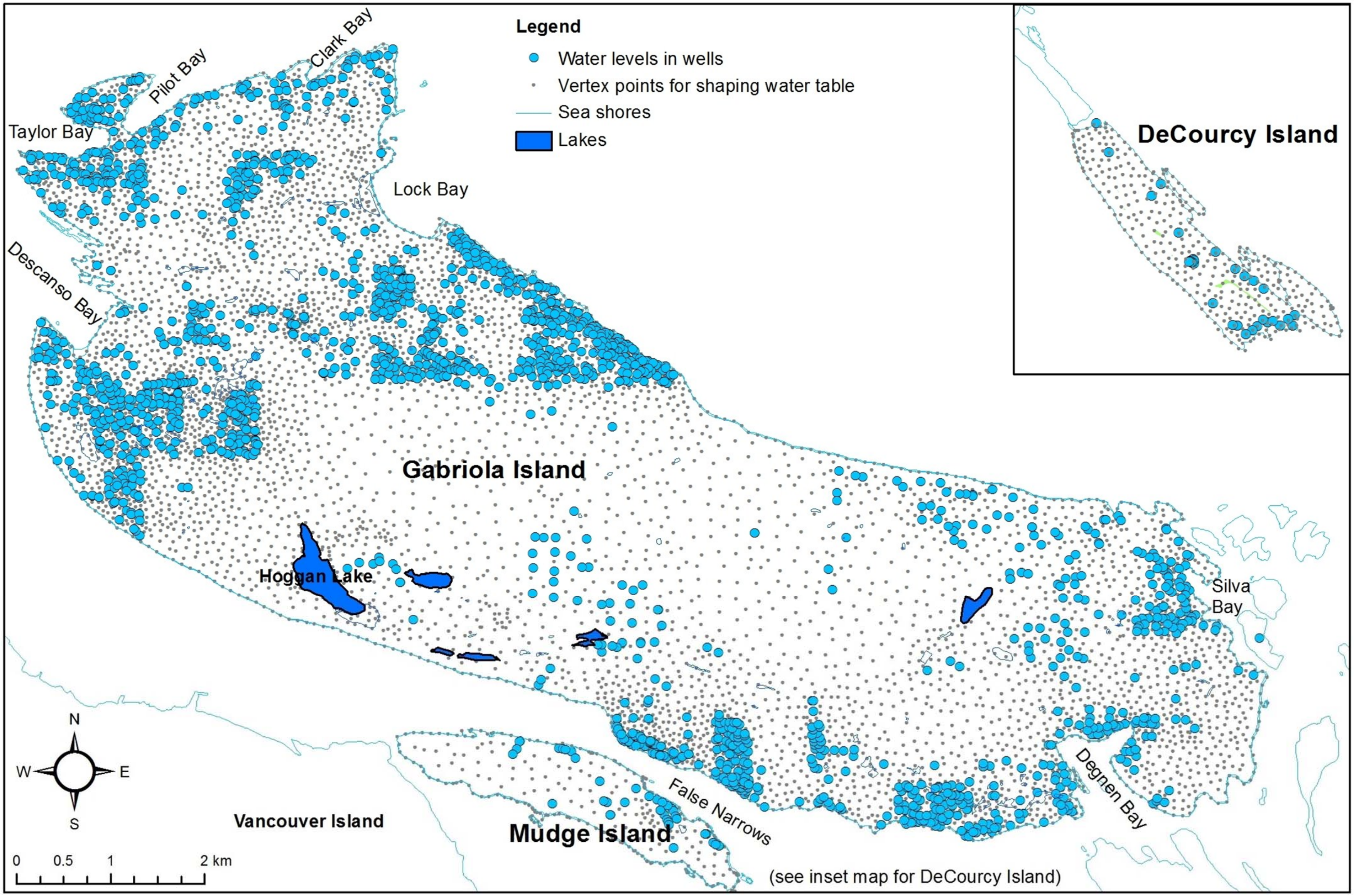

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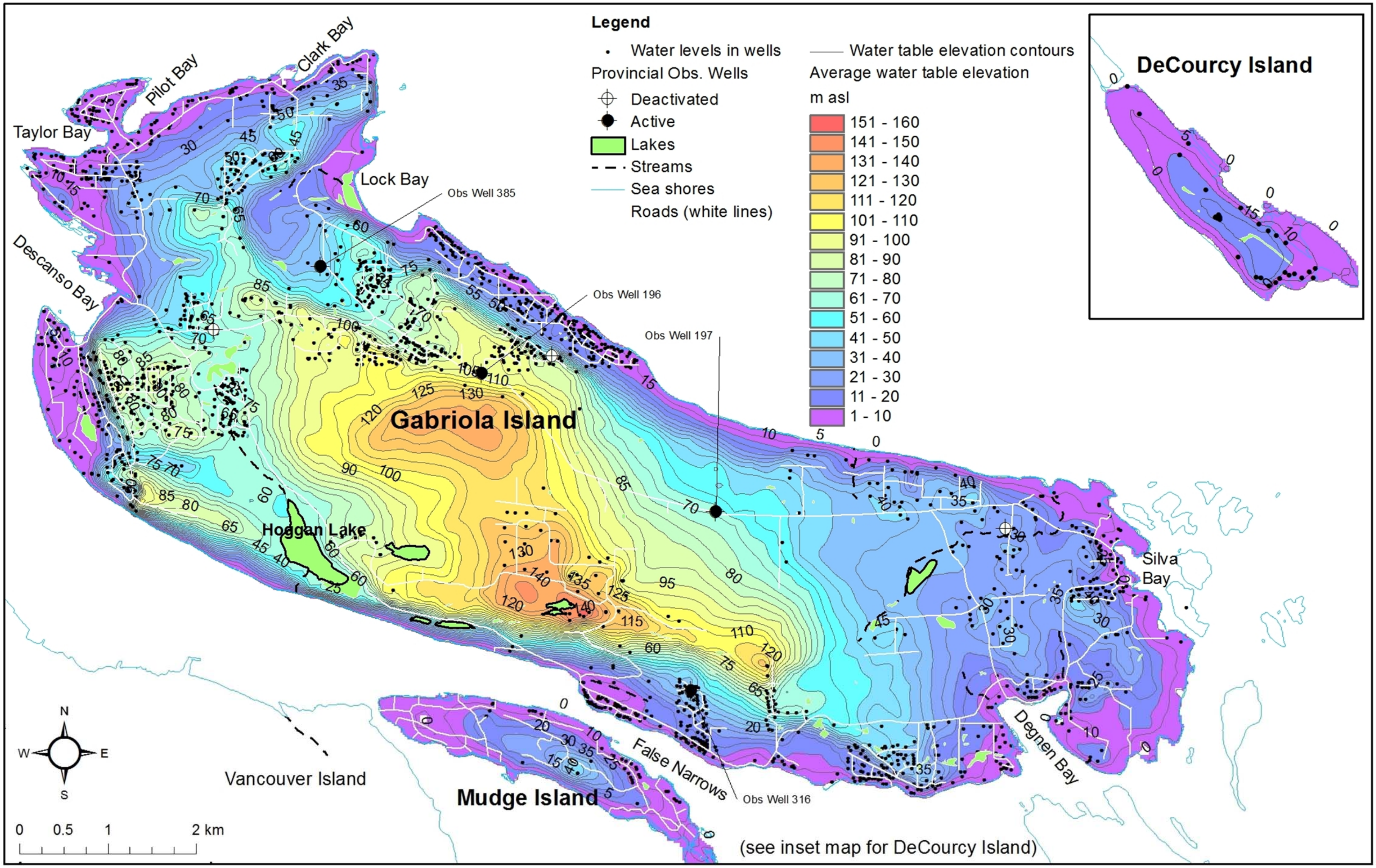
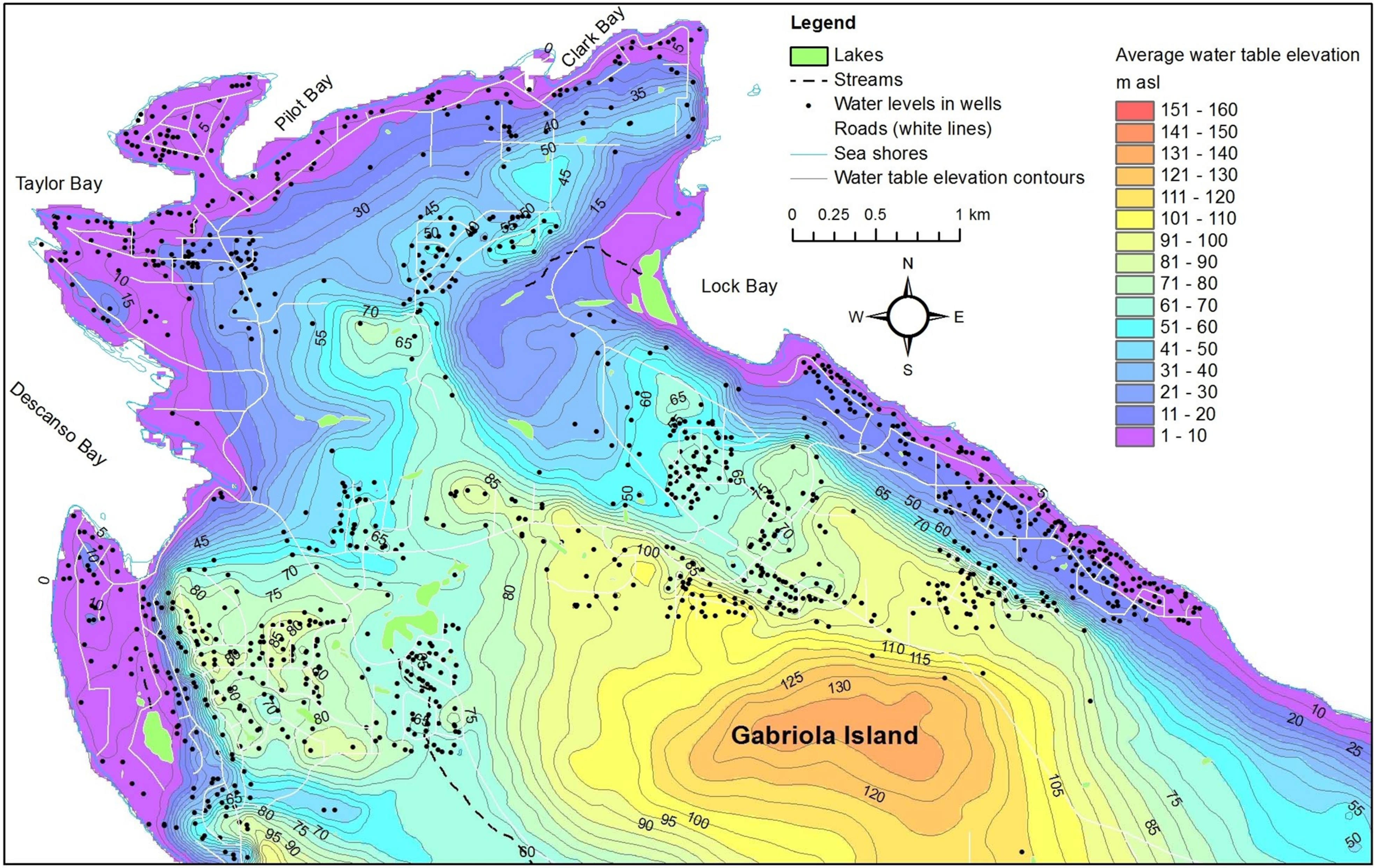
		Water table control points
Job No: 1CR010.000 Filename: Figures B-2 to B-10.pptx	Gabriola Island	Date: April 2013 / Approved: JS / Figure: **B-4**



srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)
		Average water table surface and contours for Gabriola, Mudge, DeCourcy Islands
Job No: 1CR010.000 Filename: Figures B-2 to B-10.pptx	Gabriola Island	Date: April 2013 · Approved: JS · Figure: **B-5**



Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Average water table surface and contours in West part of Gabriola Island

Job No: 1CR010.000

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Gabriola Island

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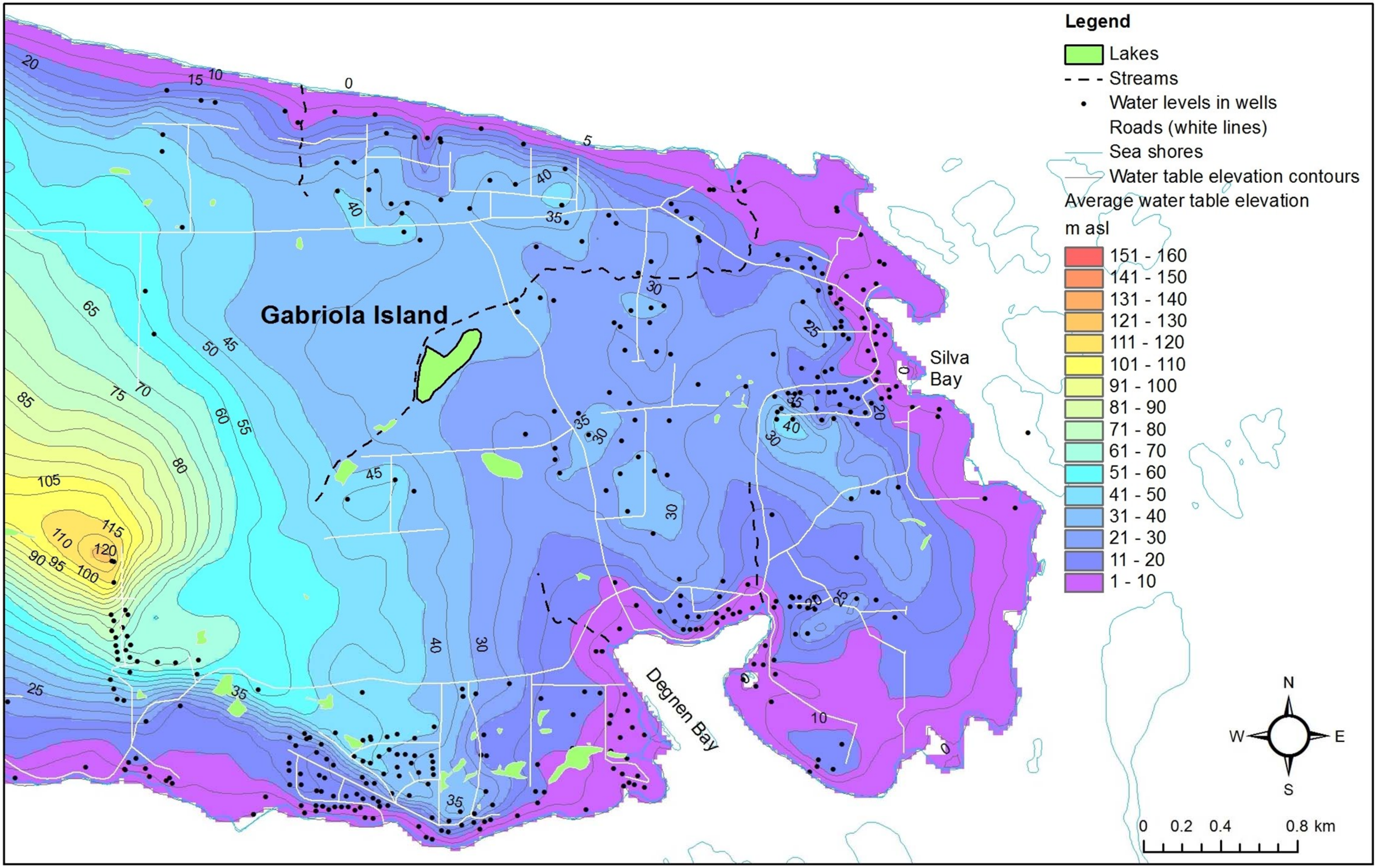

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		Average water table surface and contours in East part of Gabriola Island
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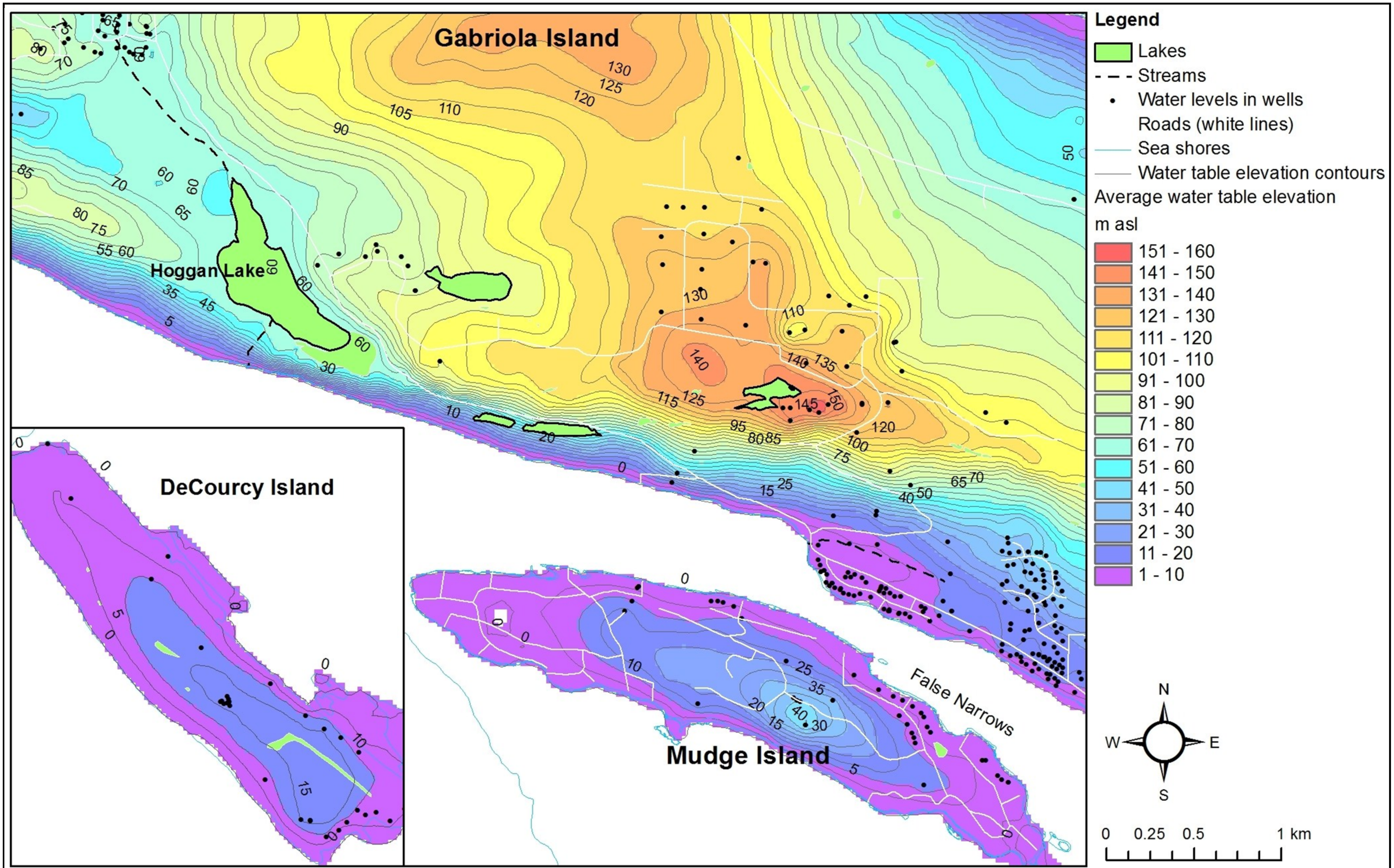

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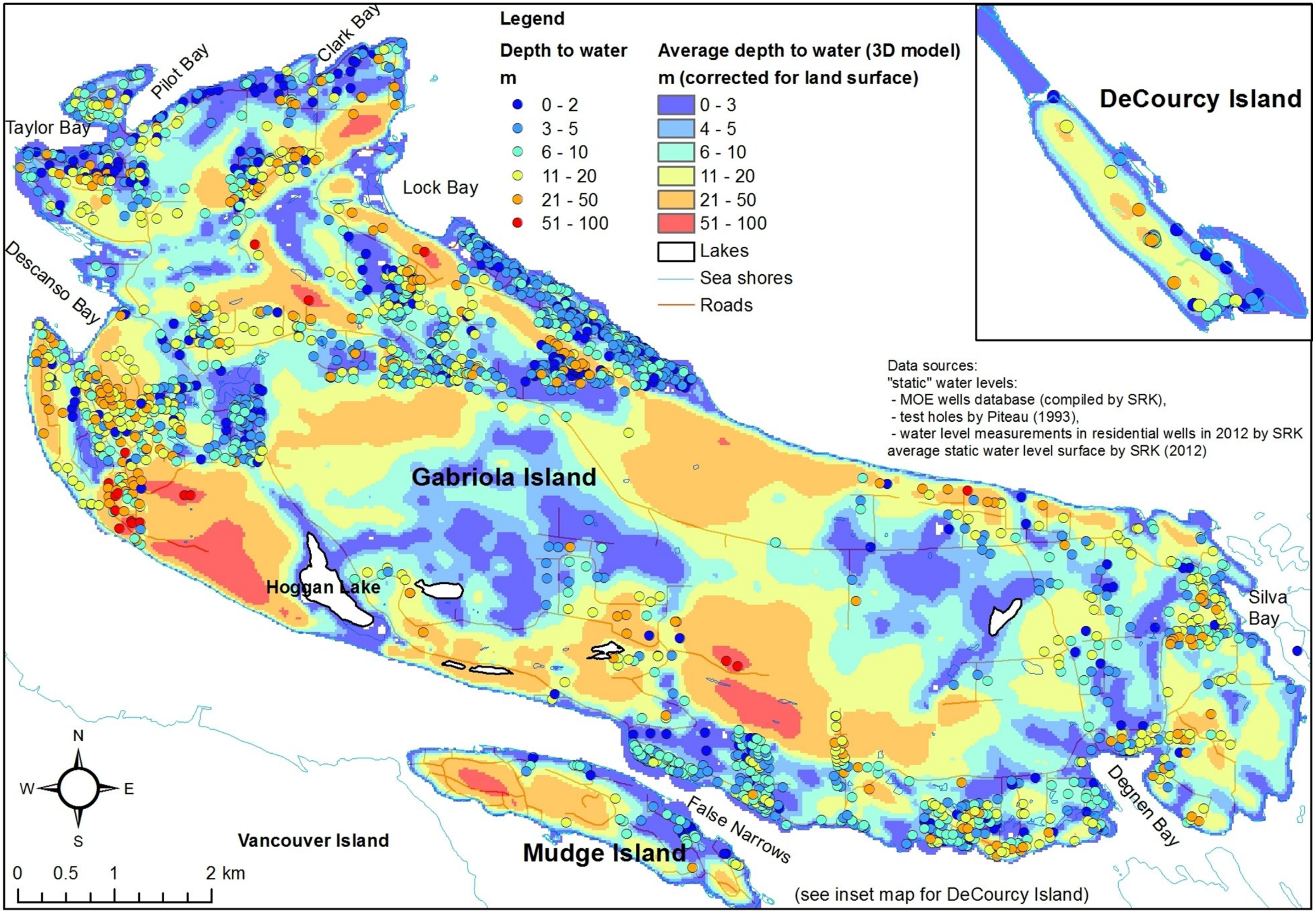
Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Average water table surface and contours in South part of Gabriola Island, Mudge and DeCourcy Islands

Job No: 1CR010.000	Gabriola Island	Date: April 2013	Approved: JS	Figure: **B-8**
Filename: Figures B-2 to B-9.pptx				



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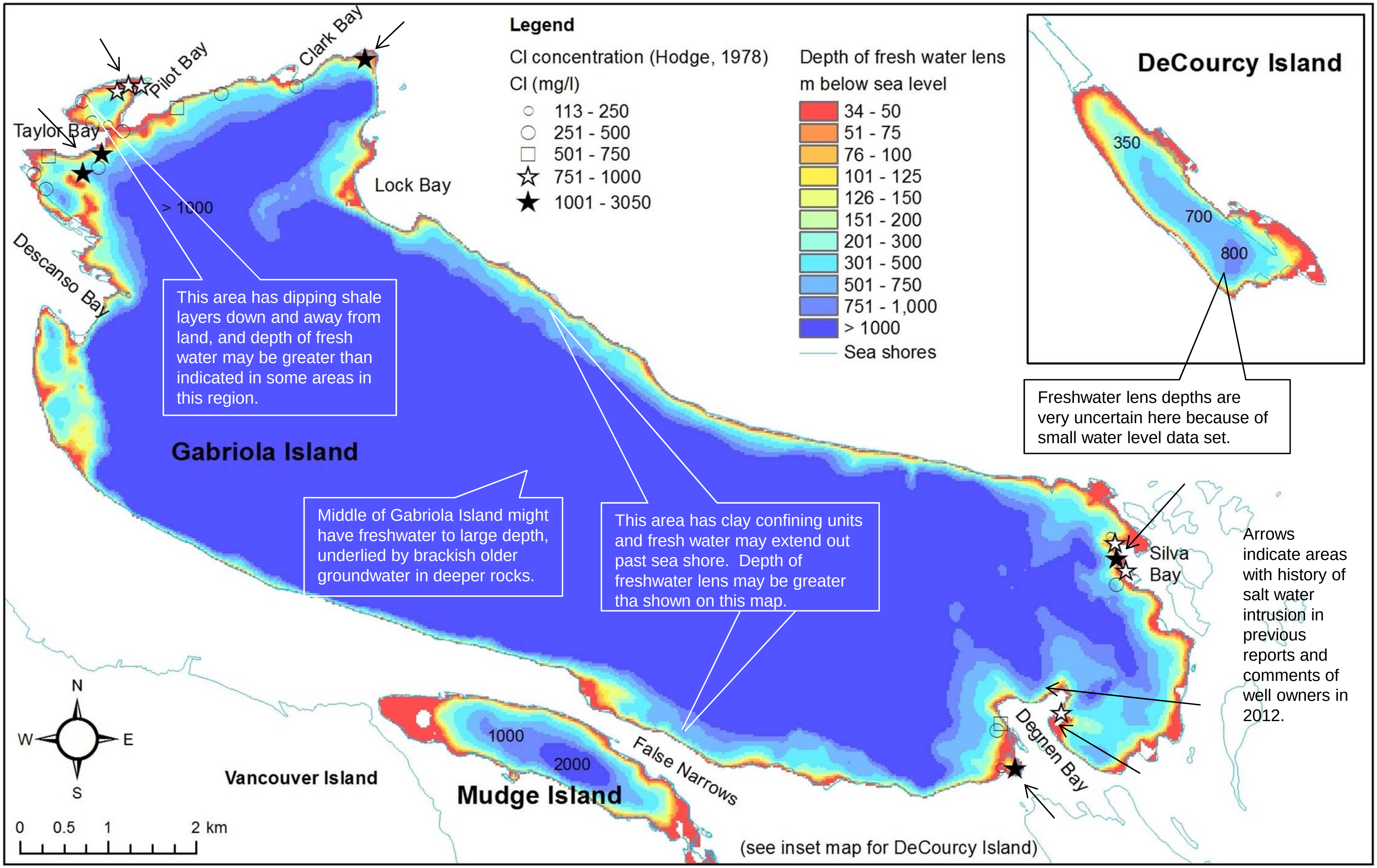
REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Depth to water in well logs and average value calculated from water table and ground surface

Job No: 1CR010.000 Filename: Figures B-2 to B-10.pptx	Gabriola Island	Date: April 2013	Approved: JS	Figure: B-9



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Theoretical depth of fresh water lens and areas of salt water intrusion.

Job No: 1CR010.000

Filename: Figures B-2 to B-10.pptx

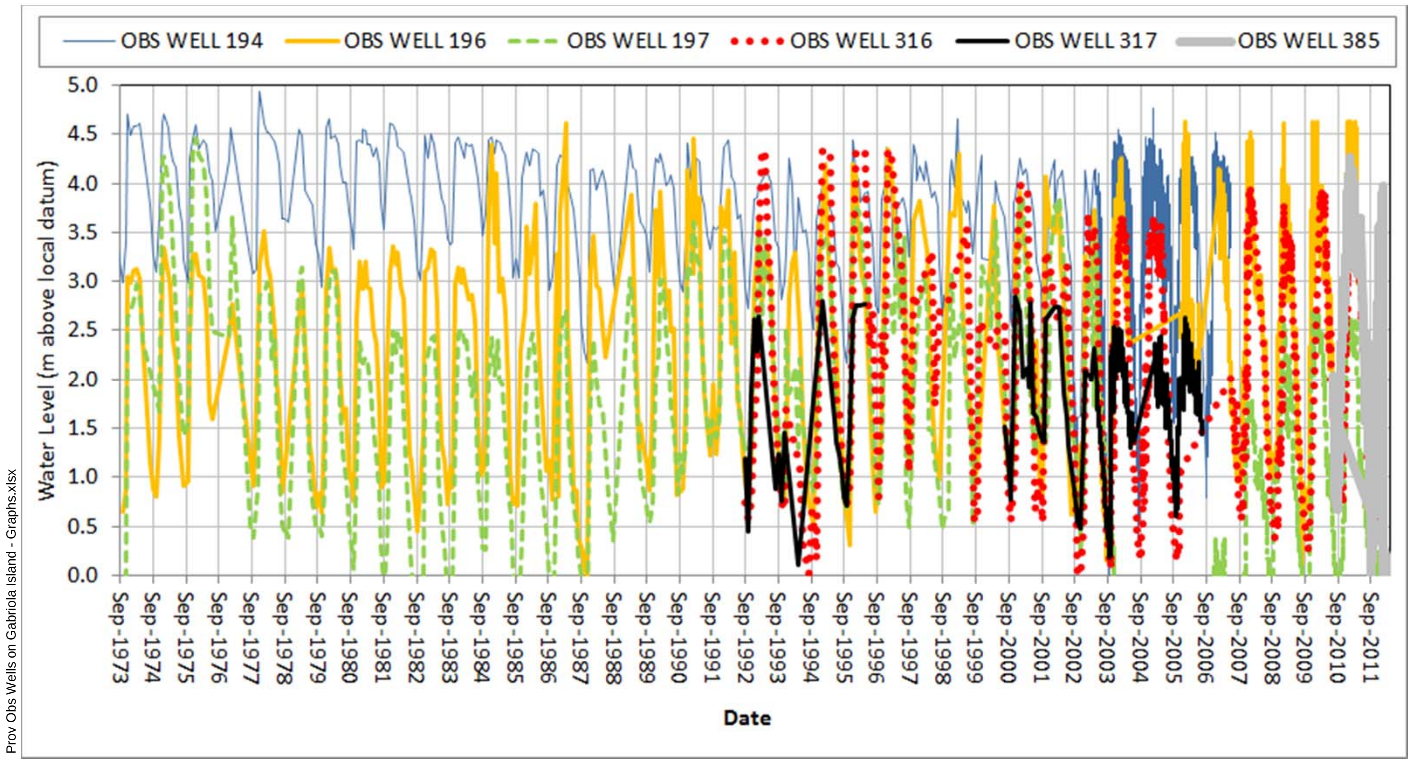
Gabriola Island

Date: April 2013

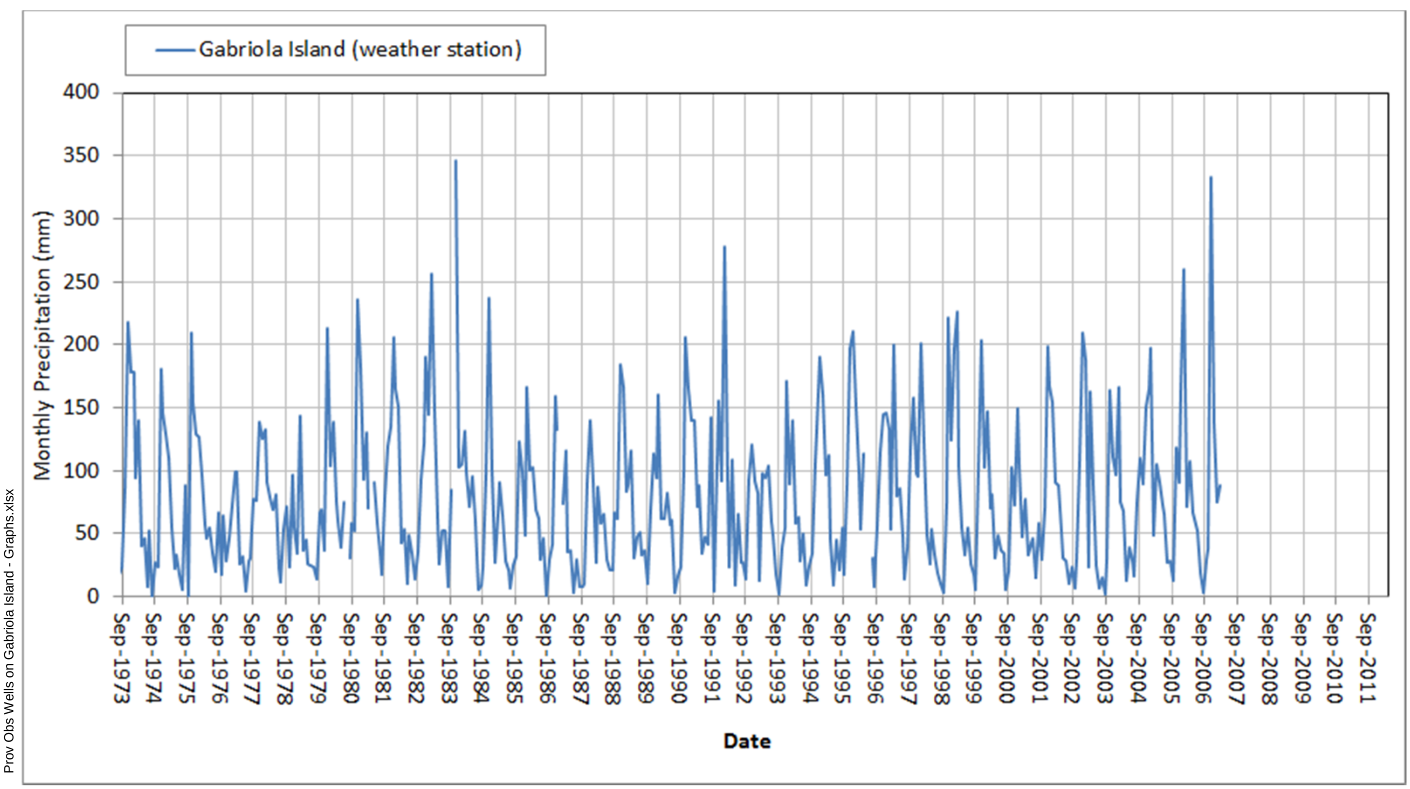
Approved: JS

Figure: **B-10**

All Provincial observation wells on Gabriola Island (active and deactivated)



Monthly Precipitation



srk consulting

Regional District of Nanaimo

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Water level record in all MOE obs. wells on Gabriola Island, and monthly precipitation

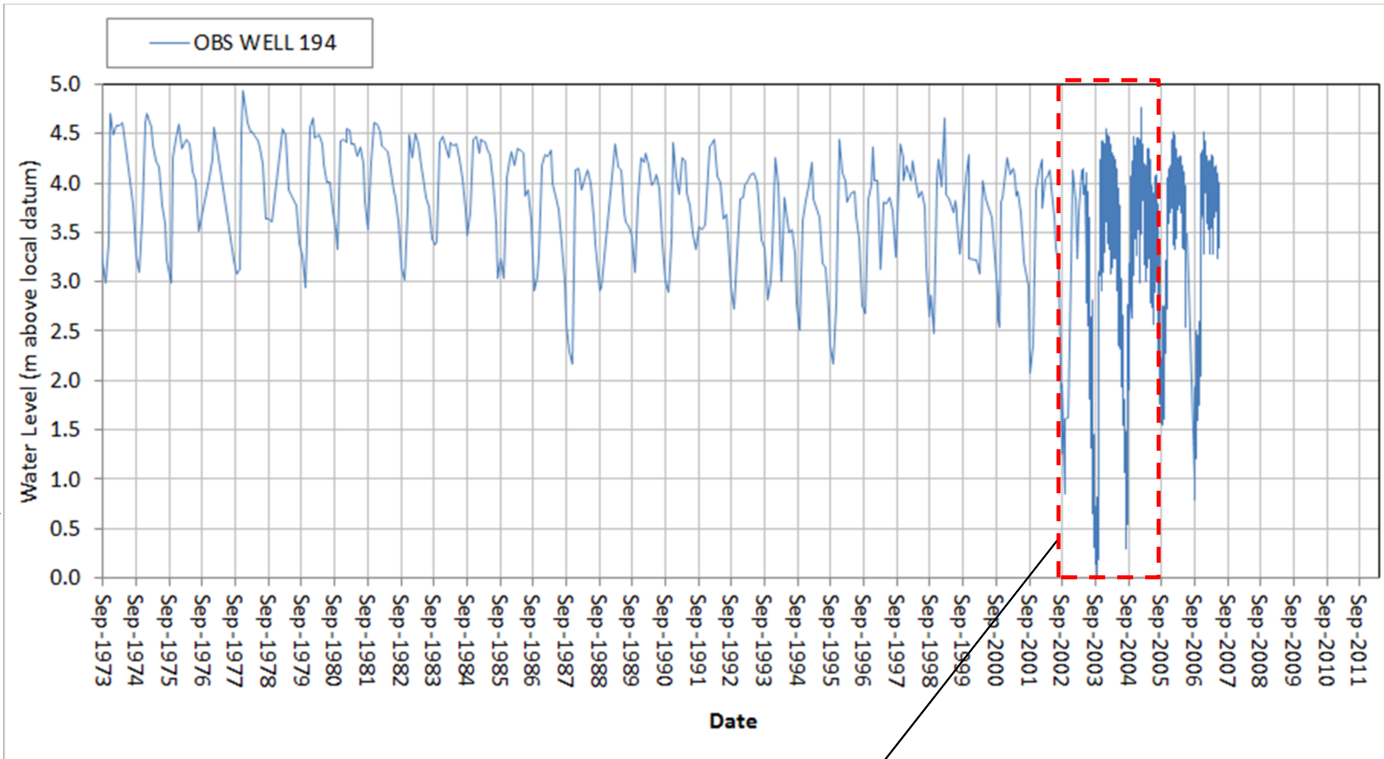
Job No: 1CR010.000

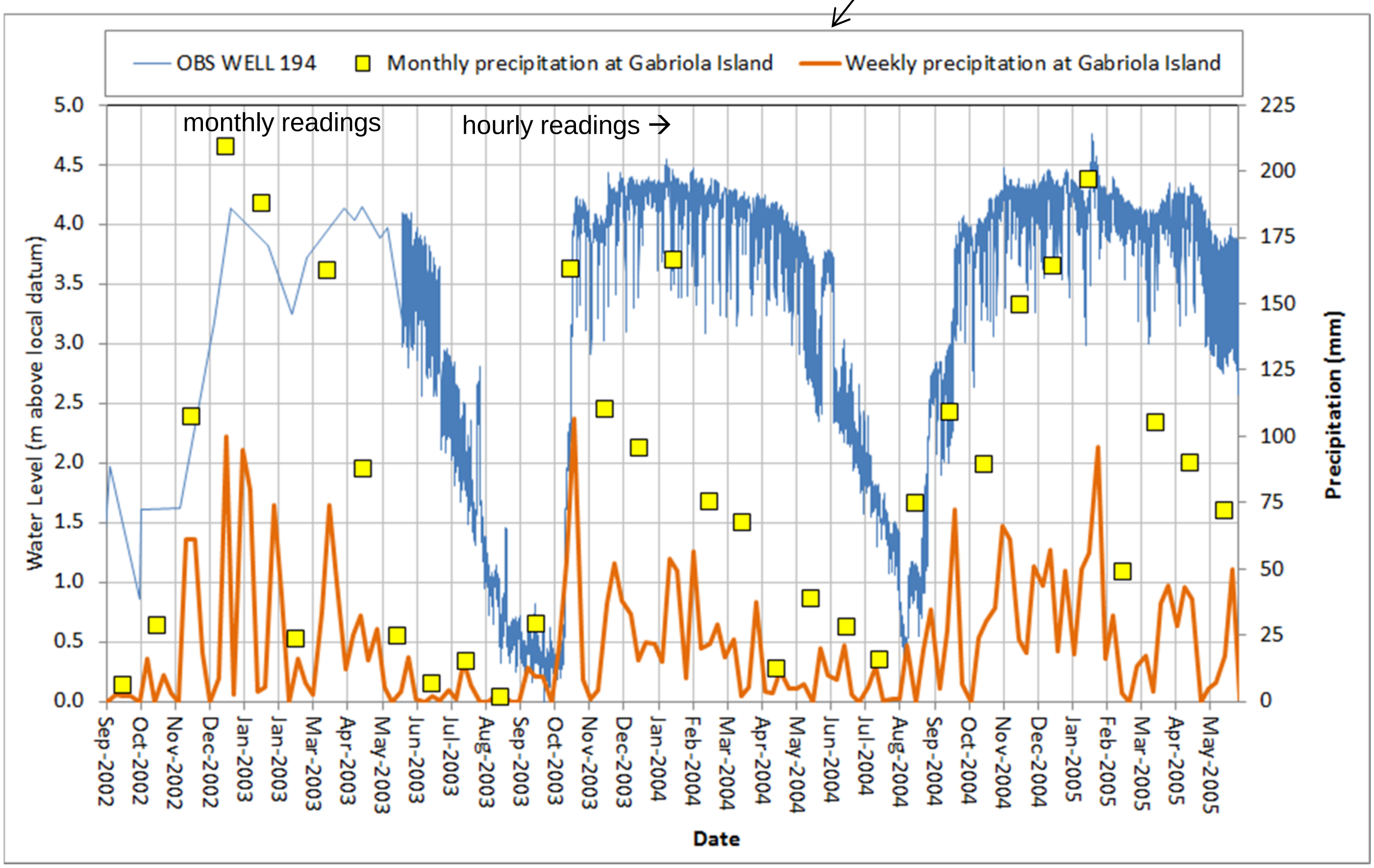
Filename: Figures B-11 to B-16.pptx

Gabriola Island

Date:	Approved:	Figure:
April 2013	JS	**B-11**

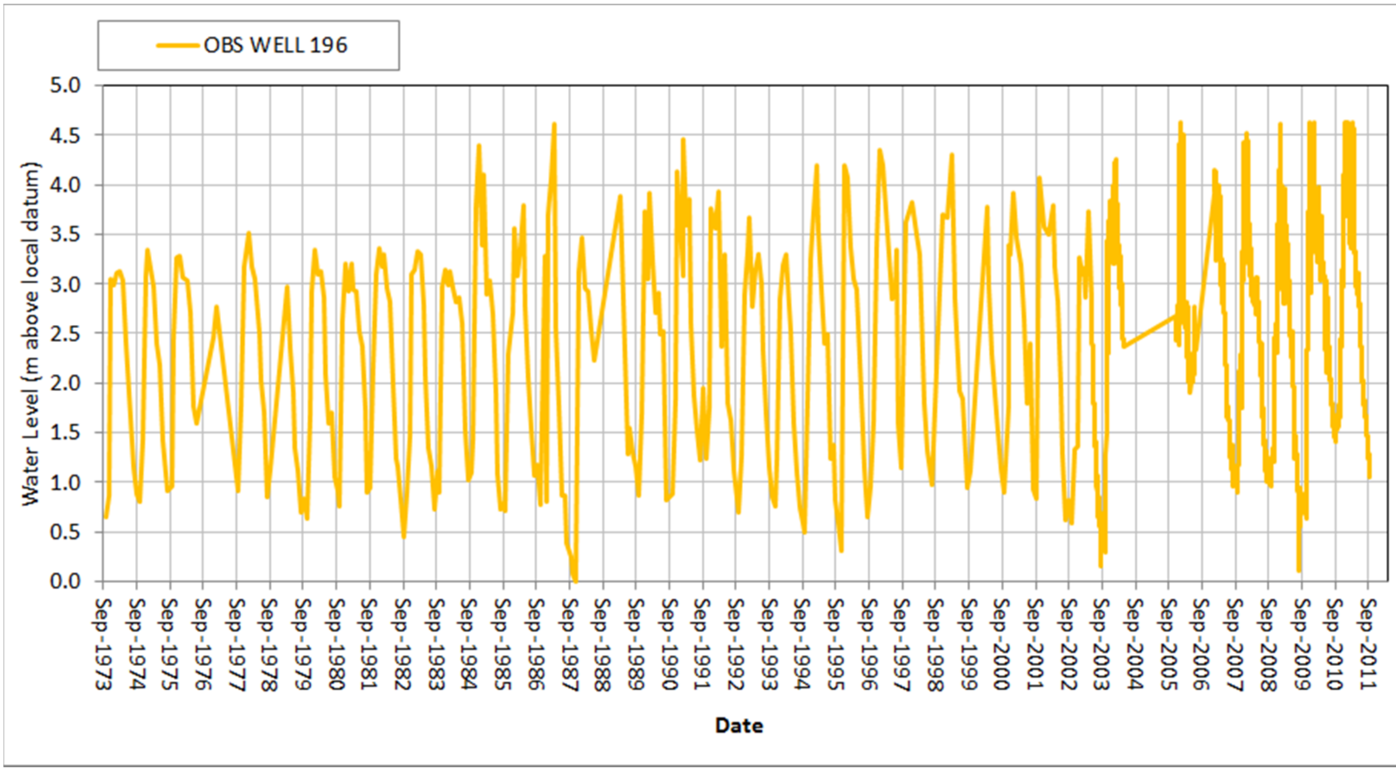
Obs Well 194





srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Water level record in Provincial observation well 194 and precipitation.
Job No: 1CR010.000 Filename: Figures B-11 to B-16.pptx	Gabriola Island	Date: April 2013 | Approved: JS | Figure: **B-12**

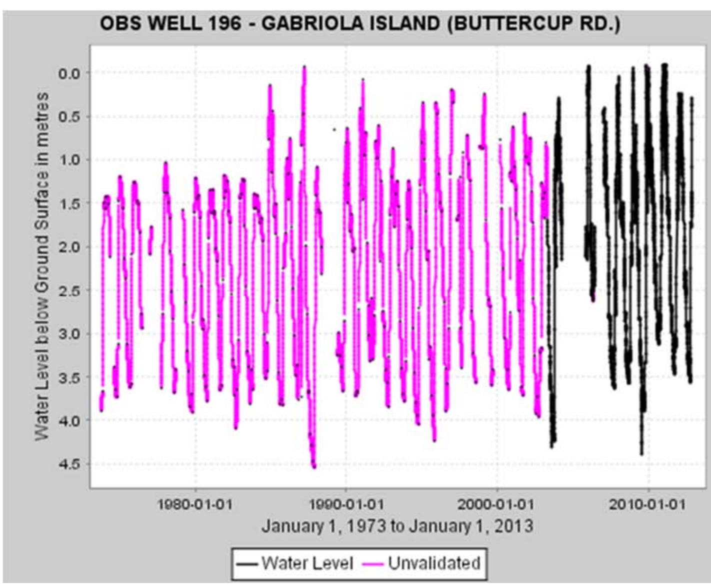
Obs Well 196 (active)



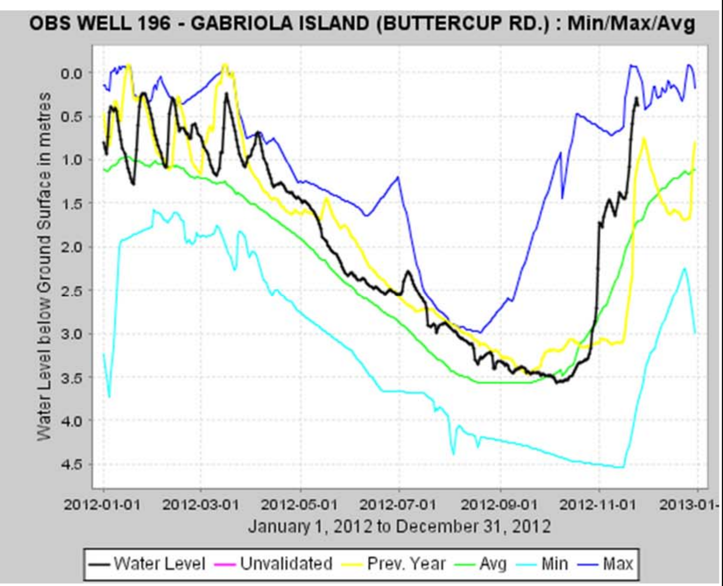
Prov Obs Wells on Gabriola Island - Graphs.xlsx

Graph created from downloaded data.

Water level below ground for complete record:



Min/Max/Average for 2012:

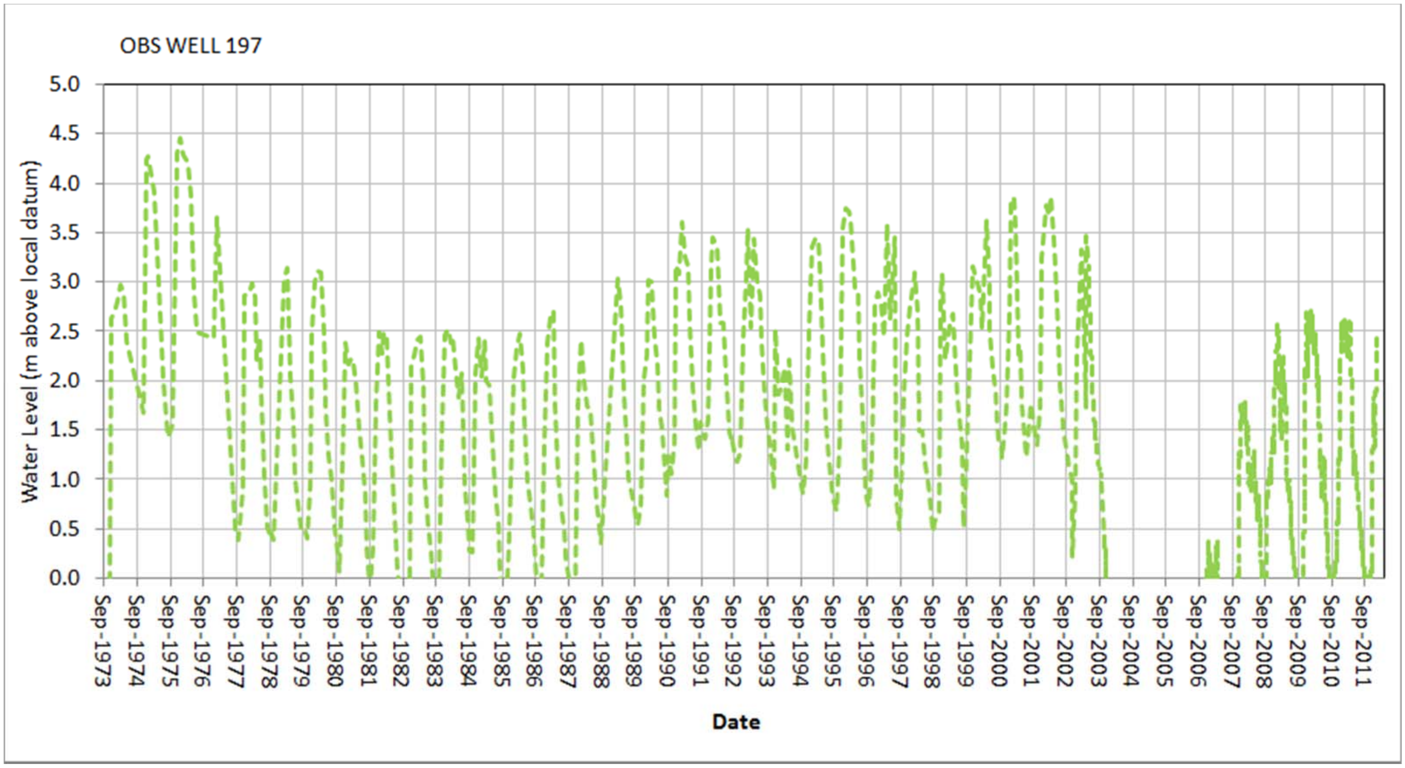


Graphs generated by MOE website: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html

srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Water level record in Provincial observation well 196
Job No: 1CR010.000 Filename: Figures B-11 to B-16.pptx	Gabriola Island	Date: April 2013 | Approved: JS | Figure: **B-13**

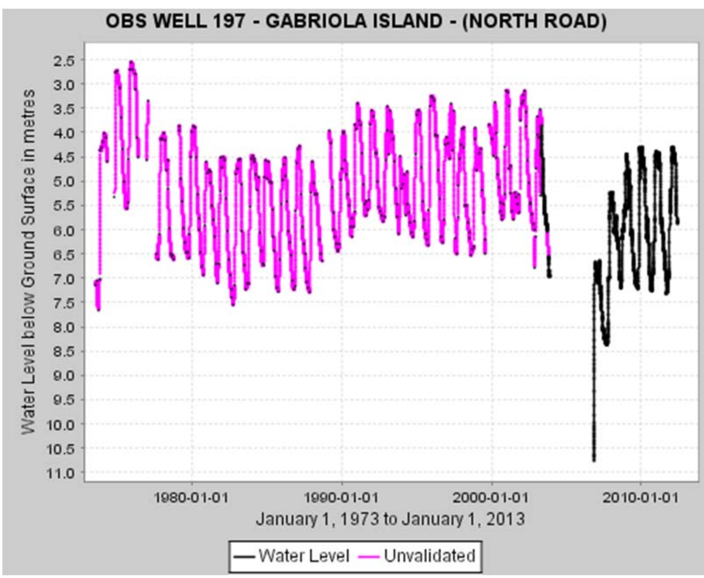
Obs Well 197 (active)

Prov Obs Wells on Gabriola Island - Graphs.xlsx

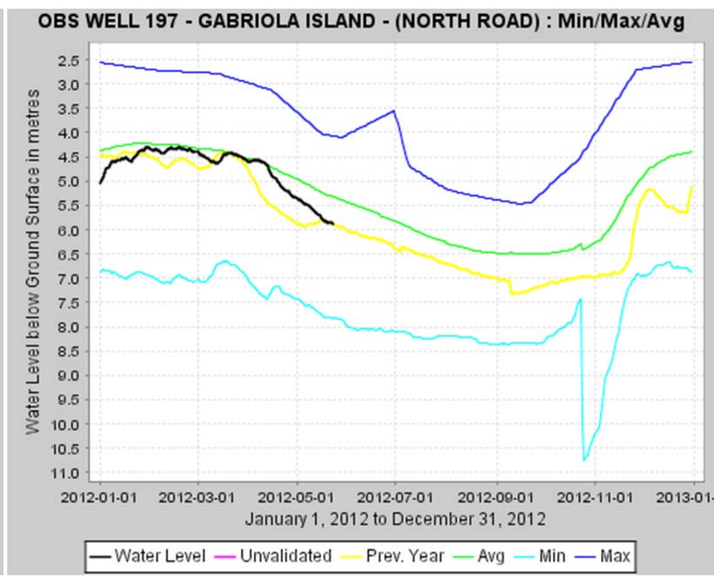


Graph created from downloaded data.

Water level below ground for complete record:



Min/Max/Average for 2012:



Graphs generated by MOE website: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html

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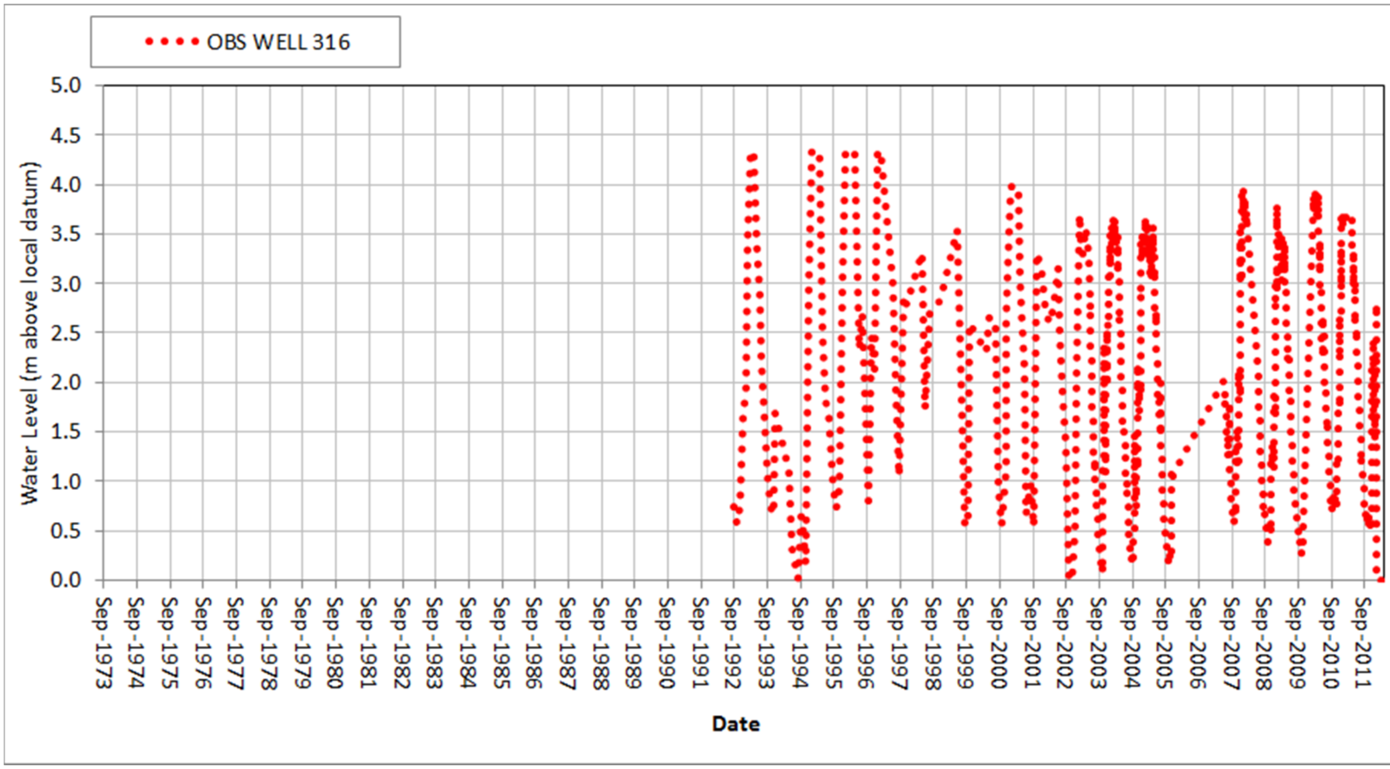
REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Water level record in Provincial observation well 197

Job No: 1CR010.000 Filename: Figures B-11 to B-16.pptx	Gabriola Island	Date: April 2013	Approved: JS	Figure: **B-14**

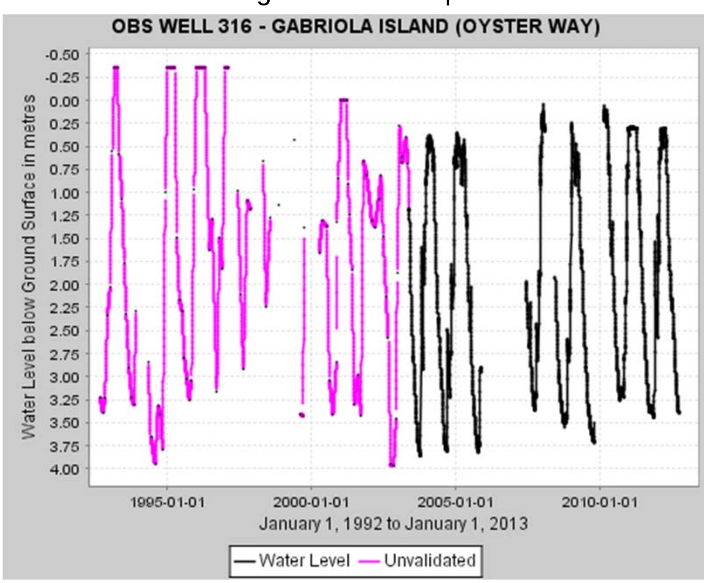
Obs Well 316 (active)



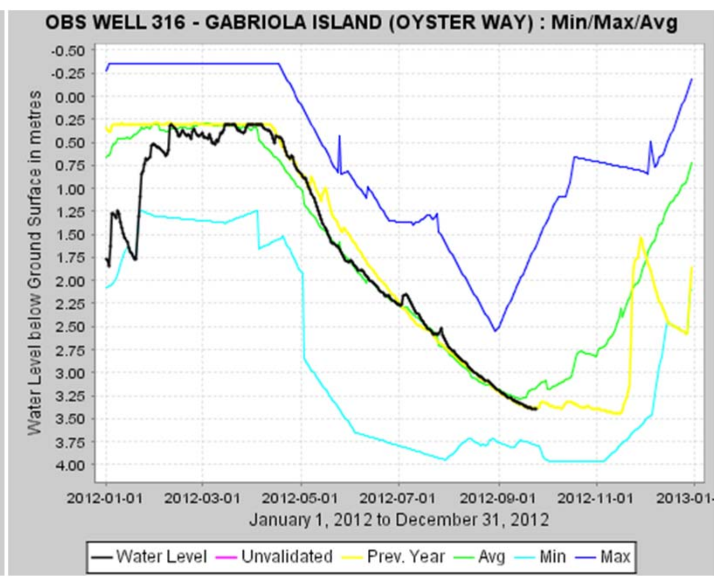
Prov Obs Wells on Gabriola Island - Graphs.xlsx

Graph created from downloaded data.

Water level below ground for complete record:



Min/Max/Average for 2012:



Graphs generated by MOE website: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html

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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Water level record in Provincial observation well 316

Job No: 1CR010.000

Filename: Figures B-11 to B-16.pptx

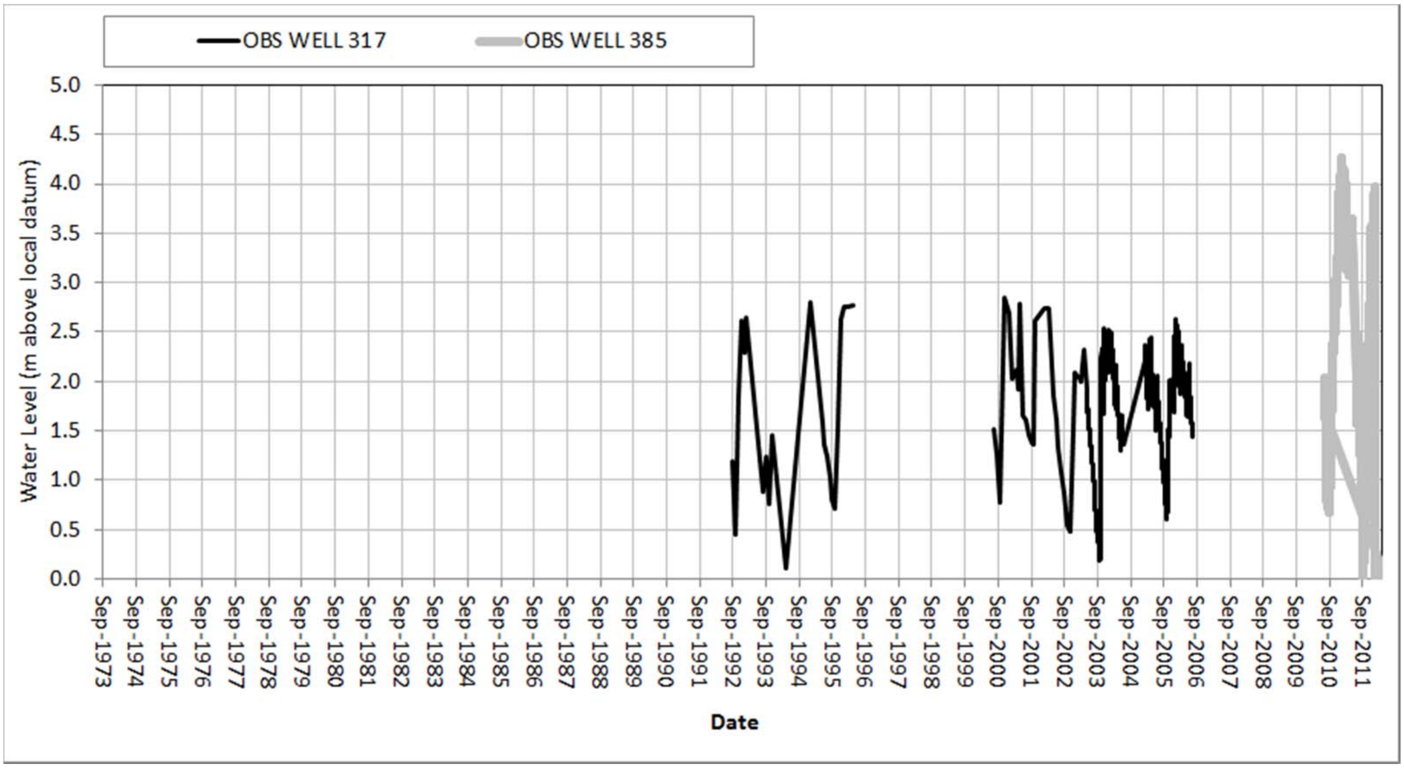
Gabriola Island

Date: April 2013

Approved: JS

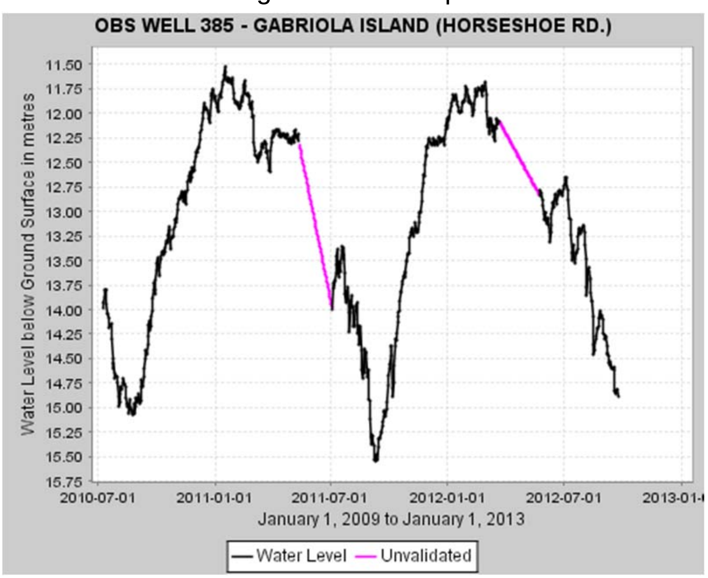
Figure: **B-15**

Obs Well 385 (active) and 317

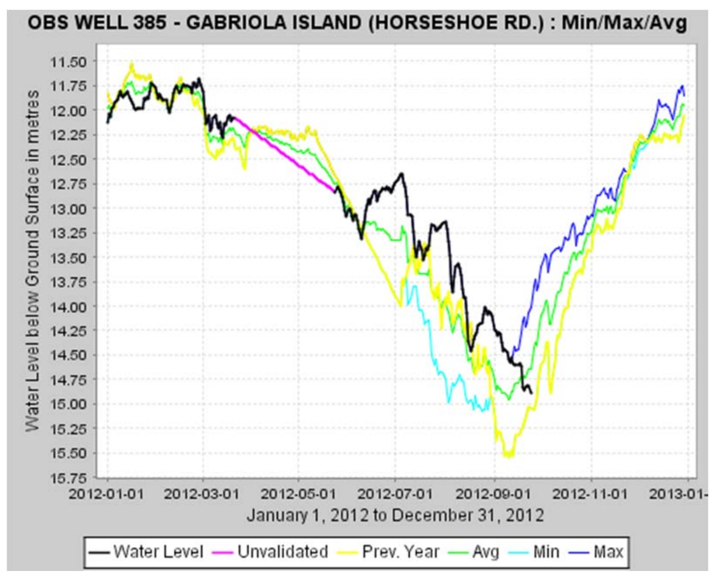


Graph created from downloaded data.

Water level below ground for complete record:



Min/Max/Average for 2012:

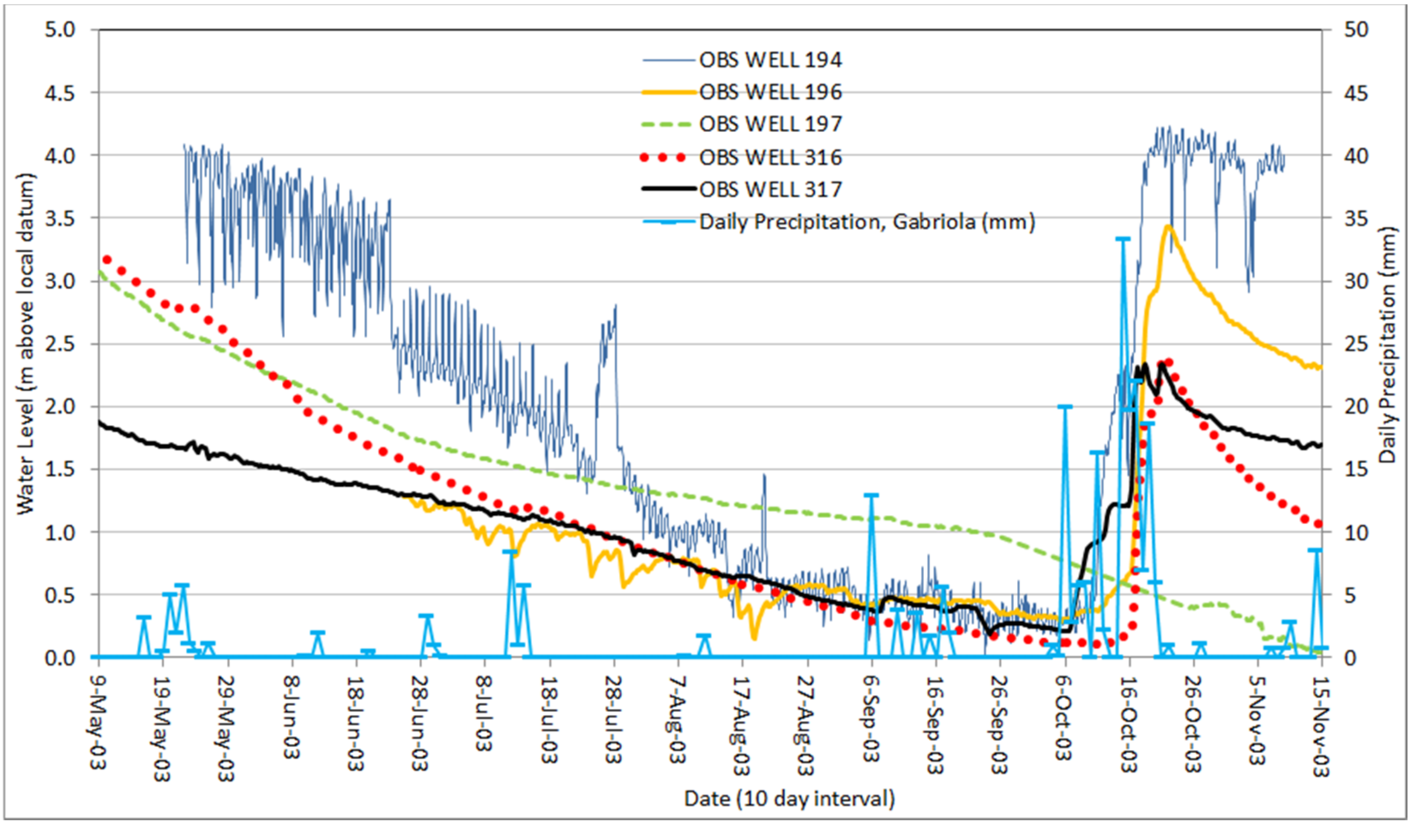


Graphs generated by MOE website: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html

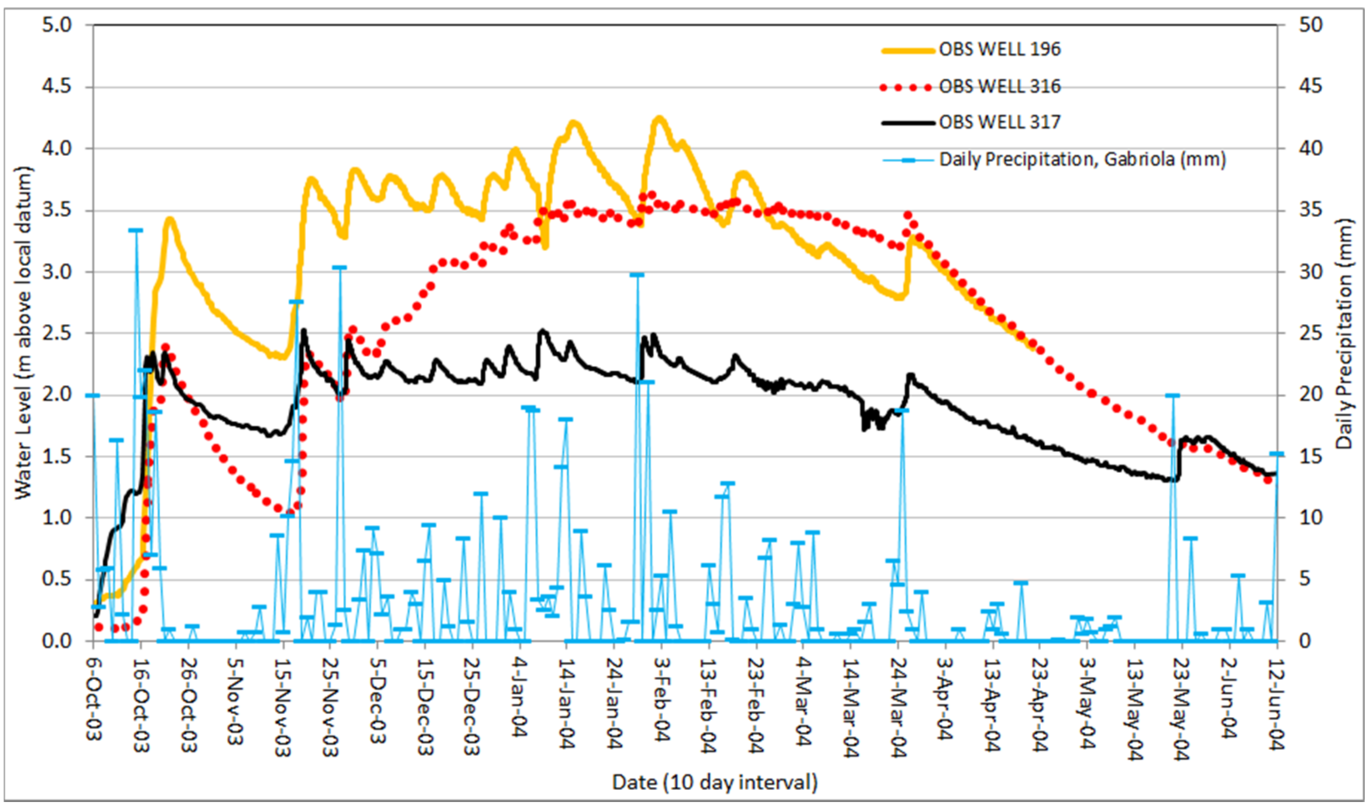
No graph available from MOE for Well 317, only raw data.

srk consulting	Regional District of Nanaimo	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Water level record in Provincial observation wells 385 and 317
Job No: 1CR010.000 Filename: Figures B-11 to B-16.pptx	Gabriola Island	Date: April 2013 · Approved: JS · Figure: **B-16**

Detail in Summer 2003



Winter of 2003/2004



BC GW obs wells on Gabriola Island Data Graphs.xlsx

srk consulting

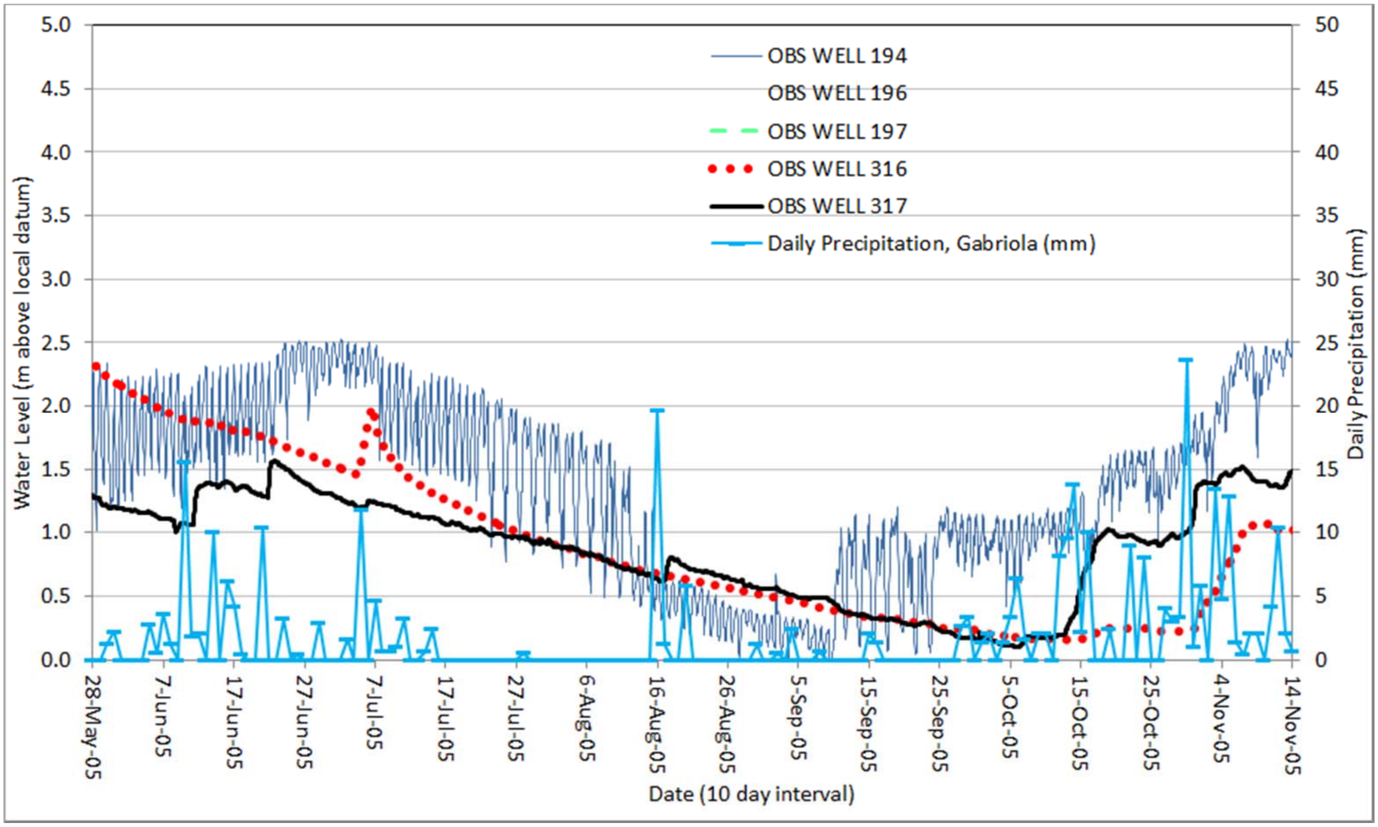
REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

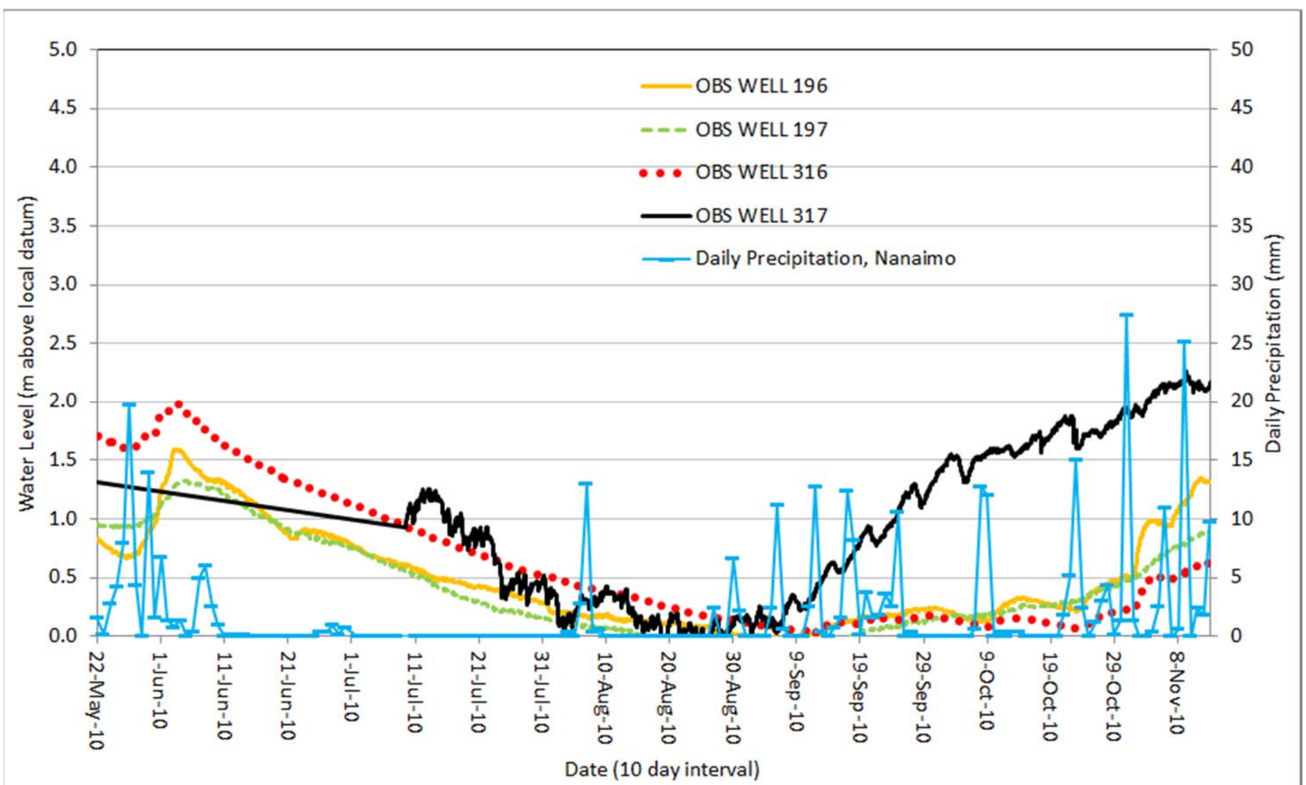
Water level in Provincial obs. wells and daily precipitation - examples from 2003-2004

Job No: 1CR010.000 Filename: Figures B-17 to -20.pptx	Gabriola Island	Date: April 2013	Approved: JS	Figure: **B-17**

Summer 2005

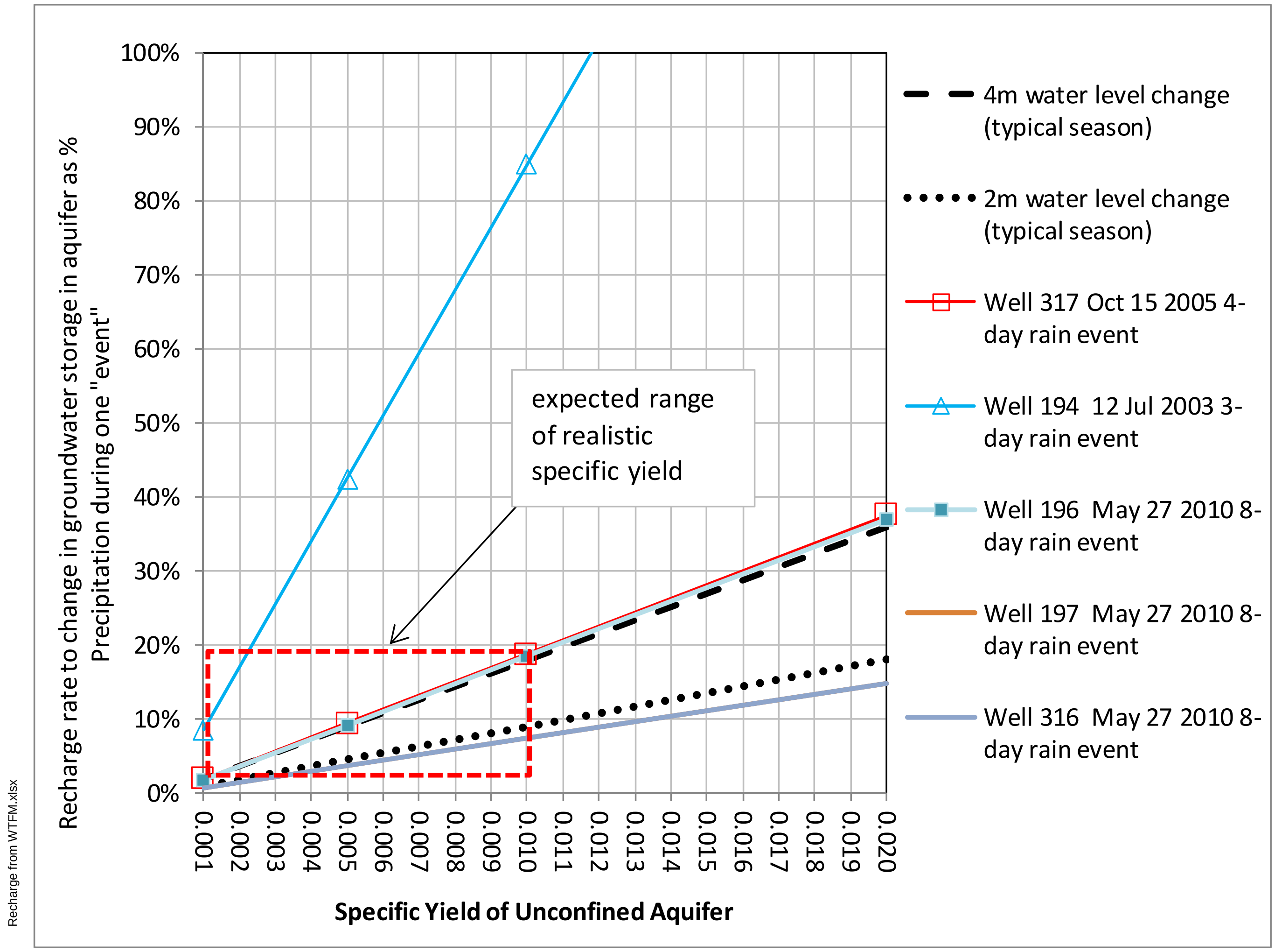


Summer 2011

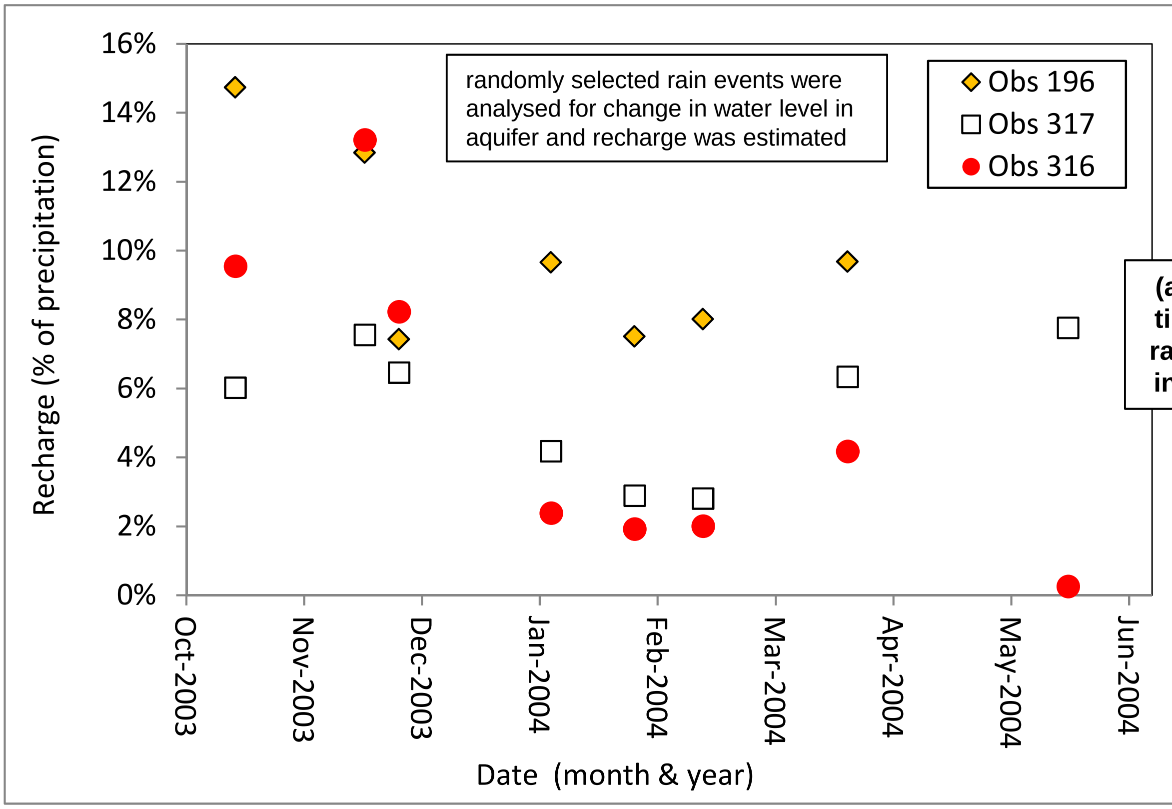


BC GW obs wells on Gabriola Island Data Graphs.xlsx

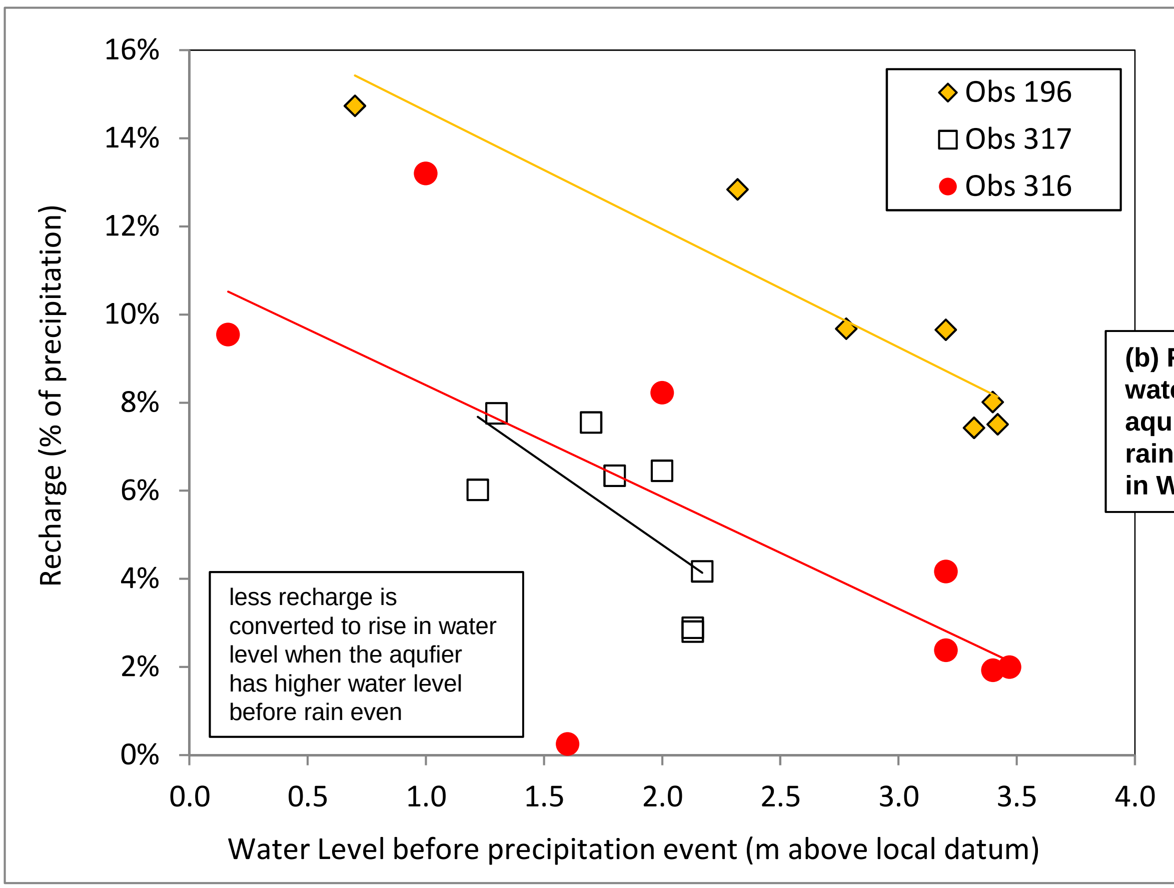
srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands) **Water level in Provincial obs. wells and daily precipitation - examples from 2005-2011**
Job No: 1CR010.000 Filename: Figures B-17 to -20.pptx	Gabriola Island	Date: Feb, 2013 | Approved: JS | Figure: **B-18**



srk consulting	REGIONAL DISTRICT OF NANAIMO	Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)
		Estimated recharge from WTF method for different rain events and values of specific yield
Job No: 1CR010.000 Filename: Figures B-17 to -20.pptx	Gabriola Island	Date: April, 2013 / Approved: JS / Figure: **B-19**



(a) Recharge vs time in selected rain events used in WTF analysis



(b) Recharge vs water level in aquiffer before rain event used in WTF analysis

Recharge from WTFM.xlsx

srk consulting

Regional District of Nanaimo

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Recharge vs time (a) and water level in aquiffer before rain event (b)

Job No: 1CR010.000	Gabriola Island	Date: April, 2013	Approved: JS	Figure: **B-20**
Filename: Figures B-17 to -20.pptx				

Appendix C: Tidal Analysis

Appendix C - Table of Contents

Appendix C - Figures

Appendix C - Tables

1 Water Levels in Residential Wells

1.1 Monitoring Program in 2012

SRK monitored water levels in ten residential wells in August 2012, and one well on Mudge Island in October 2012, to determine tidal fluctuation in groundwater and to calculate aquifer diffusivity from tidal analysis. The wells were named R1 to R10 and the locations are shown on Figure C-1 at approximate locations (the locations have been shifted away from actual location to protect privacy of residents). Each well owner completed a consent form to monitor the wells (sample form is attached in this appendix).

All monitored residential wells are vertical in orientation and have steel casing. Some wells were empty of pumps and some contained submersible pumps and pipes. The water level pressure sensor was lowered down the space between the pipes, and the pumps were turned off during water level monitoring for a period of one week in each well. Land elevation was estimated from the nearest topographic contour on the digital topographic map (approximately 2m accuracy) because none of the wells were surveyed. Well details are listed in Table C- 1.

Pressure transducer water level sensors were suspended with wirelines at some depth in water for the duration of monitoring, and depth to water was measured with water level tape after installation of the sensor and before removal of sensor one week later. Water level and water temperature were recorded at 5 minute intervals. This is sufficient to measure tidal fluctuation and other effects.

Table C- 1 Residential monitoring wells on Gabriola and Mudge Islands (SRK, 2012)

Well ID	Island	Monitoring Period	Distance to Ocean Shore at Average Tide (m)	Elevation (m asl)	Depth to Water (m) Below Ground	Well Depth (m)	Approx. Water Level (m asl)
R1	Gabriola	Aug 19 to Aug 26 2012	35	12	12.9	30	0
R2	Gabriola	Aug 19 to Aug 26 2012	180	8	7.8	46	0
R3	Gabriola	Aug 19 to Aug 26 2012	75	6	5.9	50	0
R4	Gabriola	Aug 19 to Aug 26 2012	455	6	2.6	20	3
R5	Gabriola	Aug 26 to mid Oct 2012	115	40	35.9	30	4
R6	Gabriola	Aug 26 to mid Oct 2012	220	10	33.3	30	<0
R7	Gabriola	Aug 19 to Aug 26 2012	165	4	1.6	5	4
R8	Gabriola	Aug 19 to Aug 26 2012	90	8	17.9	36	<0
R9	Gabriola	Aug 19 to Aug 26 2012	120	16	8.9	12	7
R10	Mudge	Oct 10 to Oct 30 2012	75	6	5	15	1

1.2 Tide Gauge Data Sources

Ocean tide observations were obtained from Fisheries and Oceans Canada tide gauges (see map in Figure C-1) at Point Atkinson (West Vancouver), Victoria Harbour, and Campbell River on Vancouver Island. Predicted ocean tides were downloaded from Fisheries and Oceans Canada Tide Prediction 2012 Tables, Volume 5 for Silva Bay (Gabriola Island) and Nanaimo Harbour.

The tide graphs were compared and the most similar tide observation and prediction was matched (see Figure C-2). Point Atkinson has the most similar observations (timing and magnitude of tide peaks) to Silva Bay on Gabriola Island, which is used as the most representative predicted tide location for this analysis. There will be small differences in tide cycle and timing of low and high tide maxima on different shores of Gabriola Island because of local ocean currents. The differences should be small and the analysis method does not require that the timing of tides be exact, only that the amplitude of tide be correct.

1.3 Water Level Processing

The water levels in residential wells were processed in several steps to remove barometric pressure effects and linear trends. An example of this processing methodology is shown for point R6 Figure C-3 and is described in this section.

The raw water levels (as water pressure above sensor) were compensated for barometric pressure variation because the transducers read total pressure of water above them plus the barometric pressure acting on the water table. Therefore these “unvented” transducers will show apparent water level variation equal to barometric pressure variation even if actual water elevation does not change.

Barometric pressure was compared for various locations around Gabriola Island during a short period of monitoring of barometric pressure in one dry well. There is barometric pressure recorded also at the Provincial observation wells (MOE pers. comm.), but the data were not available for the Aug-Oct months in 2012 during completion of this report. The barometric pressure had nearly identical hourly values on Gabriola Island, Nanaimo Airport, and Vancouver Airport (YVR). The YVR hourly data were used because they have the most complete and 24 hour coverage. This accuracy of barometric pressure is sufficient for this analysis.

There are also local trends in groundwater level not related to atmospheric effects or tides. These trends were not consistent between different wells, suggesting local effects only. Causes may be natural drainage of the aquifer during the dry summer period and local drawdown of water levels by nearby wells (only seen strongly at one monitoring point R8). For tidal analysis, the most unchanging or the most linearly changing section of water level record was selected. Linear trends were calculated subtracted from the record to leave only tidal signal.

1.4 Observed Water Levels and Tides in Wells

Almost all water well observations show clear tidal cycle which can be fitted to sea tides after data processing. There are a variety of groundwater level responses to ocean tides observed and most wells show a dominant response to atmospheric pressure variation, which was subtracted out during data processing, and other local trends in groundwater level. All processed water levels and selections of the tide cycle for tidal analysis, along with the amplitude-shifted water level to match ocean tide were graphed and are included in Figure C-4 to Figure C-13 for the R-wells. The Provincial observation well tidal cycles selected for analysis are included in Figure C-14 to Figure C-16.

A summary of observations of tidal cycles in wells is:

- R1 has very strong tide cycle, with tide amplitude about half that of ocean tide (Figure C-4). The tide graph is similar to sea tides (a close match to predicted tide at Silva Bay), without any lag time observed. This well is located near shore and it is connected by large fractures to the sea, such that water levels respond strongly to sea level changes during tides. This well is 3M from shore and has some salt water intrusion which occurred in the past few years.
- R2 (Figure C-5) has a clearly defined tidal response with small lag time. The tide cycle amplitude was increased by factor of 6 to match ocean tides. This is a strong tide cycle considering that this well is 180m away from shore.
- R3 (Figure C-6) has a very small tidal response which required a large increase of tide cycle amplitude in well by factor of 700 to match ocean tides. The data are noisy but acceptable.
- R4 (Figure C-7) has a clearly defined tidal response with a small lag time. The tide cycle amplitude was increased by factor of 250 to match ocean tides. However, this point is quite far from shore (455m), so the tide response is very strong at this distance.
- R5 (Figure C-8) is much closer to shore (115m) than R4, but nevertheless has a much weaker tide cycle than R4. The tide cycle is clear and its amplitude was increased by factor of 280 to match ocean tides.
- R6 (Figure C-9) has a strong tide cycle and moderate transmissivity of fractures in that area. The tide cycle amplitude was increased by a factor of 23.5 to match ocean tides. There was a strong trend in water level in this well, perhaps due to pumping of the aquifer in that area. This observed trend was removed before analysing the tidal influence.
- R7 (Figure C-10) has a small response to ocean tides and a noisy tide signal. The tide cycle amplitude in the well was increased by factor of 1,000 to match ocean tides.
- R8 (Figure C-11) was influenced by pumping of nearby well (25m away from R8) to fill two 1,200 USgal reserve cisterns. The tide data are only useful for a few hours on August 19th and at 16:00 there is large drawdown of groundwater level, which reduced water level in well to below the depth of water level sensor. The water level did not recover for the whole week during the monitoring, possibly due to continuous pumping of nearby wells. The water quality in these two wells, which are located only 90m from the shore, and pumped often, is very good. Tidal analysis was done to the short tide signal, which is not ideal, but the tide cycle amplitude was increased by factor of 4 to match ocean tides during that short time of monitoring.

- R9 (Figure C-12) had a clear, but weak, tide cycle. The tide cycle amplitude in the well was increased by factor of 160 to match ocean tides.
- R10 (Figure C-13) was the only tide monitoring point on Mudge Island because other wells could not be accessed during the site visit. The tide cycle in this well is small, although this point is located only 75m from shore. The tide cycle amplitude in well was increased by factor of 300 to match ocean tides.
- Provincial observation well 194 (Figure C-14) has a strong tide cycle, with a long lag time of peak tides because this observation well is located 1.6km away from ocean shore (in the westerly direction which is closest distance). For a well located so far from shore, it has a very strong tide response.
- Provincial observation well 196 (Figure C-14) had a strong tide cycle observed, despite the large distance from shore (1.1km). The tide cycle amplitude was increased by factor of 120 to match ocean tides.
- Provincial observation well 197 (Figure C-15) has a strong tide cycle (amplitude is 140 times less than ocean tide).
- Provincial observation well 317 (Figure C-15) is located near observation well 196 and much closer to shore, but it has a relatively weaker tide cycle. The tide cycle amplitude was increased by factor of 220 to match ocean tides.
- Provincial observation well 316 (Figure C-16) has a small tidal cycle which is very noisy and difficult to detect. Tide cycle amplitude was increased by factor of 1700 to match ocean tides (and only approximately).
- Provincial observation well 385 (Figure C-16) has a moderate tide cycle, considering that this well is located 808m away from shore. Tide cycle amplitude was increased by factor of 50 to match ocean tides. The data are very noisy because of local drawdowns caused by frequent pumping. For tidal analysis the least affected time period was chosen during a recovery of water levels (the non-linear trend was removed).

2 Tidal Analysis

2.1 Method

The ocean tide acts as a naturally changing hydraulic boundary and the aquifer water level responds. The pressure wave propagates inland and the effect decreases with distance from shore along the most permeable fracture network (it may not be the shortest straight line distance to shore). The tidal cycle has several components, semi-diurnal, diurnal and others.

Tidal analysis is a very useful analytical method for determining aquifer properties of relatively large volume of rock mass. The tidal analysis method (Jacob, 1950; Ferris, 1951; Townley, 1995) is a simple analytical method for estimating tidal efficiency and aquifer diffusivity.

Tidal efficiency (TE) is a ratio of the amplitude of water level fluctuations in the aquifer (detected in wells) to the amplitude of fluctuations in ocean tides, with a value range from 0 to 1.

$$TE = \text{aquifer response} / \text{ocean tide} = H_x / h_0 = \exp [-x ((\pi S) / (T t_p))^{0.5}]$$

where x is the distance from the tidal boundary (the ocean shore at mid tide), S is the aquifer storage coefficient, T is aquifer transmissivity, t_p is the period of tidal cycle, Hx is tide height in aquifer at distance x, h0 is tide height in ocean.

Diffusivity (or hydraulic diffusivity) is the ratio of transmissivity and storativity (T/S). For the analysis of the observed tidal groundwater level fluctuation, Jacob's solution provides two methods: the amplitude attenuation method and the time lag method.

Amplitude method: $\text{diffusivity} = T/S = (\pi / t_p) * [-x / \ln (Hx/h_0)]^2$

or $S/T = (t_p / \pi) * [\ln (Hx/h_0) / (-x)]^2$

Time-lag method: $\text{diffusivity} = T/S = x^2 P / (4 \pi (\text{lag})^2)$

where x is the distance from the tidal boundary (the ocean shore at mid tide), S is the aquifer storativity, T is aquifer transmissivity, P is the period of tidal cycle, and lag is the time shift between tide cycle phase between tide detected in aquifer and sea tide.

The true tidal efficiency of the aquifer at the seacoast is then determined from the apparent tidal efficiency and used to obtain the specific storage. This result and the tidal time lag are used to calculate the hydraulic conductivity. The method was originally tested in P.E.I. in Canada, and yielded results compatible with pumping test data (Carr and Van Der Kamp, 1969). Since then many studies have used tidal analysis and several were used as a source of methodology description here (Smith and Hick, 2001; Merritt, 2004). However, the lag time is difficult to measure because the time of peak tide is slightly different at different locations and tide gauges are not available in most places. In this report, the time lag method was not used, only the amplitude method.

The limitation of using only one method (e.g. amplitude method) is that only the aquifer diffusivity can be calculated and not the separate values of transmissivity and storativity. If the aquifer storativity can be estimated by other test methods, the aquifer transmissivity can also be determined from the diffusivity and the storativity. In this report, at four wells (TH1, TH2, Obs Wells 194 and 196), the transmissivity from pumping tests was used, along with diffusivity ratio from tidal analysis, to estimate the storativity values.

2.2 Assumptions and Limitations

These solutions assume that the aquifer water and sea water boundary is vertical (which is approximately true), a straight coastline (true at small scale), and one-dimensional flow in a coastal confined aquifer. The solution is also applicable as a good approximation to water table fluctuations of an unconfined aquifer if the range of fluctuation is small in comparison to the saturated aquifer thickness. This is the case at Gabriola Island.

Where there are confining (less permeable) layers between the coastal aquifer and the sea bed, or a very irregular coast shape, or a small length of the aquifer, etc., the simple solution may be not applicable or may produce large error. Analytical solutions for complicated aquifer configurations have been derived for L-shaped coastal aquifers, confined aquifers extending under tidal water, three layered (aquitard/aquifer/aquitard) systems, and other types.

There are also solutions for asynchronous dual-tide propagation from different directions (e.g. on small islands or narrow peninsulas). On Gabriola Island, this may be a strong effect on peninsulas of land such as in north-west part of island near Taylor Bay, Descanso Bay, or in land peninsulas near Silva Bay. On Mudge and DeCourcy Islands, tides may affect wells from different directions, producing superimposed tide cycles which may be difficult to separate. In those cases, the overall amplitude of tide can be used, as was done in this report, without adjustment for lag time. Essentially, the most dominant tide cycle from nearest or most connected shore is used.

Since the geometry and properties of hydrogeological units on Gabriola and Mudge Islands is not known very well, only a simple solution method for a straight coast infinite confined aquifer was used in this report. The values obtained are indicative but not exact.

Some of the very small tide signals in wells may be caused partly by earth tides rather than only by ocean tides.

2.3 Results

2.3.1 Diffusivity and Transmissivity

The results show that the hydraulic diffusivity of aquifer has a large variation on Gabriola Island (Table C-2). The largest diffusivity and transmissivity are near large fracture zones in sandstone. The smallest values are in sandstone or shale. There is not enough information to determine what type of geologic units the wells are screened in or do meaningful averages for geologic units at this time, but most of these wells are completed in sandstone of Geoffrey Formation or in Northumberland Formation shale. Such an analysis can be done once the well depths and casing depths are confirmed.

Transmissivity (T) was estimated (as an indicator of permeability) by assuming a value of storativity of $1x10^{-4}$. The calculated transmissivity value is dependent on the assumed storativity value and may be larger or smaller by an order of magnitude. There is uncertainty in all values presented and values should be viewed as order-of-magnitude estimates.

Observations at particular wells are:

- R2 – relatively high diffusivity and transmissivity of aquifer in this area, compared to other places monitored
- R3 – low diffusivity and transmissivity of aquifer in this area
- R4 - high diffusivity and transmissivity, perhaps a large fracture zone along middle of Descanso Valley, possibly at a contact along Spray Fm. shale and Geoffrey Fm. sandstone
- R5 - much lower diffusivity and transmissivity of sandstone aquifer here, compared to middle of the valley at R4
- R6 – this well lies in a small valley along a fracture zone, and diffusivity is moderate
- R7 – low diffusivity and transmissivity. R7 is closer to shore than nearby R6, but it has much lower diffusivity of aquifer. It is likely not in a fracture zone and the well may be completed below a shale layer which can decrease the response to ocean tides in this well.
- R8 - moderate diffusivity and transmissivity in this area. The shale layers in this area which dip down away from land are likely responsible for reducing the tidal cycle in wells and also reducing risk of salt water intrusion.
- R9 - this well and other wells in this area are very productive but there are clay layers within the productive shale aquifer of the Northumberland Formation, which are likely responsible for reducing the connection of well to ocean tide influence. The resulting diffusivity and transmissivity were calculated to be relatively low, but are an average of the clay and shale layers in this area. The shale fractures are likely more conductive than indicated by tidal analysis.
- R10 – low diffusivity and transmissivity of rocks in this area.
- Provincial observation well 194 – this well has the highest diffusivity and transmissivity value of any wells monitored on Gabriola Island.

- Provincial observation well 196 - This well is close to the fracture zone tested by Piteau Associates in 1993. Diffusivity of the aquifer is moderate.
- Provincial observation well 197 - moderate diffusivity in this area.
- Provincial observation well 317 - moderate diffusivity, but lower than the fracture zone in which the more distant from shore well 196 is located in.
- Provincial observation well 316 – moderate diffusivity in this area.
- Provincial observation well 385 – moderate but higher than average diffusivity and transmissivity of aquifer in this area.

2.3.2 Hydraulic Conductivity

Hydraulic conductivity (K) was calculated as an example, to show an order-of-magnitude value of K assuming that the fractured rock mass can be represented by an equivalent porous medium (EPM), having some average bulk properties. The calculation requires a saturated aquifer thickness value (b), which was estimated from the open borehole depth below water table level.

$$K = T / b$$

Depth to water was known in some wells and in other wells it was estimated from the water table map. Saturated well depth for TH test holes was estimated from reported drawdown during testing. The b-values are uncertain and the assumption is that groundwater flow occurs over that rock mass thickness.

The geomean of hydraulic conductivity is approximately $2x10^{-6}$ m/s, where 12 test results are clustered. There are 4 results larger than $1x10^{-5}$ m/s and 3 test results smaller than $5x10^{-7}$ m/s. This indicates a “fairly conductive” fractured rock in most places, which forms a productive aquifer. This magnitude of K would be expected from the groundwater use demand and typical water yields in most pumping wells on Gabriola Island.

This is a simple estimate to indicate the order of magnitude of K resulting in tidal analysis, but the actual K values are unkonwn.

2.3.3 Storativity

The estimated storativity values range from $1x10^{-6}$ to $1x10^{-4}$ based on four wells analysed (Table C-3). These are indicative values and do not represent the whole island. Most values are less or equal to $1x10^{-5}$. The expected true value of storativity of sandstones, in which these wells are mostly completed, is between $1x10^{-6}$ and $1x10^{-5}$. However, there is a wide range of estimated values and it is very uncertain.

Table C-2 Results of tidal analysis calculations.

Well	Amplitude of Sea Tide	Tidal Period		Amplitude Change Factor (h0/Hx)	Amplitude at Point x	Distance to Shoreline	Hydraulic Diffusivity Ratio		T = S/T * S (estimated assuming S = 1x10-4)	Open Well Interval (estimated well depth below water table)	Hydraulic Conductivity (estimated using Equivalent Porous Media assumption)	Notes
	h_o (m)	hours	t_p (s)		H(x) (m)	x (m)	S/T	T/S	T (m^2/s)	b (m)	K (m/s)	
R1	1.33	11.10	39960	2.1	0.63333	35	5.72	0.17	$2x10^{-5}$	17	$1x10^{-6}$	1
R2	1.33	11.10	39960	6.0	0.22167	180	1.26	0.79	$8x10^{-5}$	38	$2x10^{-6}$	
R3	1.33	11.10	39960	700	0.0019	75	97.05	0.01	$1x10^{-6}$	44	$2x10^{-8}$	
R4	1.35	11.80	42480	250	0.0054	455	1.99	0.50	$5x10^{-5}$	17	$3x10^{-6}$	
R5	1.45	11.24	40464	280	0.00518	115	30.9	0.03	$3x10^{-6}$	14	$2x10^{-7}$	5
R6	1.70	13.10	47160	23.5	0.07234	220	3.09	0.32	$3x10^{-5}$	17	$2x10^{-6}$	5
R7	1.70	13.10	47160	1000	0.0017	165	26.31	0.04	$4x10^{-6}$	3	$1x10^{-6}$	
R8	1.13	11.58	41700	4	0.28125	90	3	0.32	$3x10^{-5}$	18	$2x10^{-6}$	
R9	1.13	11.58	41700	160	0.00703	120	24	0.04	$4x10^{-6}$	3	$1x10^{-6}$	
R10	1.15	12.93	46548	300	0.00383	75	86	0.01	$1x10^{-6}$	10	$1x10^{-7}$	2
TH1	1.2	12	43200	24	0.05	1060	0.12	8.09	$8x10^{-4}$	50	$2x10^{-5}$	3, 8
TH2	1.2	12	43200	24	0.05	288	1.67	0.60	$6x10^{-5}$	40	$1x10^{-6}$	3, 8
TH5	1.2	12	43200	30	0.04	985	0.16	6.10	$6x10^{-4}$	40	$2x10^{-5}$	3, 8
Obs Well 385	1.45	12	43200	50	0.029	808	0.32	3.10	$3x10^{-4}$	29	$1x10^{-5}$	7
Obs Well 316	1.45	12	43200	1700	0.00085	567	2.37	0.42	$4x10^{-5}$	11	$4x10^{-6}$	7
Obs Well 317	1.45	12	43200	220	0.00659	483	1.71	0.58	$6x10^{-5}$	19	$3x10^{-6}$	7
Obs Well 196	1.45	12	43200	120	0.01208	1125	0.25	4.02	$4x10^{-4}$	97	$4x10^{-6}$	7
Obs Well 197	1.45	12	43200	140	0.01036	1030	0.32	3.16	$3x10^{-4}$	78	$4x10^{-6}$	7
Obs Well 194	1.2	12	43200	15	0.08	1100	0.08	12.0	$1x10^{-3}$	56	$2x10^{-5}$	6

Tidal analysis 2012 FINAL.xlsx

Notes:
1 strong tide signal, connected through large fractures, close to shore
2 close to shore but low K (Mudge Island well)
3 estimated from reported values of amplitude of sea tide (Piteau, 1993)
4 very strong tide signal, despite large distance to shore
5 well depth was estimated
6 depth to water was from water table map
7 depth to water was from chart recorder data
8 b-value estimated from drawdown during pump test

Table C-3 Estimated storativity in wells by using pumping test transmissivity and diffusivity from tidal analysis.

Well	Diffusivity	Transmissivity from Pumping Tests (m^2/s)		Storativity = S/T x T	
	S/T	min	max	min	max
TH1	0.12	$3x10^{-6}$	$2x10^{-5}$	$4x10^{-7}$	$2x10^{-6}$
TH2	1.67	$7x10^{-6}$	$8x10^{-5}$	$1x10^{-5}$	$1x10^{-4}$
Obs Well 196	0.25	$3x10^{-6}$	$2x10^{-5}$	$8x10^{-7}$	$4x10^{-6}$
Obs Well 194	0.08	$2x10^{-5}$	$3x10^{-4}$	$1x10^{-6}$	$3x10^{-5}$

Tidal analysis 2012 FINAL.xlsx

3 References

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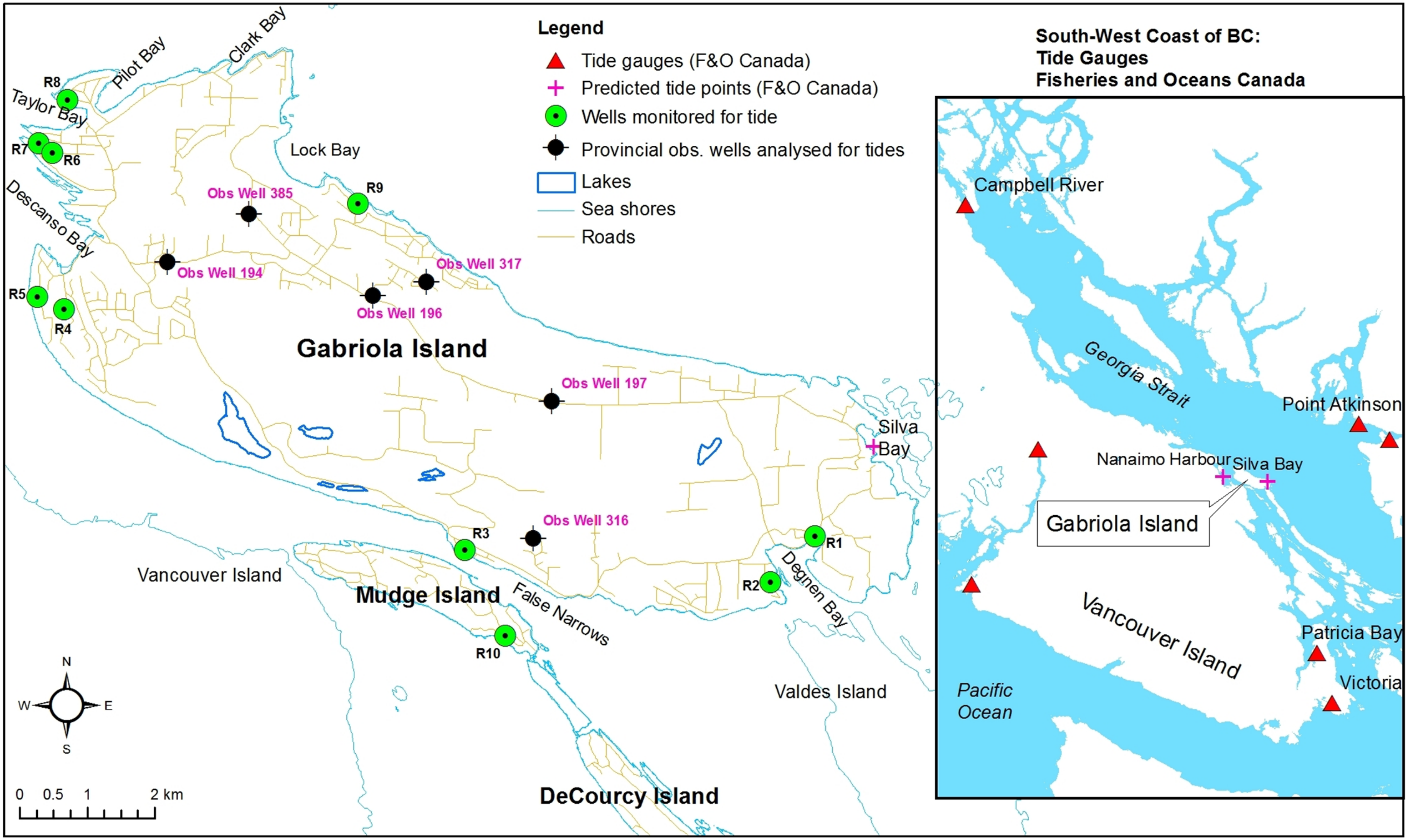

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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands)

Tide monitoring locations in wells on Gabriola and Mudge Islands, and tide gauges.

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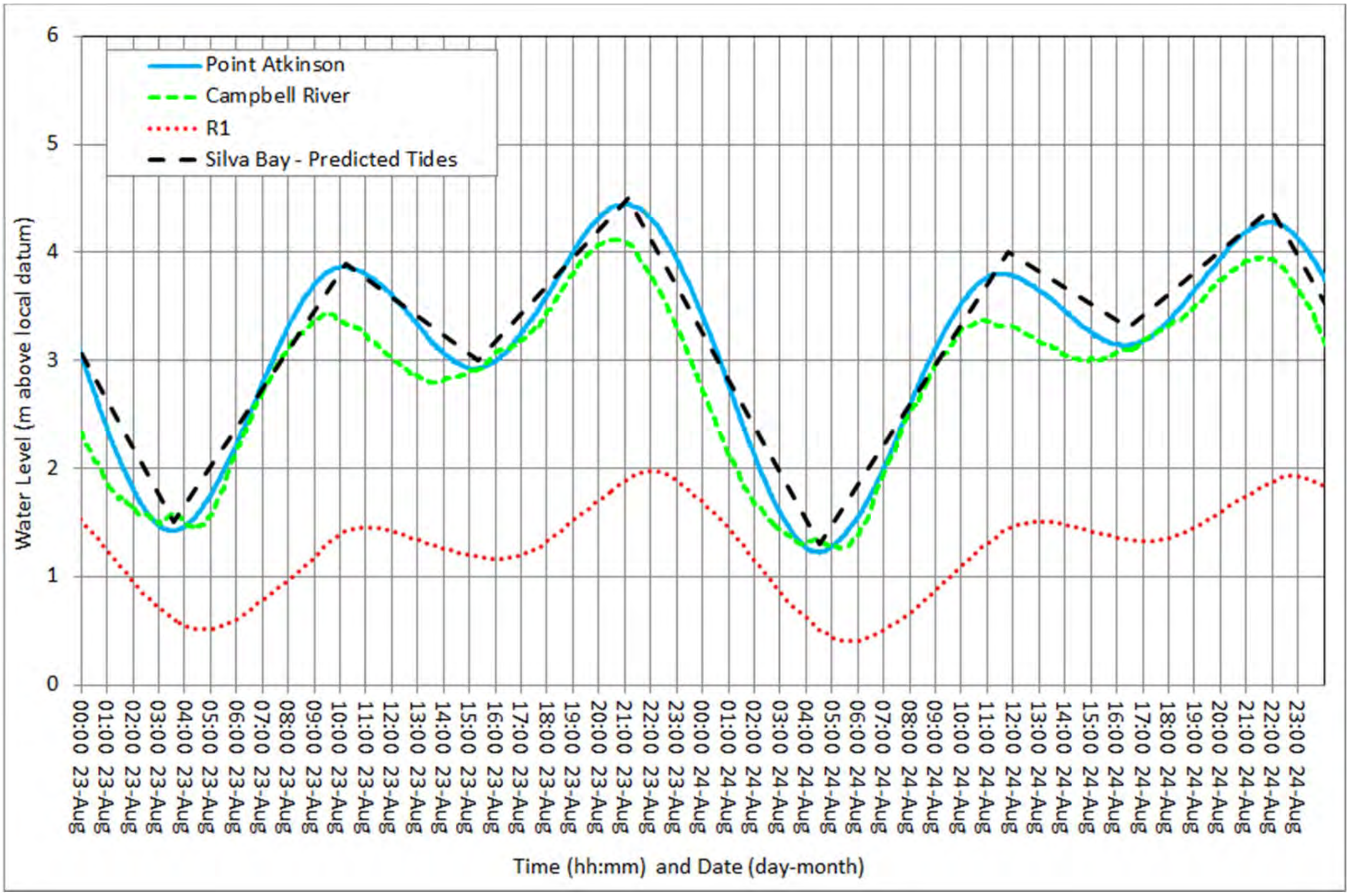

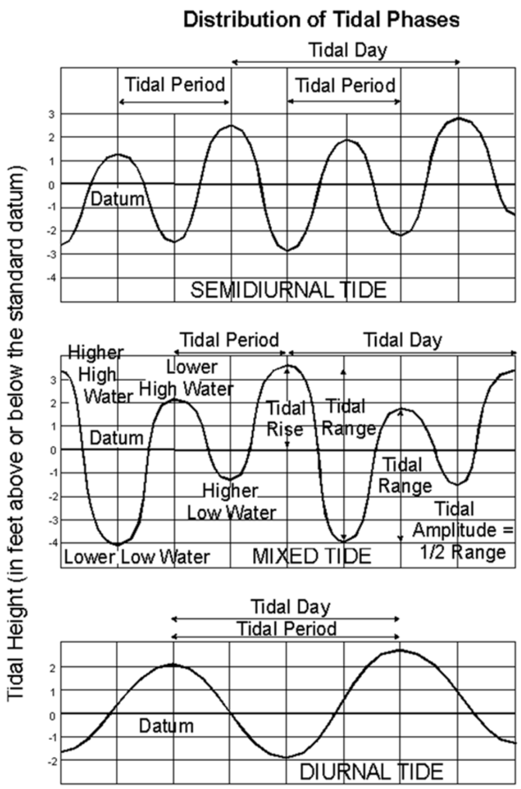

Water levels for tide - summary graphs FINAL

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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

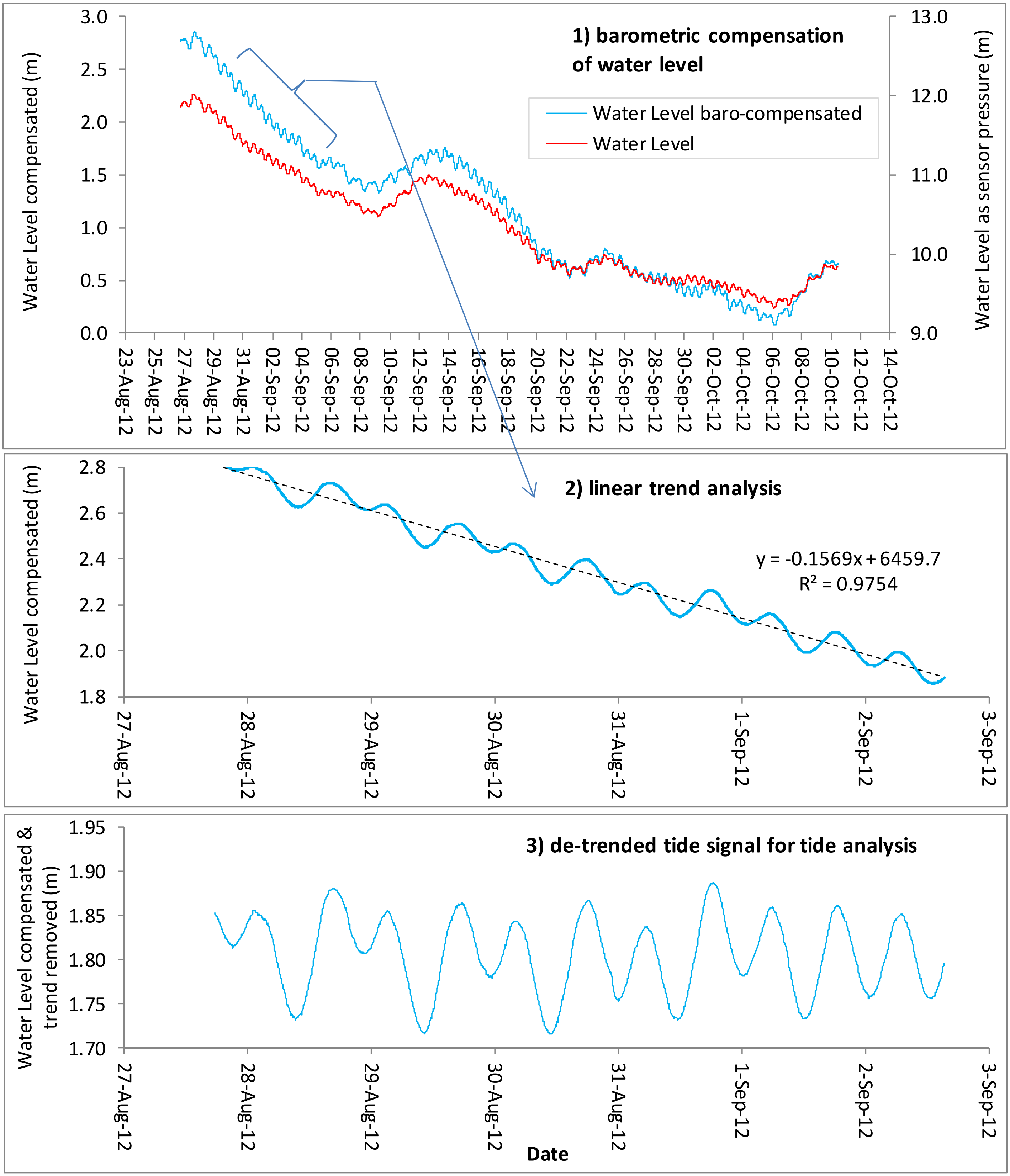
Comparing obsereved tides at gauges near Gabriola Island and predicted tide at Silva Bay

Job No: 1CR010.000

Filename: Figures C2-C16 tides in wells.pptx

Gabriola Island

Date:	Approved:	Figure:
April 2013	JS	**C-2**



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Tidal data processing example from residential well R6

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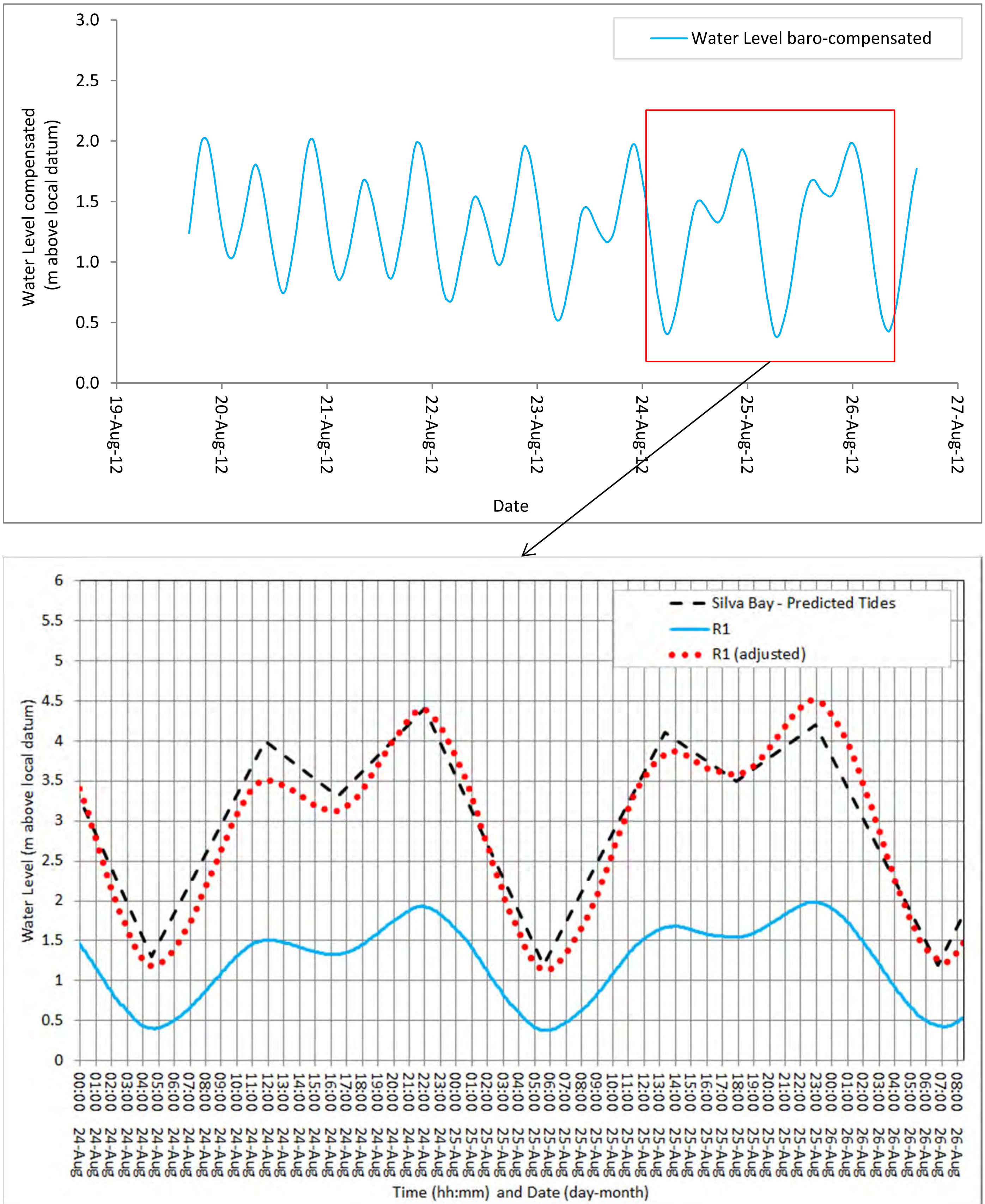

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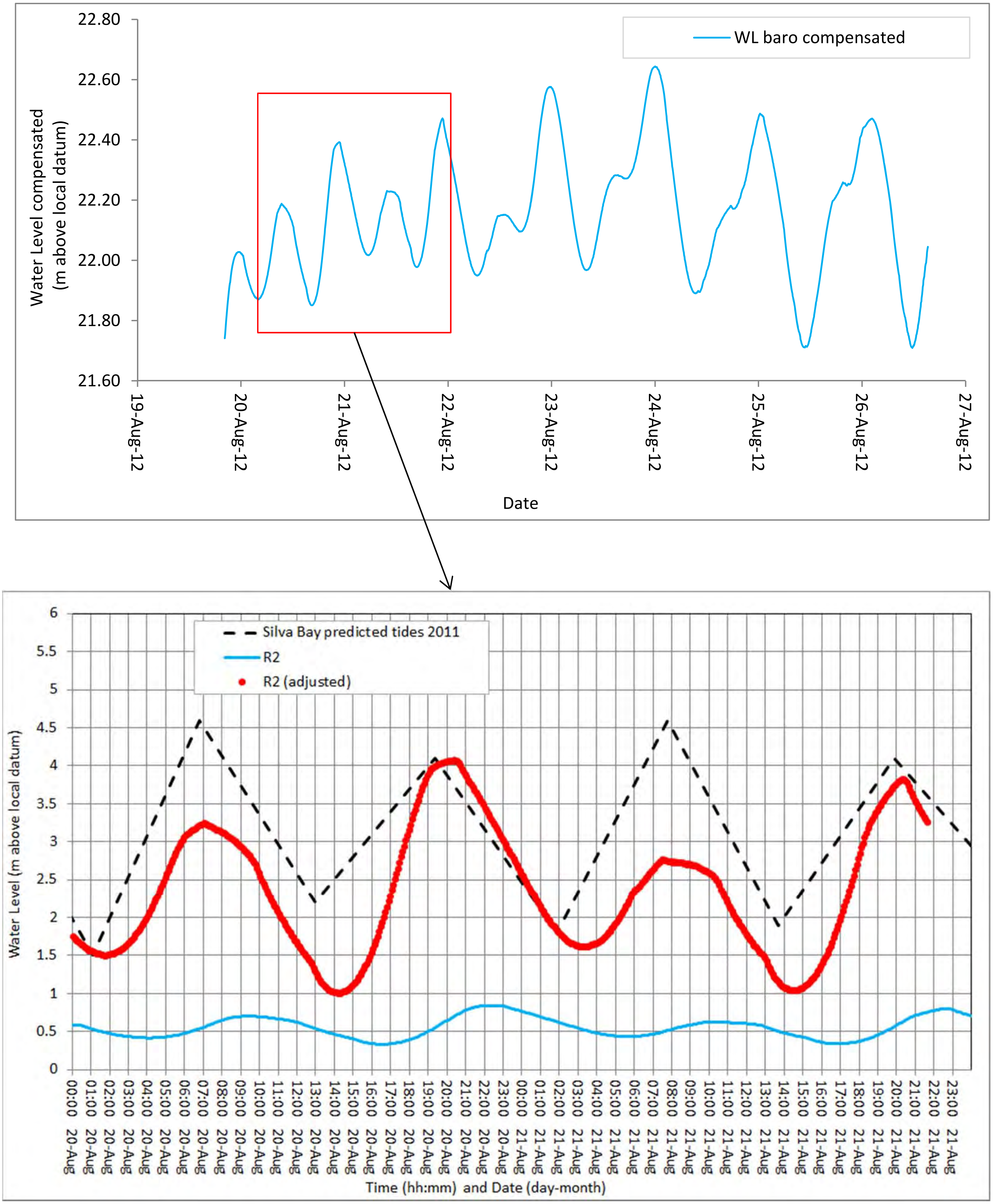
Job No: 1CR010.000 Filename: Figures C2-C16 tides in wells.pptx	Gabriola Island	Date: April 2013 / Approved: JS / Figure: **C-4**

Water levels for tide - summary graphs FINAL



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

R2 Water Level and Tides

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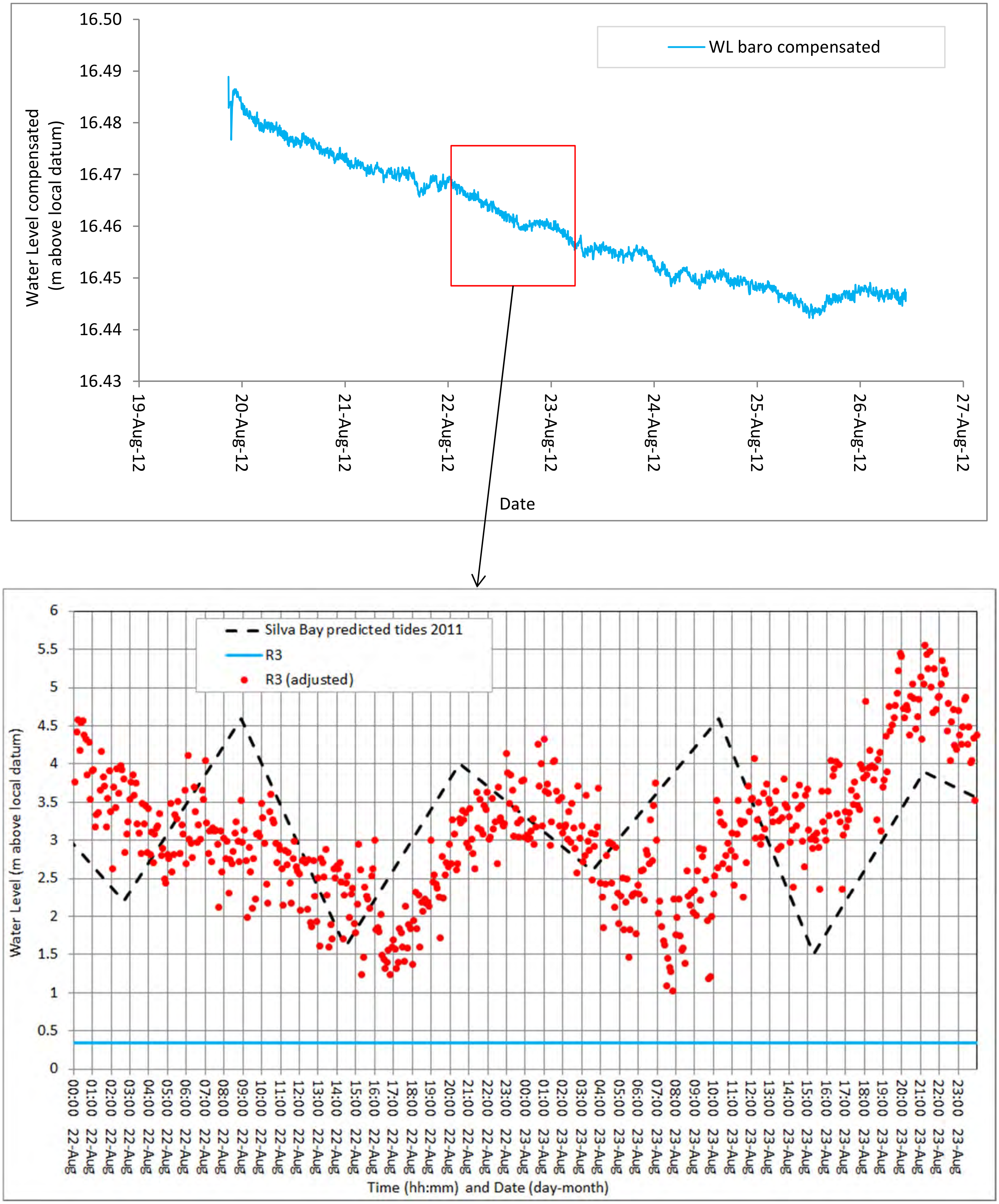
Water levels for tide - summary graphs FINAL



Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

R3 Water Level and Tides

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Gabriola Island

Date:	Approved:	Figure:
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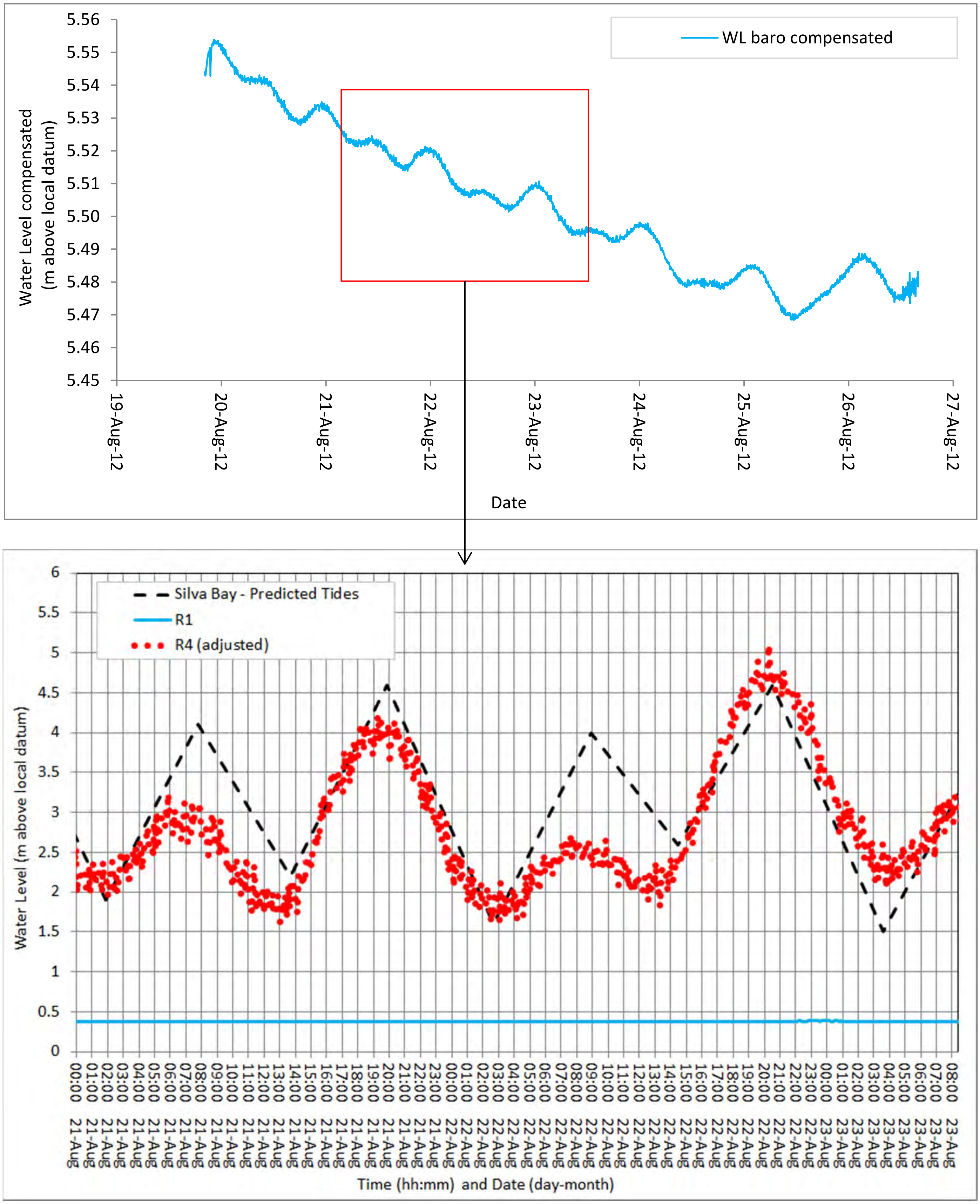
Water levels for tide - summary graphs FINAL



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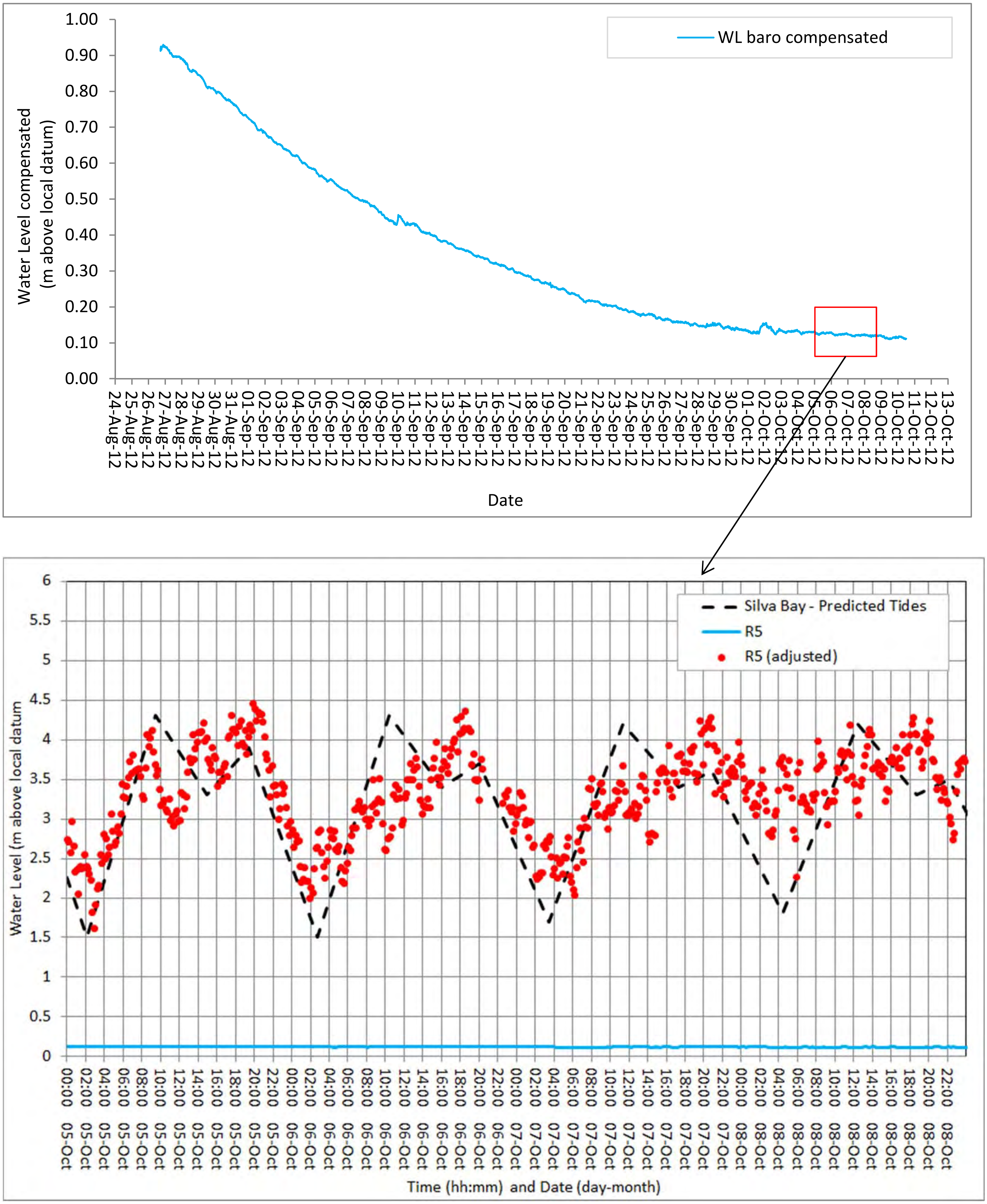

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

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REGIONAL DISTRICT OF NANAIMO

Gabriola Island

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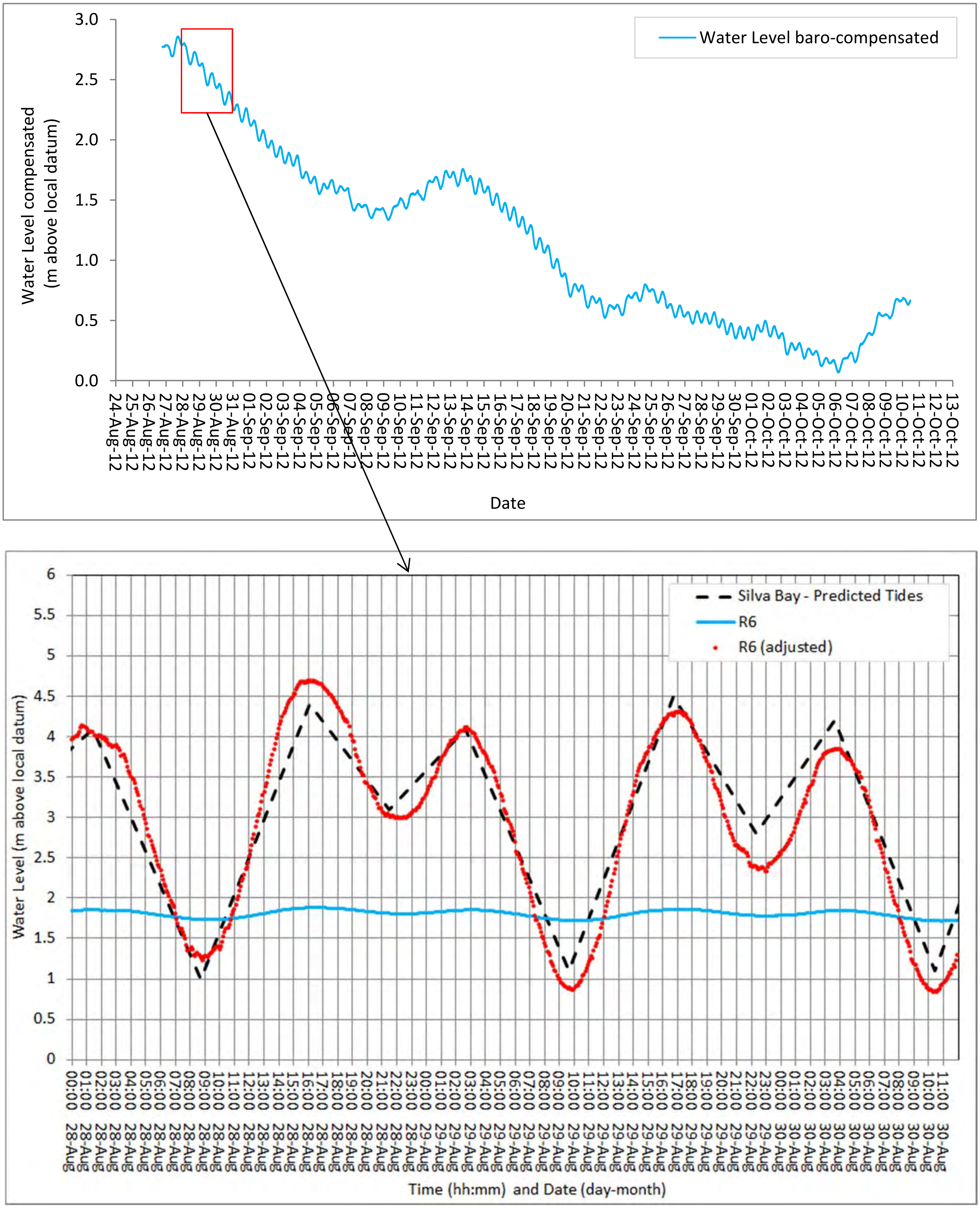

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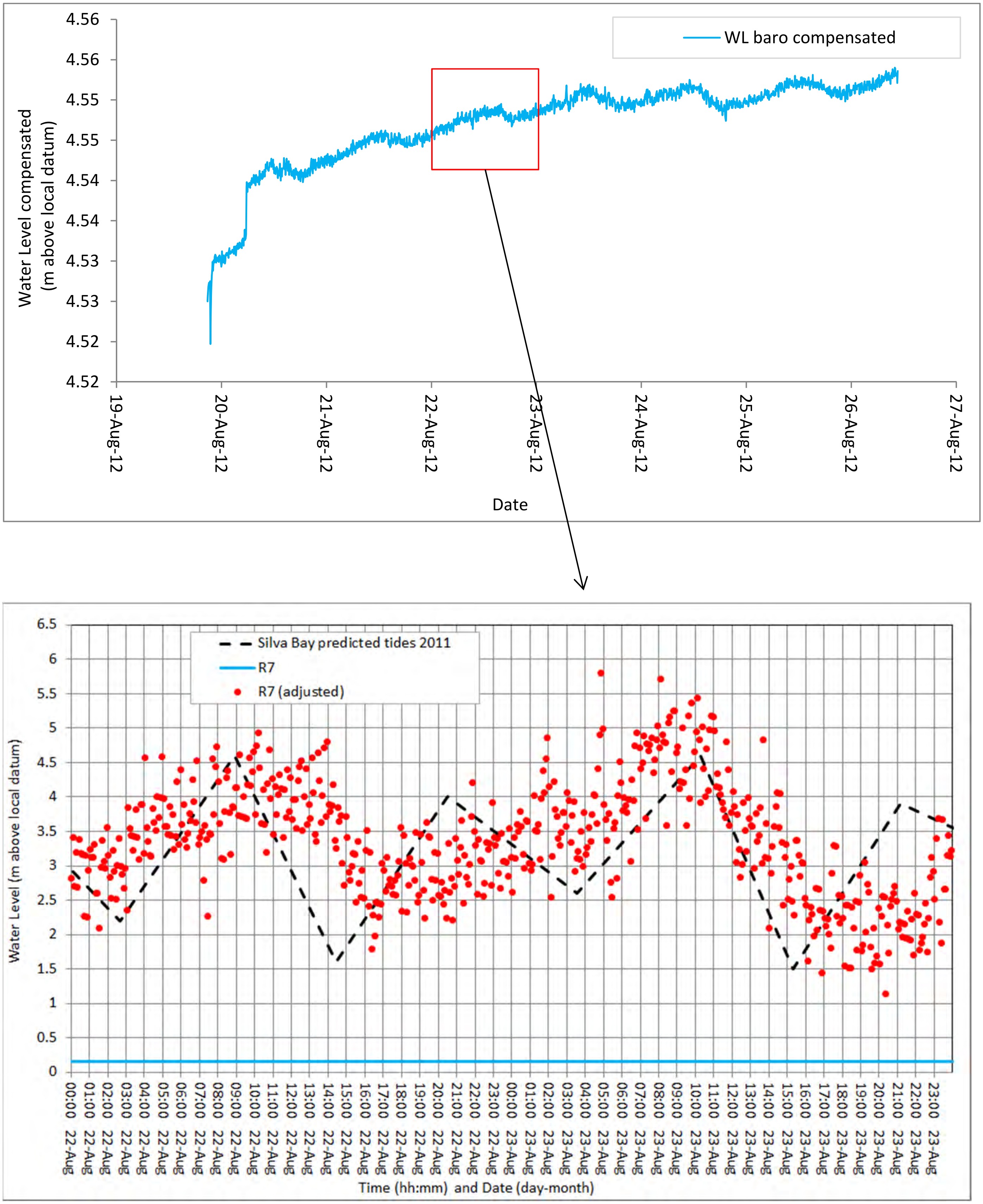

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

R7 Water Level and Tides

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Job No: 1CR010.000

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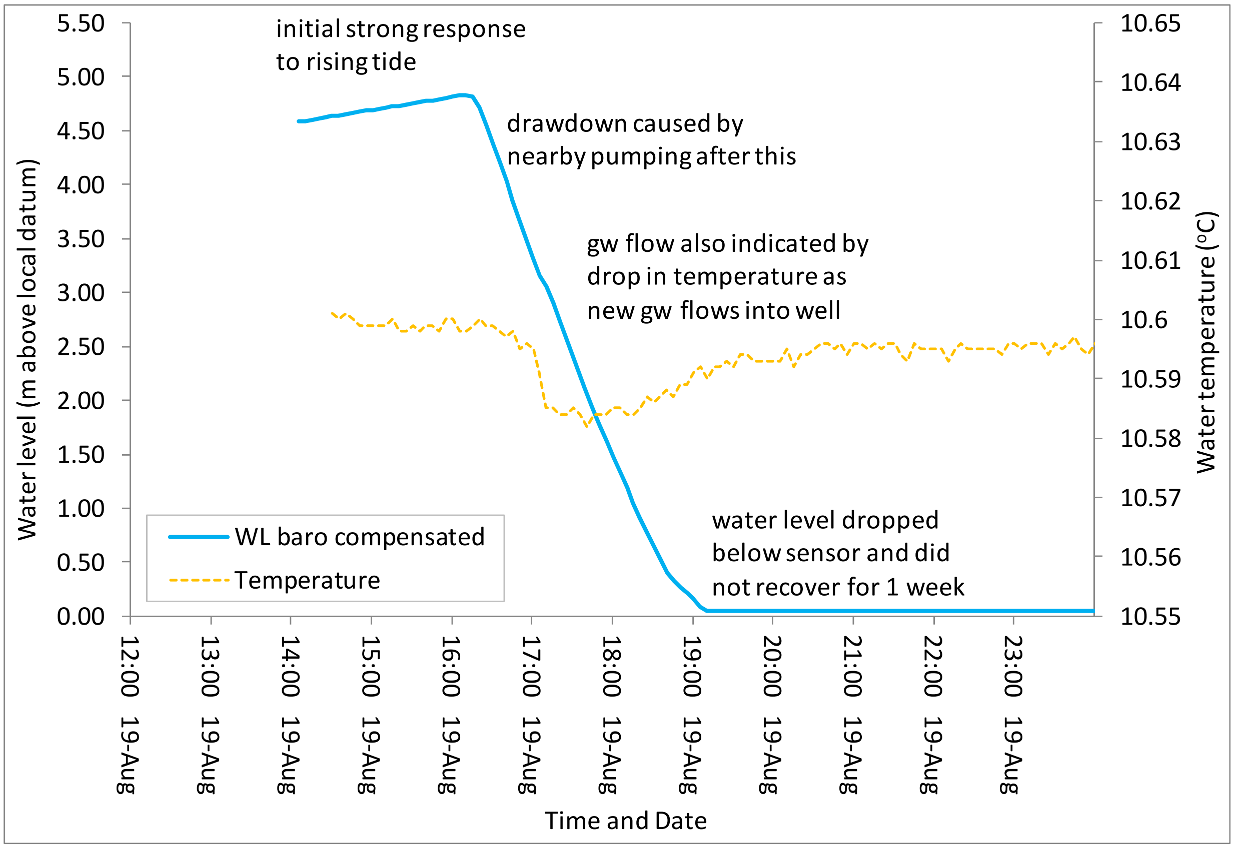
Gabriola Island

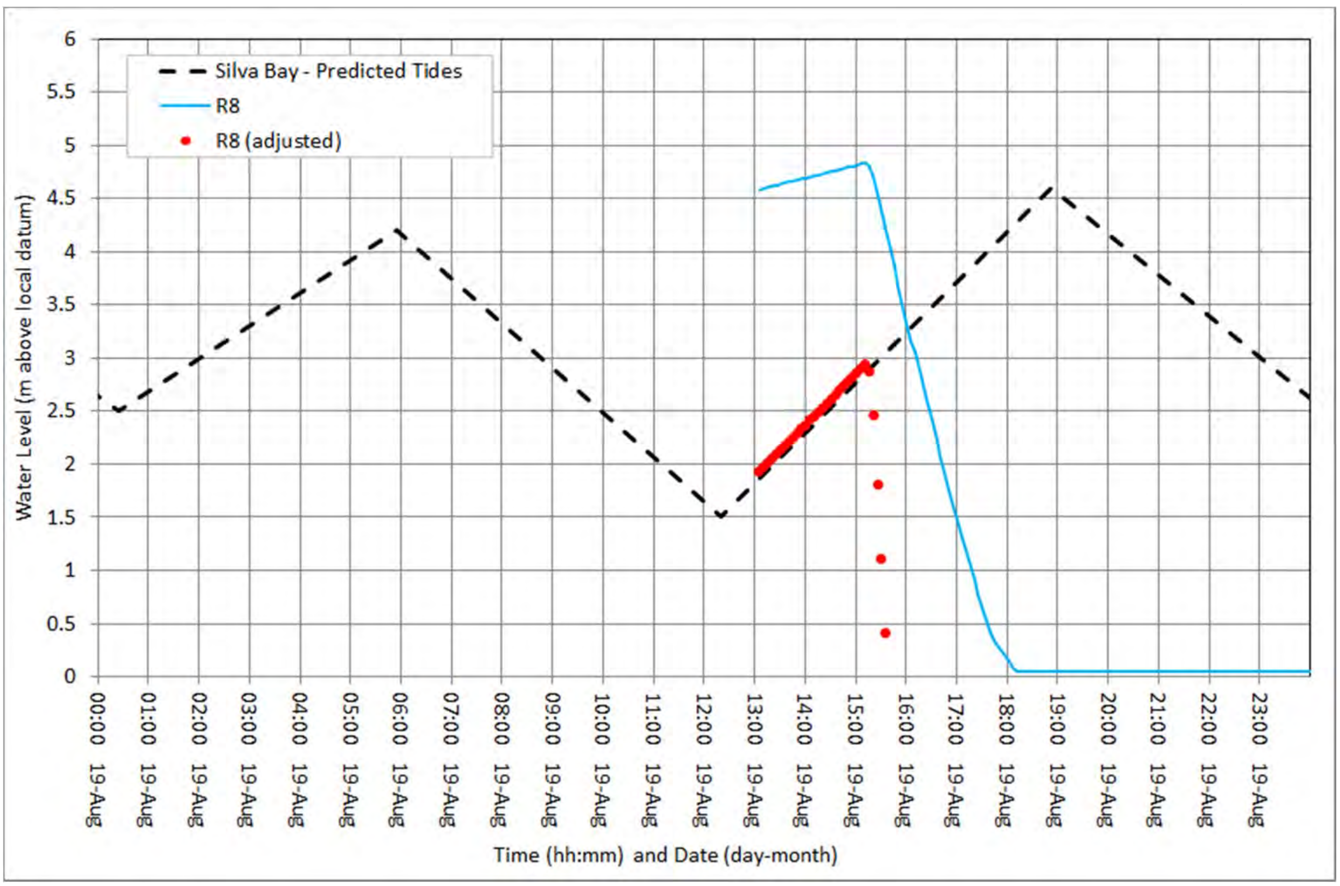
Date: April 2013

Approved: JS

Figure: **C-10**

Water levels for tide - summary graphs FINAL





Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

R8 Water Level and Tides

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Job No: 1CR010.000

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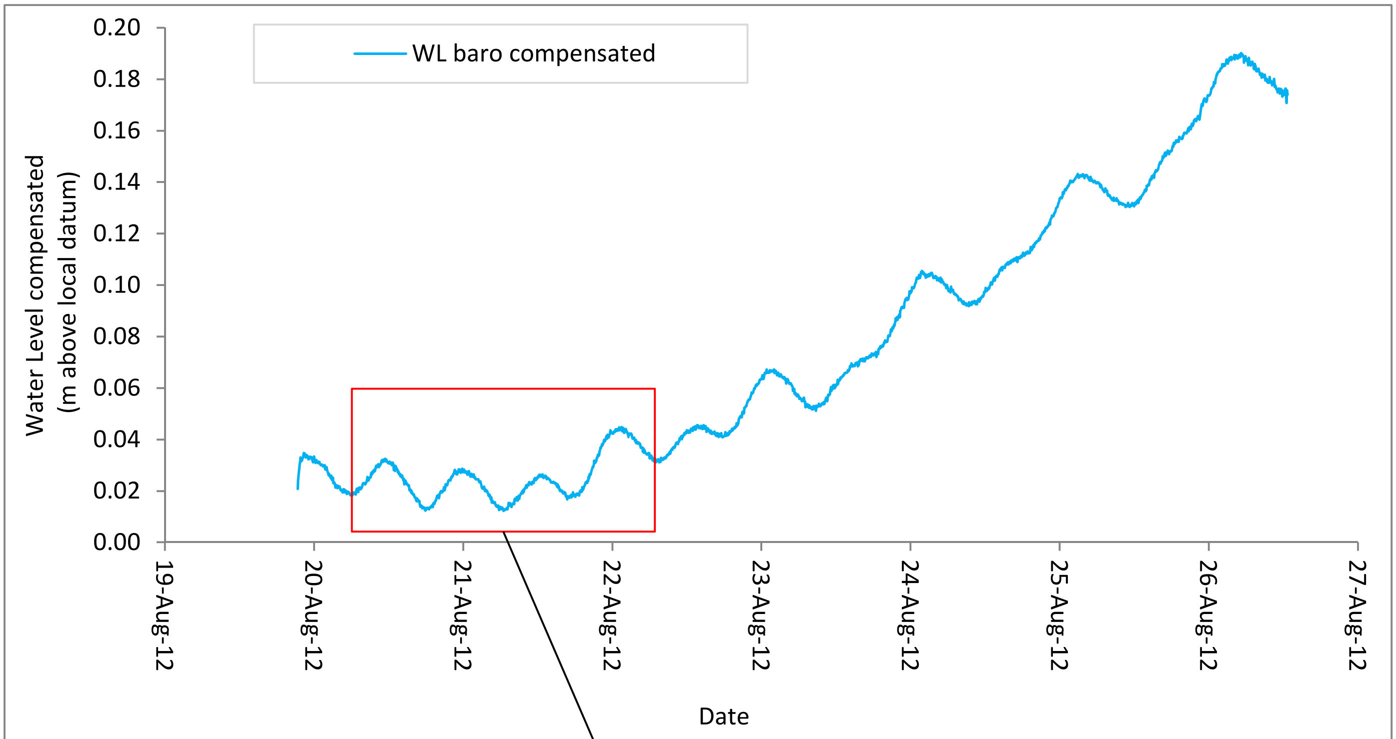
Gabriola Island

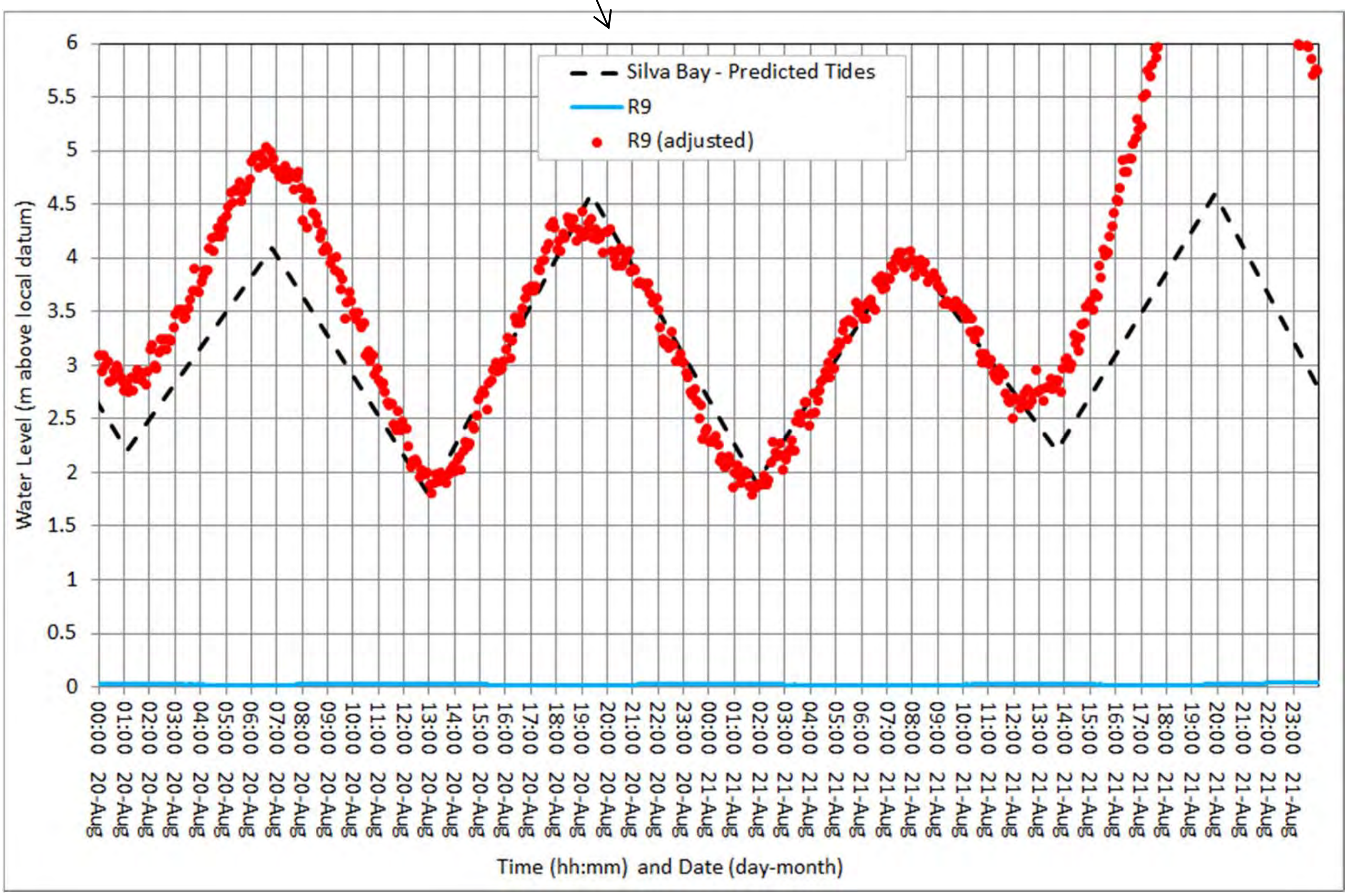
Date: April 2013

Approved: JS

Figure: **C-11**

Water levels for tide - summary graphs FINAL





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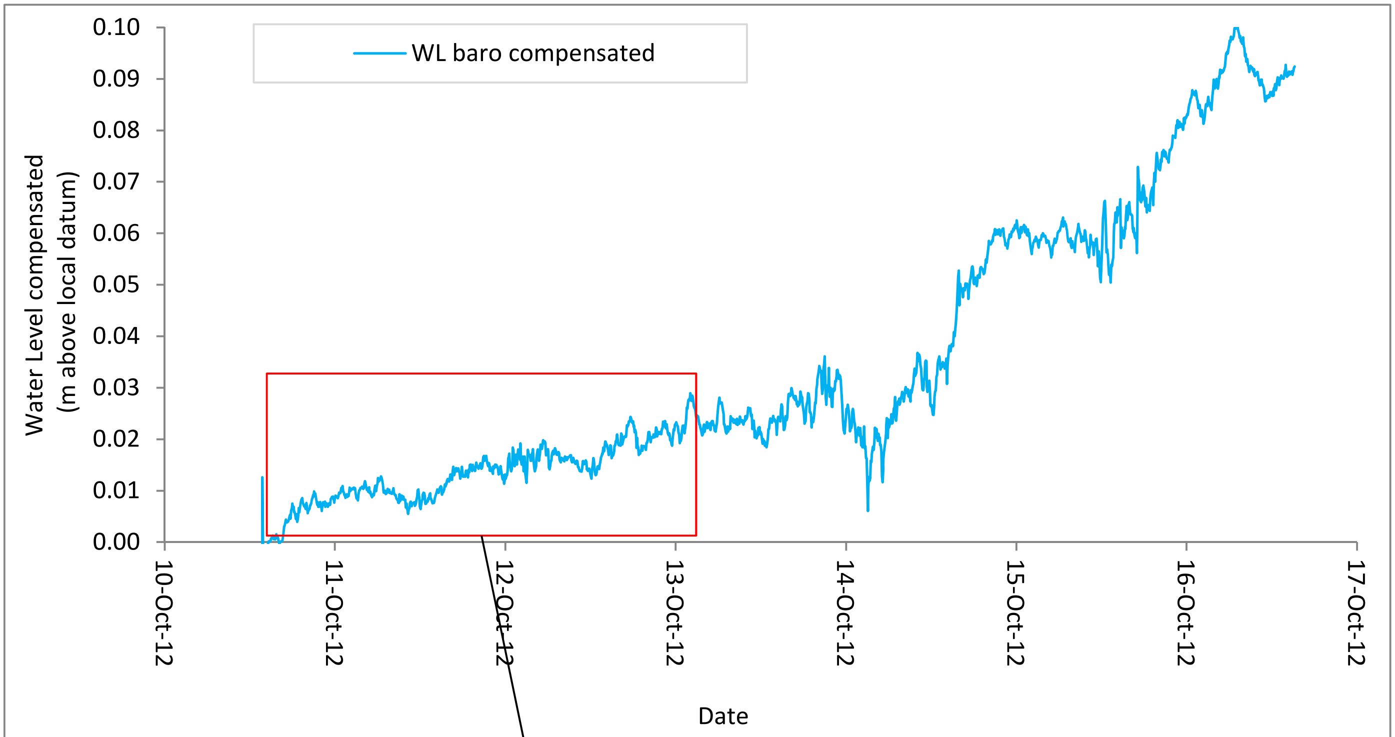

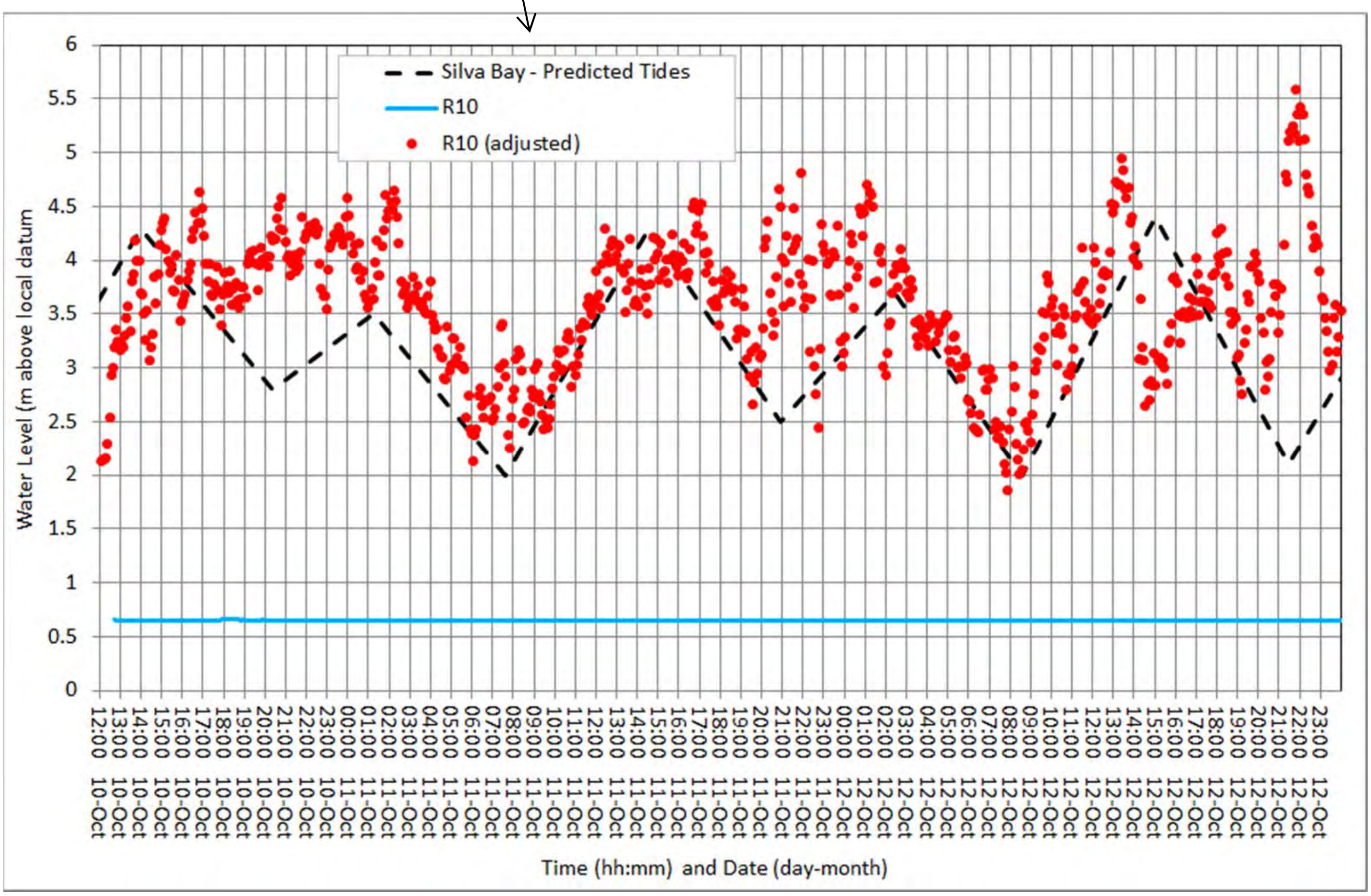

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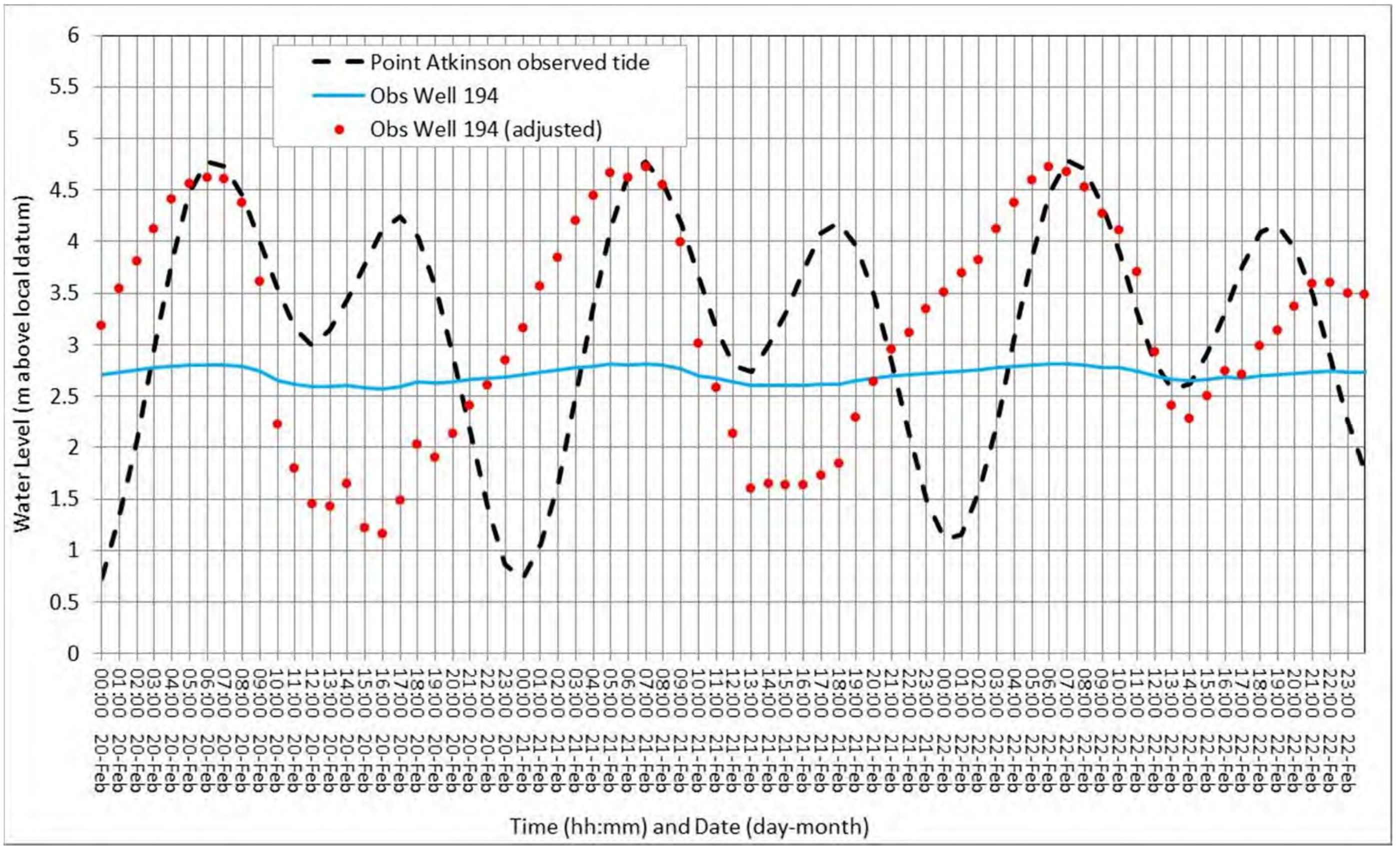
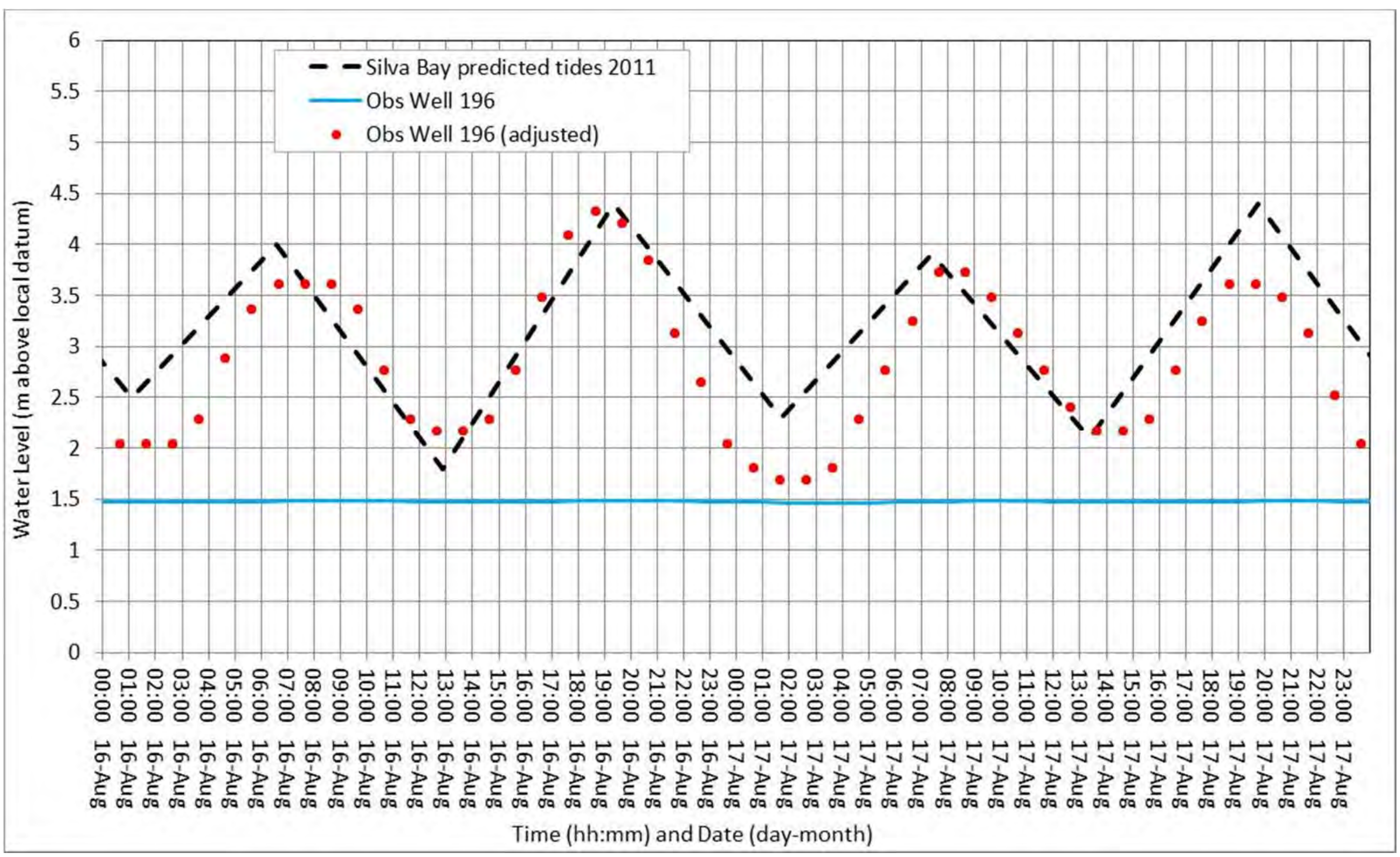
Water levels for tide - summary graphs FINAL





srk consulting

REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Provincial Obs. Well 194 and 196 Water Level and Tides

Job No: 1CR010.000

Filename: Figures C2-C16 tides in wells.pptx

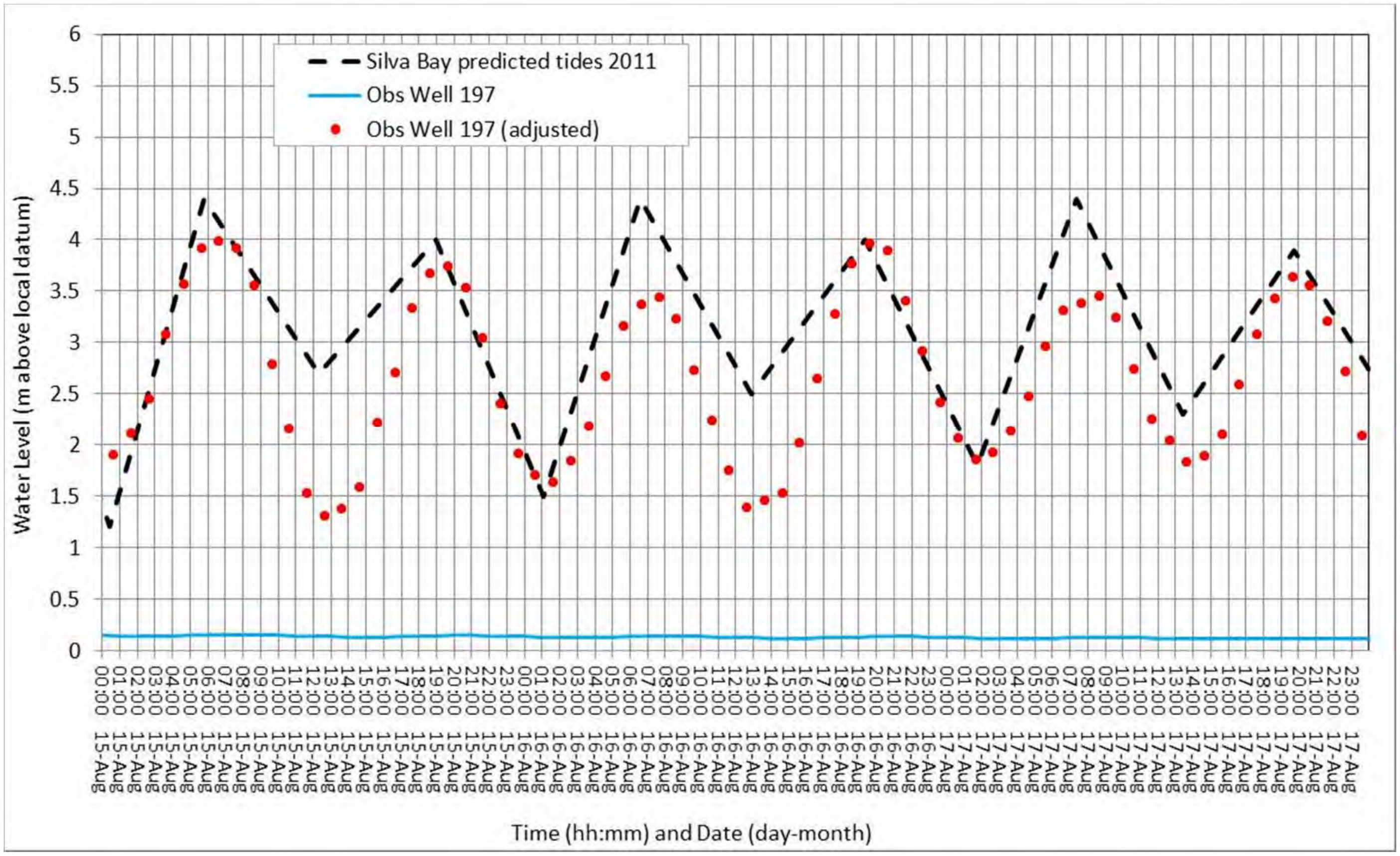
Gabriola Island

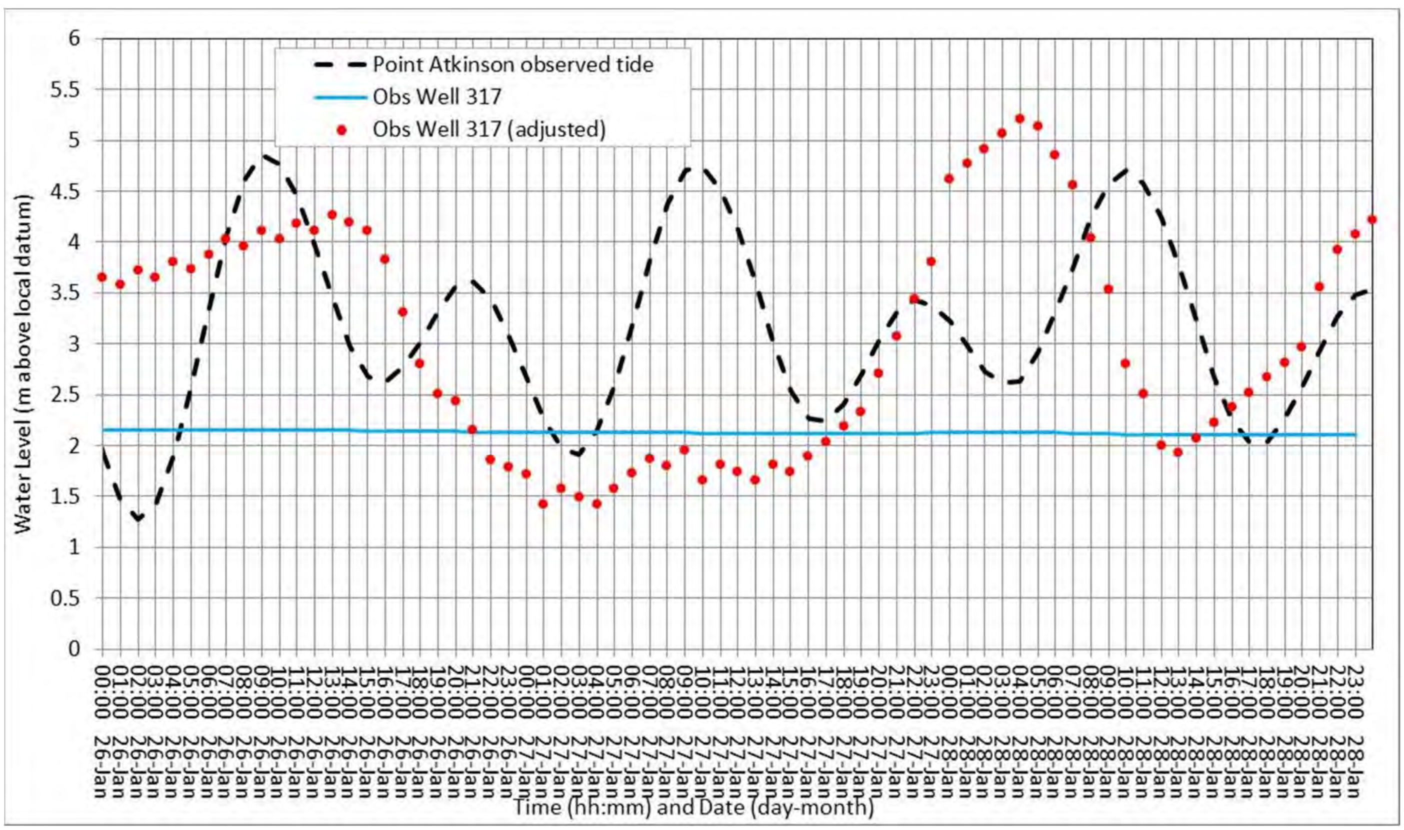
Date: April 2013

Approved: JS

Figure: **C-14**

Water levels for tide - summary graphs FINAL





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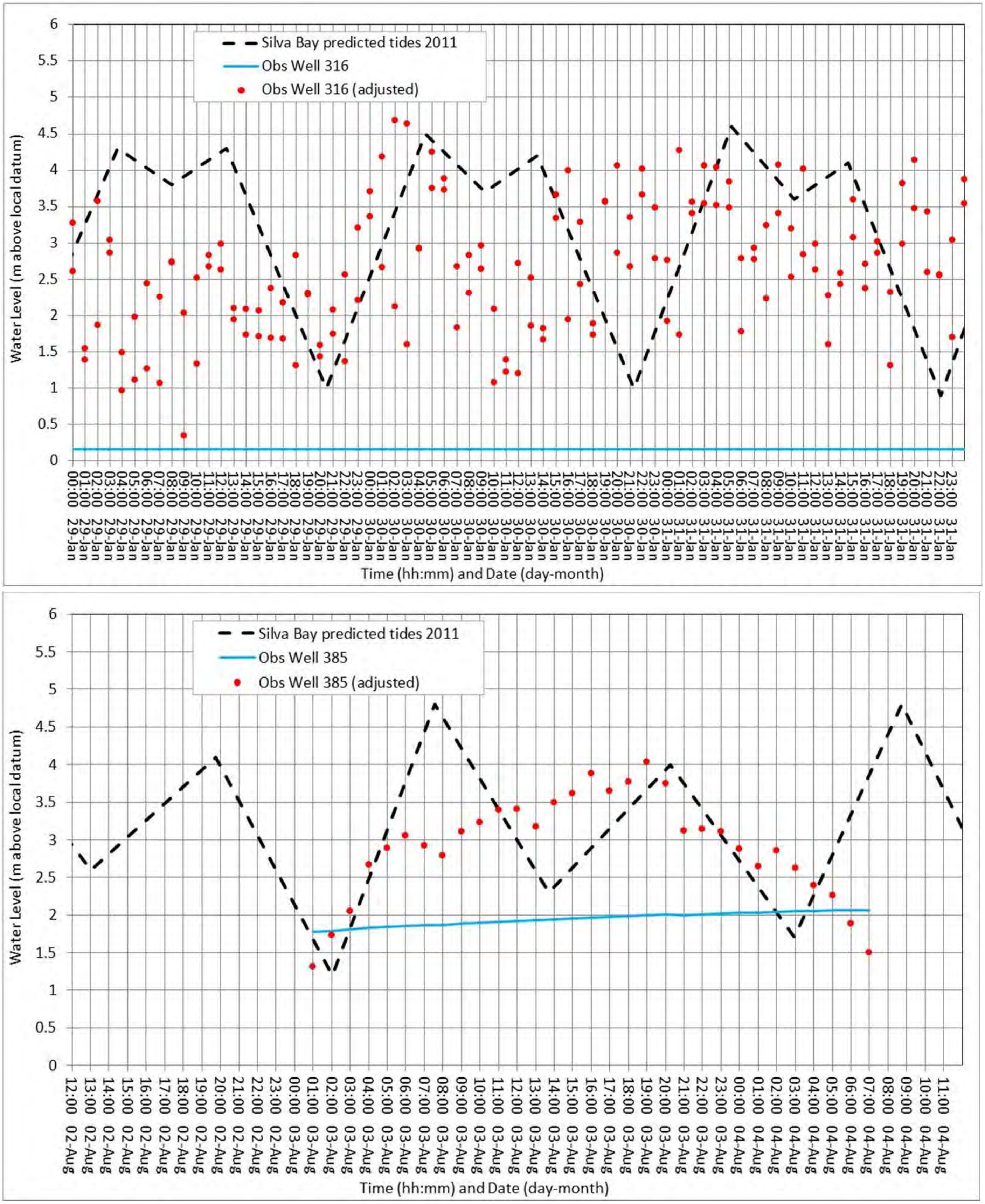

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Job No: 1CR010.000	Gabriola Island	Date: April 2013
Filename: Figures C2-C16 tides in wells.pptx		Approved: JS
		Figure: **C-16**

Water levels for tide - summary graphs FINAL

To: Regional District of Nanaimo
6300 Hammond Bay Road
Nanaimo BC V9T-6N2

EXAMPLE OF CONSENT FORM

Subject: Private Well Monitoring for Gabriola, Mudge, and DeCourcy Water Budget Project

I/we are the owner(s) of ____
(Hereinafter the "Property") upon which a water well is located.

I/we consent to the Regional District of Nanaimo (herein referred to as the "RDN") and its employees and agent, SRK Consulting Services, entering the Property in order to install groundwater level monitoring equipment in the well.

Such entry may include taking photographs of the well, establishing the well location, removing the well cap, installing a water level sensor in the well, removing the water level sensor from the well, measuring the well, and measuring the distance from the well to the ocean. The activities will not include removing any pumps from the well, removing pipes connecting to pumps, or adding or removing water from well

The well owner will be contacted prior to entering the property.

In signing this Consent I/we understand that:

1. the purpose is to measure the level of water in the well in order to understand the influence of tides on groundwater levels as part of the Gabriola, Mudge, and DeCourcy Water Budget Project;
2. the RDN will upon request provide me/us with any information obtained from the visit, including the results of any monitoring performed;
3. due care well be taken when removing well caps. If a well cap bolt is rusted or rotting and breaks while it is being unscrewed, the agent will not continue with installing monitoring equipment and instead return any unscrewed bolts to their original position. In the case of any broken bolts, the RDN agrees to replace them.
3. results from the monitoring will be stored in the RDN's files and/or the files of SRK Consulting;
4. any personal information obtained from entry, including the address at which any tests were performed, will only be used and/or disclosed in accordance with the requirements of the Freedom of Information and Protection of Privacy Act;
5. my/our anonymous results will be summarized and the information gained from them will be used in the development of the Gabriola, Mudge, and DeCourcy Water Budget report that will be publicly available;
6. I/we may rescind this consent at any time by notifying the RDN in writing.

____
Owner's Signature

Date: ________________________________

____
Owner's Name (Please Print)

Address:_____________________________
____
____

Telephone:___________________________

____
Witness Signature

____
Witness Name (Please Print)

Regional District of Nanaimo Contact Person:

Christina Metherall
Drinking Water and Watershed Protection Coordinator
RDN Water Services
Telephone: (250) 390-6586
Email: cmetherall@rdn.bc.ca

Appendix D: Water Budget Data and Calculations

Appendix D - Table of Contents

Appendix D - Figures

Appendix D - Tables

1 Introduction

Gabriola Island has a mild, temperate climate, with wet winters and dry summers. In the whole Electoral Area B of the RDN, the population census data shows 4045 residents in 2011, which shows no significant change since 2006. The population increases to about 6000 in the summer months from tourists and seasonal residents (Statistics Canada, 2007). There are 3590 residential households, but some are not used during winter months.

Gabriola residents who spend the entire year on the Island are very water conscious and employ practices to minimize their draw on groundwater. Most of the water demand is from residential and agricultural use, with an increased stress to the water resources of the Island in the summer due to the influx of summer residents. Commercial water use is significant during the summer months, but many businesses are seasonal and do not operate at as high a capacity in the fall to spring months.

The purpose of this water budget is to present estimates of the water demand and stress by watershed sub-region on Gabriola Island, and to provide a screening tool to identify gaps in the available data. This study is designed as a simple accounting of groundwater recharge against residential, commercial, and agricultural demand. Many of the numbers used and calculations made require assumptions to simply the process and to fill in data gaps.

The water balance is calculated using the following data sets:

- Mean precipitation from historical records for the entire Island (all sub-regions);
- Estimated groundwater recharge by water sub-region using high and low recharge scenarios;
- Monthly domestic and non-domestic net demand from domestic and commercial water use surveys conducted by the Gabriola Groundwater Management Society and the Regional District of Nanaimo;
- Domestic water use values estimated from other published reports.

The water demand stress is estimated from the water balance as an indicator of what proportion of the annually replenished groundwater resource is used.

The results have large uncertainty in some water balance components, therefore, reasonable ranges of results are presented and the uncertainties, assumptions and limitations are discussed.

2 Data Sources

2.1 Climate Data

There is one weather station on Gabriola Island operated by Environment Canada (Figure D- 1), two marine weather stations on Entrance Island lighthouse (just north-east of Gabriola Island), and several weather stations near Nanaimo city and on Gulf Islands south of Gabriola Island. The nearest weather station on Vancouver Island is Nanaimo City and Nanaimo Airport (south of Nanaimo) and both are have higher precipitation than Gabriola Island because of the closer proximity to mountains. There was a weather station at Nanaimo Departure Bay, with similar precipitation to Gabriola Island, but the data ends in 1992. Other weather stations exist along the east coast of Vancouver Island and mainland, and many weather stations are located in the mountainous areas.

A map of interpolated mean annual precipitation (MAP) exists for British Columbia and is available on ClimateBC (University of British Columbia, 2012). The map is a raster grid, based on analysis by Wang et al, (2012), which is based on PRISM (Oregon State University, 2012) baseline climate data. The methodology in ClimateBC uses a combination bilinear interpolation and elevation adjustment to downscale the baseline climate data into scale-free point data. In other words, it represents an interpolation of climate normals between weather stations and adjustment for orographic effects (precipitation increase with elevation). The map is a scientific guess at what the precipitation might be over the region and is used here for discussion of climatic setting and to show the uncertainty in precipitation distribution over the islands. The distributed precipitation map was not summed up and used in any water balance calculations.

The climate normals are long term averages. In this assessment, the 30-year normals (average for years 1971-2000) total precipitation was used at the Gabriola Island weather station to represent the whole of Gabriola Island. These are the same precipitation normals published by Environment Canada for weather stations, where there is enough available precipitation record (see Table D- 1).

Table D- 1 Weather stations near Gabriola Island (Environment Canada, 2013)

StationID	Latitude	Longitude	Elev. (mas)	Weather Station Name	Data Record	M.A.P. Normals 1971-2000 (mm)	M.A.P. for 2012 (mm)	Active
1023042	49.15389	-123.73361	46	Gabriola Island	1967-2013[1]	924	990	Yes
102BFHH	49.20891	-123.80889	5	Entrance Island	1987-2013		946	Yes
1022689	49.21667	-123.80000	5	Entrance Island CS	1992-2013		(note 2)	Yes
10253G0	49.19889	-123.98778	114	Nanaimo City	1981-2013	1141	1355	Yes
1025C70	49.21667	-123.95000	7.6	Nanaimo Departure Bay	1913-1992	938	(note 3)	--
1025370	49.05444	-123.87000	28	Nanaimo Airport	1947-2013	1163	1279	Yes
10130MN	48.98501	-123.57334	6	Galiano North	1975-2013		1049	Yes
1011500	48.93502	-123.74167	75	Chemainus	1919-2013		1478	Yes
1016995	48.88806	-123.54639	45.7	Saltspring St Mary's L	1975-2012	974	(note 2)	Yes

Weather stations near Gabriola Island.xlsx [List]

Note 1 – Data for Feb 2008 to Dec 2010 is missing, invalid, or subject to review (Environment Canada).
Note 2 – Data is available but annual total is still under review and will be published when available.
Note 3 – Climate normals are very useful for deactivated weather stations, although no recent data exist.

All weather records are useful and all these weather stations are used in ClimateBC precipitation map (it uses 1961-1990 normals), and most have data verified for 2012 to allow a comparison. Although the most representative weather station was interpreted to be the Gabriola Island weather station, it should be viewed in as only one point on Gabriola Island and the spatial variability of precipitation should be acknowledged. The precipitation gauges are just samples in space and there is some uncertainty of what actual MAP is for Gabriola, DeCourcy and Mudge islands.

2.1.1 Mean Annual Precipitation

The Electoral Area B (Gabriola, Mudge, DeCourcy Islands) of the Regional District of Nanaimo lies in a “rain-shadow” zone of Vancouver Island as shown on Figure D- 1. Regionally, Gabriola Island has similar mean annual precipitation as on shores of city of Nanaimo and on Valdez Island, and Saltspring Island, but it has more rain than the southern-most Gulf Islands (Pender, Saturna islands).

The mean annual precipitation (1971-2000) at Gabriola Island weather station is 924 mm (Environment Canada, National Climate and Research Archive, 2012). Gabriola Island is expected to have some variability in total annual precipitation from north end of the island to the south-east end as shown on inset map on Figure D- 1. The north end of Gabriola Island is predicted to have a mean annual precipitation between 1000 and 1025 mm per year. Central and eastern part of the island might have less precipitation. The Gabriola Island weather station lies in a drier part of the island, according to ClimateBC map, where mean annual precipitation is between 900 and 950 mm per year. Mudge and DeCourcy Islands are expected to have between 950 and 1000 mm per year.

2.1.2 Seasonality of Precipitation

The whole region has the same seasonal patterns of precipitation occurrence. Winter and autumn (wet season) precipitation accounts for most of the annual precipitation and variability in annual precipitation. The monthly precipitation normals (1971-2000) are shown in Table D- 2. The “wet” season begins in October and ends in March, although there is inter-annual variability and in some years the wet season can extend into June. Spring is the transition period and is usually much drier than the winter on Gulf Islands. The “dry” season occurs in the summer months from July to September. July and August receive the smallest amount of precipitation on a typical year. There have been summer months where only trace rainfall has been recorded, but these are rare.

Table D- 2 Monthly Precipitation Normals (published for period of record 1971-2000) at Gabriola Island Weather Station 1023042 (Environment Canada, 2012).

Season:	Wet season (Autumn and Winter)						Spring			Dry season (Summer)			Annual
Month:	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
Rainfall (mm)	81	143	127	116	97	85	57	45	41	26	28	39	**884**
Snowfall (cm)	0	4	11	14	9	2	0	0	0	0	0	0	**40**
Total Precipitation (mm)	**81**	**147**	**138**	**130**	**106**	**87**	**57**	**45**	**41**	**26**	**28**	**39**	**924**

Weather stations near Gabriola Island.xlsx [Gabriola Island]

80.1% of the annual rainfall occurs between October and April inclusive, ranging from 57 mm to 143 mm mean rainfall per month. The annual mean snowfall is 489 mm, occurring mostly from November to March. It typically ranges between 23.5 mm and 127 mm per winter month. It is uncommon for there to be no snowfall during the winter (it has happened only once between 1967 and 2006) (National Climate and Research Data Archive, 2012). Environment Canada reports total precipitation which includes snow and rain, but it is unknown how much snow sublimates or enhances surface runoff. The total precipitation includes rainfall and snowfall water amounts.

2.1.3 Inter-Annual Variation of Precipitation

There is variation from year to year of total precipitation. Annual and seasonal precipitation totals for Gabriola Island weather station were calculated and plotted on Figure D- 2 (precipitation axes are scaled to show range of 800 mm to compare the variation of precipitation). Annual precipitation is between 800 and 1000 mm in most years. In the available period of record, the mean annual rainfall on Gabriola varies between 405 mm in extremely dry years, and 1270 mm in very wet years.

Spring season precipitation is between 100 and 200 mm in most years, but can be up to 300 mm in some years. Summer dry season precipitation totals are below 100 mm in most years, and less than 50 mm over two months of July and August on many years.

From 2002 to 2006 there was a trend of increasing annual precipitation, but annual totals are not verified between 2007 and 2010 (inclusive) and the most recent year did not fit that apparent recent trend. There are no apparent long term trends in spring and summer precipitation, but there is variability.

The variability in precipitation will have some effect on groundwater levels in the aquifer. Groundwater levels in Provincial observation wells 194, 196, and 197 were compared for annual and seasonal averages for different years in Figure D- 3. Each observation well responds differently.

- The recent trend of increasing annual precipitation from 2002 to 2006 appears to correlate with a small consistent increase in groundwater level in observation well 194, but when broken down by season, the trends are not consistent.

- When the whole record is considered for each well, the variability of average annual or seasonal groundwater level does not correlate to the variability in total precipitation at these time scales. The water level is always higher during the winter compared to summer, but trends in water levels form year to year are not explained by year-to year trends in total precipitation alone. The water levels correlate at much smaller time scales of single rain events or rainy periods and other climatic factors.

- The active Provincial observation wells now have more frequent measurements of water levels and this will help with tracking of trends in the future. Observation well 194 had the most consistent record but was deactivated in 2007.

In this report, the inter-annual variability is not used for water budget calculations. The analysis is based on the 1971-2000 climate normals.

2.2 Residential Water Use Data

The most recent survey of water use was done in 2012 as part of this hydrogeological assessment (this report). In summer of 2012, the Regional District of Nanaimo conducted a groundwater use survey with Gabriola, Mudge, and DeCourcy residents, regarding their general water use and water conservation practices. The goal was to capture as much high-season use statistics as possible, as well as trying to capture data for as many summer-only residents as possible.

The survey was conducted as an insert in the local weekly newspapers for the week of June 4th, 2012. The papers were delivered to those homes that subscribe as well as being available for pick up at locations which stock the papers. The survey was only available in one week's edition of two newspapers, but there were also copies available on the island throughout the summer. The surveys were collected up until mid-September. After filling out surveys, the residents dropped them off at various participating locations on Gabriola Island.

The responses of the 2012 survey are from 389 residential households in Gabriola Island, and there are 3590 residential households on the island, meaning that only 10.8% of the households returned completed questionnaires. Residential water conservation practices described in this study are acquired from survey data, and do not necessarily reflect those in practice by the entire Gabriola population. The number of completed questionnaires returned from Mudge Island, West Degnen and Northumberland Channel are particularly low (Table D- 3).

The results of the water survey were initially tabulated by RDN. The data from 389 survey results was summarized here as simple statistics of mean, minimum and maximum values and counts of responses. The most meaningful averages are for the aggregated data set of all responses. Averages per residence in different sub-regions were done but some regions do not have enough responses to estimate a meaningful mean value.

Table D- 3 Response counts from residential water use survey (RDN, 2012)

Sub-Region	Count	% of Residences
No Area Marked	12	
A - SANDS	54	10%
B - LOCK BAY	87	15%
C - GABRIOLA	27	17%
D - SILVA BAY	14	13%
E - NORTH DEGNEN BAY	16	20%
F - WEST DEGNEN BAY	5	19%
G - FALSE NARROWS	59	15%
H - HOGGAN LAKE	20	8%
I - NORTHUMBERLAND CHANNEL	8	11%
J - SOUTH DESCANSO BAY	50	18%
K - DESCANSO BAY	30	33%
L - MUDGE ISLAND	4	2%
M - DE COURCY ISLAND	0	0%
two regions assigned A/K, G/F, F/G	3	
Total	**389**	**11% of whole region**

Water Budget 2012 Resid Consumption Calcs - FINAL.xlsx [Watershed Response #s]

2.2.1 Rainwater and Water Deliveries

In all residential responses, of the total water use the average proportion of well water use was 69%. Rainwater was used on average for 30% of water use (some rainwater use was reported by 45% of respondents), and only 1% of residential water use on average came from water delivery. The proportion of well water over rain-water used per household by sub-region varies between 35% and 100%, and 15% of respondents report that they only use rain-water and no well water. 10% of the survey respondents receive water deliveries at least once every twelve years, and 82% of those who get water deliveries receive them at least once a year, the median volume of water being 4000 gallons.

2.2.2 Average Water Use Per Residential Household

Histograms of water use by fixture type (toilets, faucets, etc.) are shown in Figure D- 4 and the mean values per residential household (in all regions combined) is shown in Table D- 4. The averages are separated by summer and rest-of-year seasons, as specified on the water survey questionnaires. These are based on unadjusted original survey results and give a description of the responses.

The average respondent used most of water for faucets and showers and most responses were near the mean values shown. There was a large spread of values for faucet and shower use, and much less variability in water use reported for toilets and clothes washers. Dishwashers were reported to consume very little water (this was later adjusted up in calculations) and 60% of the residential households reported the use of dishwashers. Outdoor watering use was also reported to be small in the water survey. The overall residential water use mean is about 176 m^3 per year per household, but there is a wide distribution of responses (some people use very little water, other households use more).

In the residential water use survey, the only difference in daily (or weekly or monthly) water use was in slightly higher water use for toilets, faucets, and showers. Outdoor water use in the water use survey responses was very low, only 8.7 m^3 per summer (and same per year) compared to 176 m^3 per year of total water use. The details of outdoor water use responses are given in Table D- 5. The water volume estimate for outdoor water use assumes 50 gallon (189.2 L) water consumption per one watering. Summer consumption is based on 13 weeks from June to September (92 days).

Table D- 4 Average water per residence (household) on Gabriola Island based on residential water use survey (RDN, 2012).

	Daily		Seasonal		Annual
	Summer	Rest of year	Summer	Rest of year	
Fixture:	liters / day	liters / day	m^3	m^3	m^3
Toilets	63.6	59.4	5.9	16.2	22.1
Faucets	197.6	183.1	18.2	50.0	68.2
Showers	169.1	157.8	15.6	43.1	58.6
Dishwasher	9.7	9.7	0.9	2.7	3.6
Clothes washer	41.7	41.7	3.8	11.4	15.2
All Fixtures total:	481.7	451.7	44.3	123.3	167.6
Outdoor Use	94.31	0	8.7	0	8.7
All Residential Total:	576.0	451.7	**53.0**	**123.3**	**176.3**

Water Budget 2012 Resid Consumption Calcs - FINAL.xlsx [Fixture Summary]

Table D- 5 Responses in residential water use survey (RDN, 2012) for different type of residential outdoor lawn & garden water use systems.

Water use survey response	Automatic System	Manual Sprinkler	Handheld Hose	Watering container
no answer	41%	45%	17%	26%
Never	43%	38%	14%	10%
Rarely	3%	5%	14%	12%
less than 1 per week	3%	8%	23%	14%
2 - 5 times per week	10%	4%	31%	38%

Water Budget 2012 Resid Consumption Calcs - FINAL.xlsx [Outdoor Cons.]

2.3 Residential Well Pumping Adjusted Estimates

The water use estimate for residential households was adjusted for some water use types where the water use survey data was not sufficient. Those residents who do not have dishwashers reported their annual dishwasher water use as zero. The average percentage of residents who use dishwashers is around 60% for every sub-region. The final value for water use type in every sub-region is scaled by proportion of well and rain water used where applicable (RDN, 2012).

The population of the study area increases by 50% during the summer months according to the Southern Gulf Islands Community Tourism Study (Ecoplan International 2008; Statistics Canada, 2007). The number of households per sub-region is multiplied by 1.50 for the June to August (inclusive) period. Effectively, the assumed summer population of the study area is 150% of the year-long population, as described in the Gabriola Island Community Profile (IslandsTrust, 2009).

The adjusted average water use per residential household is presented in Table D- 6. The values are grouped by season and daily (summer, rest of year) and annual totals are shown. The main difference from unadjusted values is in larger dishwasher use. The average total residential water use per household is 193 m^3 per year.

Table D- 6 Adjusted average water per residence (household) on Gabriola Island based on residential water use survey (RDN, 2012).

	Daily		Seasonal		Annual
	Summer	Rest of year	Summer	Rest of year	
Fixture:	liters / day	liters / day	m^3	m^3	m^3
Toilets	47.8	45.5	4.4	12.4	16.8
Faucets	189.6	183.2	17.4	50.0	67.5
Showers	161.6	131.5	14.9	35.9	50.8
Dishwasher	90.1	91.1	8.3	24.9	33.1
Clothes washer	42.0	42.5	3.9	11.6	15.5
All Fixtures total:	531.1	493.7	48.9	134.8	183.6
Outdoor Use	98.48	0	9.1	0.0	9.1
All Residential Total	**629.6**	**493.7**	**57.9**	**134.8**	**192.7**

Water budget final.xlsx [Residential - calc]

Monthly pumping withdrawal was calculated from survey data for each sub-region. Within sub-regions the data were queried and summed up through a combination of spatial analysis in ArcGIS, and simple accounting-style spreadsheets in Excel. The number of residential lots per sub-region was queried number of parcels and address points per sub-region polygon in ArcGIS, based on parcel coverage provided by RDN and IslandTrust. Water use and demand values were calculated by estimating monthly water use per establishment, and extrapolating the monthly values throughout the entire year.

The annual water usage for a residential household on Gabriola Island (193 to 210 m^3/year, depending on calculation assumptions) falls roughly in the upper middle range of residential water usage on the southern Gulf Islands as per criteria described by Hughes-Adams and Burgess (2006), and by the Southern Gulf Island Community Tourism Study (2008). Full-time residential households are estimated to use between 116 m^3/year (for a rainwater dependant household with water-saving features), and 273 m^3/year (for an average household in the CRD and the North Saltspring Water District).

A residential household uses 15.0 m^3 per month in the winter (135 m^3 in 9 months), and 19.3 m^3 per month in the summer. A residential household uses 129% more water per month in the summer, compared to the winter. This falls outside the range of summer water use increase of 145-215% estimated by the Southern Gulf Islands Community Tourism Study (2008).

2.4 Commercial Well Pumping Estimates

Due to lack of data for many commercial establishments, the estimated water use and demand for non-reporting known establishments were based the monthly water use values from water requirements presented by Welyk and Baldwin (1994), as shown in Table D- 7. This method assumes that each establishment consistently uses the maximum amount of water.

Table D- 7 Volume of water licenses for use in different commercial and industrial establishments (Welyk and Baldwin, 1994).

Establishment type	Volume of water licenses for use	Units
Seasonal resorts	0.378	m^3/d/resident
Bed and Breakfasts	0.191	m^3/d/resident
Gas stations	0.0364	m^3/day/car
Campgrounds	0.095	m^3/day/person
Schools	0.095	m^3/day/pupil
Churches	0.095	m^3/day/person

Commercial pumping withdrawal is calculated by summing the water use values provided by commercial establishments through commercial water use survey, or are extrapolated from values provided by reporting establishments. In this report average water use per sub-region is reported and not for individual users to protect user privacy.

Commercial demand is only slightly seasonal, on average, although in some regions such as Silva Bay and Descanso Bay there is more summer demand than during the rest of the year. In the Descanso Bay sub-region, the Folk Life Village Mall has seasonal variation in demand from tourism and summer-related population influxes. There are several retirement villages, which report to draw consistent volumes of water year-round. A summer camp operating in the Sands sub-region draws a significant amount of water during July and August, but only a nominal amount the rest of the year. There are few parcels classified with industry land-use types, and for this study, industrial establishments are grouped within the commercial category.

There are no estimates of bulk water import from Nanaimo, although there are sightings of water delivery trucks on BC Ferries ships travelling between Nanaimo and Gabriola Island. Summer Rain Water Delivery pumps a known volume of groundwater from two sub-regions (Groundwater Solutions, 2007), but it is unknown how much of this water is transferred to other areas. Other water delivery businesses are present on the Island, but the 2012 survey did not indicate pumping demand quantities or locations of those suppliers.

2.5 Agricultural Well Pumping Estimates

Farms are classified by output types:

- crops,
- livestock, and
- mixed (crops and livestock).

For farms which produce only crops, water demands are calculated from irrigation duty described by Welyk and Baldwin (1994). A water license for farming allows for 3046 m^3 of water per unit ha for irrigation during the licensed irrigation period (April 1st to September 30th). Water use estimates for livestock and mixed-output farms is extrapolated from survey data.

Water usage for mixed crop and livestock farms during the irrigation period is calculated as above. Water use for rearing livestock is estimated through Water Survey, taking the values from reporting farms and extrapolating to all farms. Farms which are not classified as crop or livestock-only establishments are placed into this category.

This methodology assumes that each farm zoned for outputting only crops uses its entire licensed irrigation duty over the irrigation period. It also assumes that water usages reported by livestock and mixed-output farms in the survey are consistent for all non-reporting farms of similar type.

3 Water Balance

3.1 Groundwater Recharge

Groundwater is recharged entirely from precipitation. Recharge is equal to net precipitation, the portion of precipitation which recharges the groundwater system. It can be stated as:

$$R = P(net) = P — ET – RO_{surface}$$

where, R = net recharge to aquifer, P = precipitation, ET = evapotranspiration, $RO_{surface}$ = surface water runoff. In this assessment, the evapotranspiration and runoff values were not estimated and not measured directly, and only the total precipitation is known (Table D-8). Total precipitation uncertainty is at least 10% for the long term mean because of slightly unequal precipitation distribution on Gabriola Island.

Table D-8 Total monthly precipitation normals (1971-2000) per sub-region at Gabriola Island weather station (Environment Canada, 2012).

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly total precipitation (mm)		130	106	87	57	45	41	26	28	39	81	147	138
Sub-region	Area (km^2)	Total monthly precipitation volume in 1000's of m^3 per sub-region (Volume = Area * Monthly precipitation rate)											
Sands Region	3.8	488	398	327	214	169	154	98	105	146	304	552	518
Lock Bay Region	8.1	1050	856	703	460	363	331	210	226	315	654	1187	1115
Gabriola Region	12.9	1682	1372	1126	738	582	531	336	362	505	1048	1902	1786
Silva Bay Region	2.1	278	227	186	122	96	88	56	60	83	173	314	295
North Degnen Bay Region	2.0	255	208	171	112	88	80	51	55	76	159	288	271
West Degnen Bay Region	2.6	334	273	224	147	116	105	67	72	100	208	378	355
False Narrows Region	5.3	692	564	463	303	239	218	138	149	208	431	782	734
Hoggan Lake Region	9.7	1260	1027	843	552	436	397	252	271	378	785	1424	1337
Northumberland Channel Region	0.8	105	85	70	46	36	33	21	23	31	65	118	111
South Descanso Bay Region	1.9	246	201	165	108	85	78	49	53	74	153	278	261
Descanso Bay Region	3.0	392	319	262	172	136	124	78	84	118	244	443	416
Mudge Island	2.2	280	228	187	123	97	88	56	60	84	174	316	297
De Courcy Island	2.0	255	208	171	112	88	80	51	55	76	159	288	271

Water budget final.xlsx [Precipitation]

The groundwater recharge rate was assumed to be within a known range of high to low recharge rates, expressed as a percentage of mean total monthly and annual precipitation. The high recharge scenario was 25% and the low scenario was 10% of mean annual precipitation, estimated from published data sources (see Appendix B).

To estimate total recharge volume of water, the precipitation depths were converted to volume of water by multiplying total precipitation by % recharge and then by the sub-region area (Table D- 9).

Table D- 9 Total monthly groundwater recharge volume per sub-region for low and high recharge scenarios (estimated)

	Sub-regions	Total groundwater recharge volume in 1000's of m^3/month											
	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
10% recharge scenario	Sands	48.8	39.8	32.7	21.4	16.9	15.4	9.8	10.5	14.6	30.4	55.2	51.8
	Lock Bay	105.0	85.6	70.3	46.0	36.3	33.1	21.0	22.6	31.5	65.4	118.7	111.5
	Gabriola	168.2	137.2	112.6	73.8	58.2	53.1	33.6	36.2	50.5	104.8	190.2	178.6
	Silva Bay	27.8	22.7	18.6	12.2	9.6	8.8	5.6	6.0	8.3	17.3	31.4	29.5
	North Degnen Bay	25.5	20.8	17.1	11.2	8.8	8.0	5.1	5.5	7.6	15.9	28.8	27.1
	West Degnen Bay	33.4	27.3	22.4	14.7	11.6	10.5	6.7	7.2	10.0	20.8	37.8	35.5
	False Narrows	69.2	56.4	46.3	30.3	23.9	21.8	13.8	14.9	20.8	43.1	78.2	73.4
	Hoggan Lake	126.0	102.7	84.3	55.2	43.6	39.7	25.2	27.1	37.8	78.5	142.4	133.7
	Northumberland Channel	10.5	8.5	7.0	4.6	3.6	3.3	2.1	2.3	3.1	6.5	11.8	11.1
	South Descanso Bay	24.6	20.1	16.5	10.8	8.5	7.8	4.9	5.3	7.4	15.3	27.8	26.1
	Descanso Bay	39.2	31.9	26.2	17.2	13.6	12.4	7.8	8.4	11.8	24.4	44.3	41.6
	Mudge Island	28.0	22.8	18.7	12.3	9.7	8.8	5.6	6.0	8.4	17.4	31.6	29.7
	De Courcy Island	25.5	20.8	17.1	11.2	8.8	8.0	5.1	5.5	7.6	15.9	28.8	27.1
	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
25% recharge scenario	Sands	122.1	99.5	81.7	53.5	42.2	38.5	24.4	26.3	36.6	76.0	138.0	129.6
	Lock Bay	262.5	214.0	175.7	115.1	90.9	82.8	52.5	56.5	78.8	163.6	296.8	278.7
	Gabriola	420.5	342.9	281.4	184.4	145.6	132.6	84.1	90.6	126.2	262.0	475.5	446.4
	Silva Bay	69.5	56.6	46.5	30.5	24.0	21.9	13.9	15.0	20.8	43.3	78.5	73.7
	North Degnen Bay	63.7	51.9	42.6	27.9	22.1	20.1	12.7	13.7	19.1	39.7	72.0	67.6
	West Degnen Bay	83.6	68.1	55.9	36.6	28.9	26.4	16.7	18.0	25.1	52.1	94.5	88.7
	False Narrows	172.9	141.0	115.7	75.8	59.9	54.5	34.6	37.2	51.9	107.8	195.6	183.6
	Hoggan Lake	314.9	256.8	210.7	138.1	109.0	99.3	63.0	67.8	94.5	196.2	356.1	334.3
	Northumberland Channel	26.1	21.3	17.5	11.5	9.1	8.2	5.2	5.6	7.8	16.3	29.6	27.8
	South Descanso Bay	61.5	50.2	41.2	27.0	21.3	19.4	12.3	13.2	18.5	38.3	69.5	65.3
	Descanso Bay	97.9	79.8	65.5	42.9	33.9	30.9	19.6	21.1	29.4	61.0	110.7	103.9
	Mudge Island	70.0	57.0	46.8	30.7	24.2	22.1	14.0	15.1	21.0	43.6	79.1	74.3
	DeCourcy Island	63.7	51.9	42.6	27.9	22.1	20.1	12.7	13.7	19.1	39.7	72.0	67.6

Water budget final.xlsx [Water Balance]

3.2 Groundwater Discharge

Groundwater discharge occurs mostly as natural groundwater flow to ocean shores and streams which flow into ocean. Some of the groundwater is discharged as active pumping in wells.

$$D_{total} = D_{natural} + D_{pumped}$$

where D_{total} = subsurface discharge from groundwater aquifers (this may be discharge to surface waters or subsurface discharge to the ocean).

Groundwater discharge is difficult to estimate due to the large uncertainty in the spatial distribution of parameters such as porosity and groundwater recharge. Groundwater discharge can't be effectively measured for the entire island. The water balance method used in this study assumes that there is a buffer of water in storage for use in periods where net recharge is exceeded by groundwater discharge. For the groundwater to be sustainable, the aquifers must recharge fully during the winter months. Any excess recharge runs off or seeps off into the ocean quickly. Pumping withdrawal has been estimated using data collected from residential and commercial survey in 2012.

There is limited runoff and evapotranspiration data available for Gabriola Island, and there are only limited estimates of groundwater discharge. Only one of the streams is gauged. Eleven of the 12 streams on the island are ephemeral (the dry months being July to September). Total annual volume estimates for un-gauged streams are calculated (by other sources) from those of the gauged stream, and are listed in Table D-10. There also seeps and springs which feed small creeks (Table D-11), but their locations are unknown and there are little flow data available. (Welyk and Baldwin, 1994). Goodhue Creek is the only creek that is gauged. Total annual volumes for all other creeks are estimated. Surface runoff is difficult to quantify without long term surface water flow data.

Natural discharge cannot be measured because groundwater flows into the ocean along all shores. There are two unknowns in the storage balance: recharge and natural discharge. Recharge can be estimated from other observations of water level fluctuation and from infiltration numerical models and other analytical solutions or calibrated 3D numerical models done on other Gulf Islands.

If total discharge was known (i.e. if groundwater discharge could be measured), then the recharge rate could be measured for the whole catchment or island. At this time, recharge can only be estimated indirectly by making some assumptions about aquifer properties.

Table D-10 Gabriola streams and runoff estimates (Welyk and Baldwin, 1994).

Creek	Area (km^2)	Description	Flow Period	Total Annual Volume (acre ft)
Goodhue Creek	10.5	Flows into Hoggan Lake	Year-round	4495
Mallett Creek	0.7	Descanso Bay	November to May	379
McCormack Creek	0.2	Sands	November to April	123
Francesco Brook	0.6	Sands	November to May	304
Ike Brook	0.3	Sands	November to April	123
Castell Brook	3.3	Lock Bay	October to June	1683
Jenkins Creek	3.7	Gabriola	October to June	2115
Stoney Creek	1.7	Gabriola	November to June	890
Jacqueline Brook	1.2	Gabriola	November to May	604
Dick Brook	4.4	Degnen Bay	October to June	2196
Martin Brook	0.6	Degnen Bay	November to May	133
Unnamed Brook	0.9	Degnen Bay	November to May	434
Other Areas	24.2	n/a	n/a	n/a

Table D-11 Flow periods and rates for springs and seeps on Gabriola Island (Welyk and Baldwin, 1994)

Spring	Flow Period	Flow (liters/minute)
Windecker	Year-round	100
Toadeye Swamp	Seasonal	n/a
Lobo Spring	Seasonal	52
Lucas Spring	Seasonal	7

Water budget final.xlsx [Surface runoff]

3.3 Groundwater Storage in Aquifer

The general water balance of the Island can be stated as:

$$\Delta S = R - D + W$$

where, ΔS = change in groundwater storage, R = net recharge to aquifer, D = net natural discharge from aquifer, W = total pumping withdrawal. Sustainability is defined as utilizing only what is recharged to a system, and a system is unsustainable when demand exceeds recharge. Groundwater is stored within the system of soil pores and bedrock fractures, providing a buffer for months where extraction exceeds recharge. Groundwater storage isn't implicitly included in the calculations. The change in storage can be estimated by calculating the change in volume of groundwater in aquifer during its seasonal water table variation (see Appendix B for this calculation)

Groundwater in storage is assumed to be constant at annual time scale, because of regular and repetitive seasonal fluctuation observed (and ignoring the inconsistent and small trends over long term between different MOE observation wells). Therefore, on annual time scale:

$$\Delta S = 0 \text{ (average annual)}$$

$$\Delta S <> 0 \text{ (seasonal or shorter time scale)}$$

When rain events occur, $\Delta S > 0$ in short term, until the water level stabilizes again. In absence of rain for prolonged time, $\Delta S < 0$ as water levels slowly decline in aquifer due to natural and pumping discharge. The natural cycle of water level fluctuation occurs naturally without pumping. Pumping only increases the total discharge and does so seasonally. The largest water level increases in the aquifer are during large rain events and the largest water level declines are in between large rain events. The natural system has much more variation than is imposed by pumping (on average). On island scale, the pumping demand is difficult to observe in observation wells, but locally it is observed as drawdown near pumping wells (water levels recover when wells are turned off). It is a dynamic water balance.

ΔS can be estimate annually from water level fluctuation in observation wells and assuming a specific yield value, but the results are completely dependent on the specific yield value, which is unknown and difficult to estimate to nearest order of magnitude.

4 Water Demand and Water Stress Calculation

4.1 Total Pumping Demand

The water demand assessed here is the groundwater pumping demand. Rain water storage and water imports are other sources of water . The pumping demand has three sources:

$$D(pumping) = W_{commercial} + W_{residential} + W_{agriculture}$$

where, $W_{commercial}$ = commercial pumping withdrawal, $W_{residential}$ = residential pumping withdrawal, and $W_{agriculture}$ = agricultural pumping withdrawal.

Total annual and monthly water demands are the sum of commercial, residential and agricultural pumping withdrawals for each sub-region. They are not necessarily actual water use volumes, which are not metered accurately or not at all at many wells, but they are estimated using the best data available. The estimated numbers are conservative, and their goal is to quantify a reasonable estimate of the water demands and stresses for each sub-region.

4.2 Water Stress on Sub-Regions

Water stress for an aquifer is a relative measure which compares the total demand of groundwater to the amount of natural recharge to the aquifer. In this assessment, water stress was calculated as the ratio of volumes of total pumping demand to the total recharge, as a percentage value. Values were calculated for monthly totals for each sub-region. This methodology was used to match similar approach in the RDN's Vancouver Island water budget study, which is presently being undertaken by others.

water stress = total demand volume / total recharge volume * 100%

Where there is large surplus of groundwater recharge, the stress on the groundwater resource is low, and where there is low surplus, the stress is moderate. Where demand exceeds recharge in some months, the stress on water resource is highest because groundwater is taken out of storage in the short term.

The categories of water stress were:

- Lower stress : demand < 50% of recharge (large excess of recharge)
- Moderate stress: demand > 50% of recharge
- Higher stress: recharge deficit where demand > recharge

The calculation was done for two annual groundwater recharge values representing the high (25%) and low (10%) recharge scenarios of a reasonable range of recharge as percentage of mean annual precipitation.

5 Results: Water Demand and Water Stress

5.1 Residential Water Demand by Sub-Region

Residential surveys were returned by only a small number of mostly year-long residents, and may not reflect actual water usage for the entire population. Assuming that the survey's results are representative of the population, the analysis was continued by sub-regions. The estimated total annual residential water use in the whole water budget region (all sub-regions on Gabriola, Mudge, DeCourcy islands) is 447,000 m^3 (Table D- 12).

Residential water use is the most strongly seasonal type of water use (Table D-16). The average monthly residential water demand is typically three times greater in a summer month than during other months. The total monthly summer residential water use is 212,000 m^3 (during 3 months) and the total monthly winter residential water use is 235,000 m^3 (during 9 months). Almost as much water is used during the summer months as during the rest of the year.

Table D- 12 Monthly residential pumping demand per sub-region (estimated).

Sub-region	Residential pumping demand volume in 1000's of m^3/month												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Sands	3.3	3.3	3.3	3.3	3.3	9.1	9.1	9.1	3.3	3.3	3.3	3.3	57.2
Lock Bay	5.9	5.9	5.9	5.9	5.9	16.0	16.0	16.0	5.9	5.9	5.9	5.9	101.5
Gabriola	1.5	1.5	1.5	1.5	1.5	4.0	4.0	4.0	1.5	1.5	1.5	1.5	25.1
Silva Bay	1.0	1.0	1.0	1.0	1.0	2.6	2.6	2.6	1.0	1.0	1.0	1.0	16.2
North Degnen Bay	1.0	1.0	1.0	1.0	1.0	2.7	2.7	2.7	1.0	1.0	1.0	1.0	16.7
West Degnen Bay	0.3	0.3	0.3	0.3	0.3	0.9	0.9	0.9	0.3	0.3	0.3	0.3	5.4
False Narrows	3.9	3.9	3.9	3.9	3.9	10.7	10.7	10.7	3.9	3.9	3.9	3.9	67.5
Hoggan Lake	2.3	2.3	2.3	2.3	2.3	6.2	6.2	6.2	2.3	2.3	2.3	2.3	38.9
Northumberland Channel	0.3	0.3	0.3	0.3	0.3	0.9	0.9	0.9	0.3	0.3	0.3	0.3	5.4
South Descanso Bay	1.7	1.7	1.7	1.7	1.7	4.8	4.8	4.8	1.7	1.7	1.7	1.7	30.0
Descanso Bay	0.4	0.4	0.4	0.4	0.4	1.1	1.1	1.1	0.4	0.4	0.4	0.4	7.0
Mudge Island	1.9	1.9	1.9	1.9	1.9	5.5	5.5	5.5	1.9	1.9	1.9	1.9	33.9
De Courcy Island	2.5	2.5	2.5	2.5	2.5	6.6	6.6	6.6	2.5	2.5	2.5	2.5	42.2
Totals	**26.1**	**26.1**	**26.1**	**26.1**	**26.1**	**70.8**	**70.8**	**70.8**	**26.1**	**26.1**	**26.1**	**26.1**	**447**

Water budget final.xlsx [Residential - tables]

Table D-13 Estimated water use per residential household by sub-region based on residential water use survey (RDN, 2012)

Region	# residential parcels	Residential pumping demand volume in 1000's of m^3									
		Toilets		Faucets		Showers		Dishwasher		Clothes Washer	Gardening
		summer	rest of year	summer	rest of year	summer	rest of year	proportion with dish washers	monthly	monthly	monthly (in summer)
Sands	522	0.76	0.72	3.04	2.90	2.59	2.08	0.63	0.91	0.06	4.73
Lock Bay	568	0.83	0.78	3.30	3.16	2.81	2.27	0.67	1.05	0.06	5.15
Gabriola	160	0.23	0.22	0.93	0.89	0.79	0.64	0.69	0.30	0.02	1.45
Silva Bay	111	0.16	0.15	0.65	0.62	0.55	0.44	0.79	0.24	0.01	1.01
North Degnen Bay	82	0.12	0.11	0.48	0.46	0.41	0.33	0.50	0.11	0.01	0.74
West Degnen Bay	26	0.04	0.04	0.15	0.14	0.13	0.10	0.67	0.05	0.00	0.24
False Narrows	385	0.56	0.53	2.24	2.14	1.91	1.54	0.63	0.67	0.04	3.49
Hoggan Lake	243	0.36	0.34	1.41	1.35	1.20	0.97	0.63	0.42	0.03	2.20
Northumberland Channel	70	0.10	0.10	0.41	0.39	0.35	0.28	0.63	0.12	0.01	0.63
South Descanso Bay	274	0.40	0.38	1.59	1.52	1.36	1.09	0.63	0.48	0.03	2.48
Descanso Bay	91	0.13	0.13	0.53	0.51	0.45	0.36	0.62	0.16	0.01	0.82
Mudge Island	174	0.25	0.24	1.01	0.97	0.86	0.69	0.25	0.12	0.02	1.58
De Courcy Island	181	0.27	0.25	1.05	1.01	0.90	0.72	1.00	0.50	0.02	1.64

Water budget final.xlsx [Residential - tables]

5.2 Commercial Water Demand

Commercial establishments have the lowest water demand. The total annual water demand for commercial establishments is 46,000 m^3 (Table D- 14). The total monthly summer commercial water use is 15,000 m^3, and the total monthly winter commercial water use is 31,000 m^3. The estimate is based on bulk water uses for several large volume commercial consumers (acquired through survey) but is likely incomplete and may be higher than shown here.

Table D- 14 Monthly commercial pumping demand per sub-region (estimated).

Sub-Region	Commercial pumping demand volume in 1000's of m^3/month												
Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Sands	1.0	0.9	0.9	1.2	1.8	1.9	1.0	1.0	1.8	1.2	1.2	0.9	14.4
Lock Bay					0.0	0.2	0.2	0.2	0.2	0.1	0.1		0.9
Gabriola					0.0	0.0	0.0	0.0	0.0				0.2
Silva Bay	0.0	0.0	0.0	0.5	1.5	1.5	1.5	1.5	1.5	0.5	0.5	0.5	9.6
North Degnen Bay					0.1	0.1	0.1	0.1	0.1				0.5
West Degnen Bay	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
False Narrows					0.1	0.1	0.1	0.1	0.1				0.7
Hoggan Lake	0.9	0.9	0.9	0.9	1.0	1.0	0.1	0.1	1.0	0.9	0.9	0.9	9.6
Northumberland Channel					0.1	0.1	0.1	0.1	0.1				0.7
South Descanso Bay					0.0	0.0	0.0	0.0	0.0				0.0
Descanso Bay	0.6	0.6	0.6	0.6	0.9	1.0	1.0	1.0	0.9	0.6	0.6	0.6	8.7
Mudge Island					0.0	0.0	0.0	0.0	0.0				0.2
De Courcy Island	No data...												0.0
Totals	**2.5**	**2.4**	**2.4**	**3.1**	**5.7**	**6.0**	**4.2**	**4.2**	**5.8**	**3.3**	**3.3**	**2.9**	**45.9**

Water budget final.xlsx [Agric and Com - tables]

5.3 Agricultural Water Demand

The total annual agricultural water use on Gabriola Island is 469,000 m^3 (Table D- 15). There are three seasons of agricultural water use in this analysis: spring (April to May), summer (June to September), and the rest of the year. Agriculture has the highest seasonal water fluctuation of all three land-use types in this study. The total monthly spring season agricultural water use is 134,000 m^3. The total summer agricultural water use is the highest at approximately 214,000 m^3, and the total monthly agricultural winter water use is lower, at approximately 121,000 m^3. There is greater agricultural water use in the Gabriola and North Degnen sub-regions because of the large area of land zoned for farming. Some sub-regions did not have any zoned agricultural land use, resulting in no agricultural water demand.

During the summer, the total agricultural pumping demand is almost the same as the total residential pumping demand (both approximately 210,000 m^3), but during the winter months, the total residential water demand (235,000 m^3) is more than double the total agricultural demand during the same period (121,000 m^3). Large proportion of water use in Agriculture is for irrigation, which is not required during the rainy season. Agricultural water demand outside the irrigation season comes from farms tending to livestock.

Table D- 15 Monthly agricultural pumping demand per sub-region (estimated).

Sub-Region	Agricultural pumping demand volume in 1000's of m^3/month												
Agricultural Season:	Rest of year			Spring		Summer				Rest of year			Annual
Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	
Sands	1.2	1.2	1.2	3.4	3.4	4.1	4.1	4.1	4.1	1.2	1.2	1.2	30.4
Lock Bay	0.6	0.6	0.6	1.6	1.6	2.0	2.0	2.0	2.0	0.6	0.6	0.6	14.6
Gabriola	1.3	1.3	1.3	17.9	17.9	18.6	18.6	18.6	18.6	1.3	1.3	1.3	118.0
Silva Bay	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	2.8
North Degnen Bay	0.4	0.4	0.4	16.3	16.3	16.5	16.5	16.5	16.5	0.4	0.4	0.4	101.0
West Degnen Bay	1.0	1.0	1.0	6.9	6.9	7.4	7.4	7.4	7.4	1.0	1.0	1.0	49.4
False Narrows	1.7	1.7	1.7	9.8	9.8	10.7	10.7	10.7	10.7	1.7	1.7	1.7	72.5
Hoggan Lake	1.8	1.8	1.8	8.4	8.4	9.4	9.4	9.4	9.4	1.8	1.8	1.8	65.1
Northumberland Channel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Descanso Bay	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	2.8
Descanso Bay	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mudge Island	0.0	0.0	0.0	2.1	2.1	2.1	2.1	2.1	2.1	0.0	0.0	0.0	12.9
De Courcy Island	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Totals	**8.3**	**8.3**	**8.3**	**66.8**	**66.8**	**71.5**	**71.5**	**71.5**	**71.5**	**8.3**	**8.3**	**8.3**	**469.4**

Water budget final.xlsx [Agric and Com - tables]

5.4 Total Pumping Demand

The water pumping demand for each sub-region varies depending on number of commercial establishments, residential households, and farms. All three land-use types show seasonal variation in water demand. Monthly water demands are consistent, but increase significantly from April to September due to irrigation (April 1st to September 30th), seasonal population increase (June 1st to August 31st), and various documented commercial demands. Commercial establishments have the lowest water demand, residential households and farming have have the highest demand.

Table D-16 Average monthly water demand for residential, commercial and agricultural water use, by sub-region and season (estimated).

Water Use Type:	Residential		Commercial		Agricultural		
Season:	Summer (Jun-Aug)	Rest of year	Summer (Jun-Aug)	Rest of year	Spring (Apr-May)	Summer (Jun-Sep)	Rest of year (Oct-Mar)
Sub-Region	1000s of m^3/month						
Sands	9.1	3.3	1.3	1.2	3.4	4.1	1.2
Lock Bay	16.0	5.9	0.2	0.0	1.6	2.0	0.6
Gabriola	4.0	1.5	0.0	0.0	17.9	18.6	1.3
Silva Bay	2.6	1.0	1.5	0.6	0.2	0.3	0.2
North Degnen Bay	2.7	1.0	0.1	0.0	16.3	16.5	0.4
West Degnen Bay	0.9	0.3	0.0	0.0	6.9	7.4	1.0
False Narrows	10.7	3.9	0.1	0.0	9.8	10.7	1.7
Hoggan Lake	6.2	2.3	0.4	0.9	8.4	9.4	1.8
Northumberland Channel	0.9	0.3	0.1	0.0	0.0	0.0	0.0
South Descanso Bay	4.8	1.7	0.0	0.0	0.2	0.3	0.2
Descanso Bay	1.1	0.4	1.0	0.6	0.0	0.0	0.0
Mudge Island	5.5	1.9	0.0	0.0	2.1	2.1	0.0
De Courcy Island	6.6	2.5	0.0	0.0	0.0	0.0	0.0
Average per month	**5.4**	**2.0**	**0.4**	**0.3**	**5.1**	**5.5**	**0.6**

Water budget final.xlsx [Residential - tables]

The total monthly pumping demand varies greatly by sub-region and month (Table D-17). Pumping demand is highest during the summer months in all sub-regions. The total monthly pumping demand during the summer is 148,000 m^3/month and during winter months it is approximately 37,000 m^3/month. The annual demand is approximately 962,000 m^3/year. The largest total demand is in Gabriola and False Narrows sub-regions and smallest total demand is in Northumberland Channel sub-region.

The largest sub-regions tend to have the largest total demand, but the ranking of sub-regions by total demand does not match ranking of sub-regions by area. The pumping demand was calculated per square kilometre to compare sub-regions of different sizes (Table D-18). The greatest pumping demand per unit area occurs in North Degnen Bay Region (because of agricultural pumping demand estimates) and lowest in Descanso Bay Region. High demand regions per unit area are listed ranked from highest to lowest in Table D- 19. The largest sub-regions (by area) have the lowest pumping demand per unit area. However, some of the differences may be due to under sampling during the water use survey because responses were voluntary.

Table D-17 Total monthly pumping demand per sub-region (estimated).

Sub-region	Total pumping demand volume in 1000's of m^3/month												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Sands	5.5	5.4	5.4	7.9	8.5	15.0	14.1	14.1	9.2	5.7	5.7	5.4	102.0
Lock Bay	6.5	6.5	6.5	7.5	7.6	18.2	18.2	18.2	8.0	6.6	6.6	6.5	117.0
Gabriola	2.8	2.8	2.8	19.4	19.4	22.6	22.6	22.6	20.1	2.8	2.8	2.8	143.4
Silva Bay	1.2	1.2	1.2	1.6	2.7	4.4	4.4	4.4	2.8	1.6	1.6	1.6	28.6
North Degnen Bay	1.4	1.4	1.4	17.3	17.4	19.3	19.3	19.3	17.6	1.4	1.4	1.4	118.2
West Degnen Bay	1.3	1.3	1.3	7.2	7.2	8.3	8.3	8.3	7.8	1.3	1.3	1.3	55.2
False Narrows	5.6	5.6	5.6	13.7	13.8	21.5	21.5	21.5	14.8	5.6	5.6	5.6	140.6
Hoggan Lake	5.0	5.0	5.0	11.6	11.6	16.5	15.7	15.7	12.6	5.0	5.0	5.0	113.6
Northumberland Channel	0.3	0.3	0.3	0.3	0.5	1.0	1.0	1.0	0.5	0.3	0.3	0.3	6.1
South Descanso Bay	1.9	1.9	1.9	1.9	1.9	5.1	5.1	5.1	2.1	1.9	1.9	1.9	32.8
Descanso Bay	1.0	1.0	1.0	1.0	1.3	2.1	2.1	2.1	1.3	1.0	1.0	1.0	15.7
Mudge Island	1.9	1.9	1.9	4.1	4.1	7.7	7.7	7.7	4.1	1.9	1.9	1.9	47.0
De Courcy Island	2.5	2.5	2.5	2.5	2.5	6.6	6.6	6.6	2.5	2.5	2.5	2.5	42.2
Totals for all sub-regions	**37**	**37**	**37**	**96**	**99**	**148**	**146**	**146**	**103**	**38**	**38**	**37**	**962**

Water budget final.xlsx [Water Balance]

Table D-18 Total monthly pumping demand in sub-regions per square kilometre (estimated)

Sub-region	Total pumping demand volume in 1000's of m^3/month / km^2													Area (km^2)
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual	
Sands	1.5	1.4	1.4	2.1	2.3	4.0	3.8	3.8	2.4	1.5	1.5	1.4	27.2	3.8
Lock Bay	0.8	0.8	0.8	0.9	0.9	2.2	2.2	2.2	1.0	0.8	0.8	0.8	14.5	8.1
Gabriola	0.2	0.2	0.2	1.5	1.5	1.7	1.7	1.7	1.6	0.2	0.2	0.2	11.1	12.9
Silva Bay	0.6	0.6	0.6	0.8	1.3	2.1	2.1	2.1	1.3	0.8	0.8	0.8	13.4	2.1
North Degnen Bay	0.7	0.7	0.7	8.8	8.9	9.8	9.8	9.8	9.0	0.7	0.7	0.7	60.3	2.0
West Degnen Bay	0.5	0.5	0.5	2.8	2.8	3.2	3.2	3.2	3.0	0.5	0.5	0.5	21.5	2.6
False Narrows	1.1	1.1	1.1	2.6	2.6	4.0	4.0	4.0	2.8	1.1	1.1	1.1	26.4	5.3
Hoggan Lake	0.5	0.5	0.5	1.2	1.2	1.7	1.6	1.6	1.3	0.5	0.5	0.5	11.7	9.7
Northumberland Channel	0.4	0.4	0.4	0.4	0.6	1.2	1.2	1.2	0.6	0.4	0.4	0.4	7.5	0.8
South Descanso Bay	1.0	1.0	1.0	1.0	1.0	2.7	2.7	2.7	1.1	1.0	1.0	1.0	17.3	1.9
Descanso Bay	0.3	0.3	0.3	0.3	0.4	0.7	0.7	0.7	0.4	0.3	0.3	0.3	5.2	3.0
Mudge Island	0.9	0.9	0.9	1.9	1.9	3.6	3.6	3.6	1.9	0.9	0.9	0.9	21.8	2.2
De Courcy Island	1.3	1.3	1.3	1.3	1.3	3.3	3.3	3.3	1.3	1.3	1.3	1.3	21.5	2.0
Totals for all sub-regions	**10**	**10**	**10**	**26**	**27**	**40**	**40**	**40**	**28**	**10**	**10**	**10**	**259**	**56**

Water budget final.xlsx [Water Balance]

Note: North Degnen Bay has high agricultural pumping demand estimated during spring and summer months (unconfirmed).

Table D- 19 Total annual pumping demand in sub-regions per square kilometre of area, sorted from highest to lowest demand value.

Sub-region	Annual water demand per square kilometre of area (1000s m^3 / km^2)	
North Degnen Bay	60.3	High ↑
Sands	27.2	
False Narrows	26.4	
Mudge Island	21.8	
De Courcy Island	21.5	
West Degnen Bay	21.5	
South Descanso Bay	17.3	
Lock Bay	14.5	
Silva Bay	13.4	
Hoggan Lake	11.7	
Gabriola	11.1	
Northumberland Channel	7.5	
Descanso Bay	5.2	↓ Low

Water budget final.xlsx [Water Balance]

5.5 Water Stress

The water stress estimate depends both on the demand and recharge values. Demand is measured with water surveys but many demand quantities are uncertain and have been estimated. Recharge is also uncertain. In this analysis, the water demand was assumed to be representative, and the water stress was calculated for two different recharge estimates (low = 10% of mean annual precipitation, high = 25% of mean annual precipitation). Results of analysis are presented in Table D-20.

On annual basis, the water stress is low in most months of the year in both high and low recharge scenarios, but during the dry summer months, there is high water stress indicated in four sub-regions in the low recharge scenario only (and one sub-region in the high recharge scenario). North Degnen Bay Region shows the most water stress because of very high agricultural water use estimates during the summer. The ratio of demand to recharge volume is typically from 10% to 30% in the low recharge scenario, and lower in the high recharge scenario.

On an annual basis, in the high recharge scenario the surplus of water is approximately 11,500,000 m^3/year, and in the low recharge scenario the surplus of water is approximately 4,000,000 m^3/year. On the annual time scale, there is no deficit of water and the overall water stress on aquifer is low because there is enough recharge to supply the demand.

On monthly time scale, in the summer months in some regions the total groundwater demand may exceed the recharge to aquifer. This occurs only in the North Degnen Bay sub-region in the high recharge scenario, and in many sub-regions during summer months in the low recharge scenario.

The water sub-regions which fall into higher stress categories, where pumping demand exceeds monthly recharge and some water is pumped from storage from aquifer and contributing to small drop in average water levels (this will depend on location and geology) during some summer months are: Sands, North Degnen Bay, West Degnen Bay, False Narrows, and Mudge Island. North Degnen Bay is classified as high water stress due to estimated farming irrigation demand based on irrigation duty and farm area from April to September,. resulting in water stress of more than 300% in July and August. The actual water pumping demand on most farms is unknown.

The different water sub-regions are connected and water demand in one region can be supplied by groundwater flow from storage (and recharge) in adjacent regions. This is especially true for the relatively small and narrow sub-regions which are adjacent to large central sub-regions. Overall, there is a large amount of groundwater available in storage which sustains pumping demand during high use dry months and which is recharged quickly at the beginning of wet season in autumn.

Table D-20 Monthly water stress by water sub-region on Gabriola, Mudge, and DeCourcy Islands for low and high recharge scenarios.

	Sub-regions	Monthly Water Stress (Groundwater Demand / Recharge) %												Annual (%)
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
10% recharge scenario	Sands	11	14	17	37	50	82	121	112	63	19	10	10	27
	Lock Bay	6	8	9	16	21	42	67	62	25	10	6	6	14
	Gabriola	2	2	2	26	33	41	64	60	40	3	1	2	12
	Silva Bay Region	4	5	6	13	28	43	67	62	33	9	5	5	13
	North Degnen Bay	5	7	8	154	197	231	364	338	230	9	5	5	64
	West Degnen Bay	4	5	6	49	62	77	121	112	78	6	4	4	23
	False Narrows	8	10	12	45	58	86	136	126	71	13	7	8	27
	Hoggan Lake	4	5	6	21	27	38	56	52	33	6	3	4	12
	Northumberland Channel	3	4	4	7	13	23	37	34	14	5	3	3	7
	South Descanso Bay	8	10	12	18	23	49	78	72	28	13	7	7	17
	Descanso Bay	2	3	4	6	10	15	23	21	11	4	2	2	5
	Mudge Island	7	8	10	33	43	70	110	102	49	11	6	7	21
	De Courcy Island	10	12	15	22	28	61	97	90	33	16	9	9	21
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
25% recharge scenario	Sands	5	5	7	15	20	33	48	45	25	7	4	4	11
	Lock Bay	2	3	4	7	8	17	27	25	10	4	2	2	6
	Gabriola	1	1	1	11	13	16	26	24	16	1	1	1	5
	Silva Bay Region	2	2	3	5	11	17	27	25	13	4	2	2	5
	North Degnen Bay	2	3	3	62	79	92	146	135	92	3	2	2	26
	West Degnen Bay	2	2	2	20	25	31	48	45	31	3	1	2	9
	False Narrows	3	4	5	18	23	34	54	50	29	5	3	3	11
	Hoggan Lake	2	2	2	8	11	15	22	21	13	3	1	1	5
	Northumberland Channel	1	1	2	3	5	9	15	14	6	2	1	1	3
	South Descanso Bay	3	4	5	7	9	20	31	29	11	5	3	3	7
	Descanso Bay	1	1	1	2	4	6	9	9	4	2	1	1	2
	Mudge Island	3	3	4	13	17	28	44	41	20	4	2	3	9
	De Courcy Island	4	5	6	9	11	24	39	36	13	6	3	4	8

Water budget final.xlsx [Water Balance]

Colour legend: water stress category

white	low stress (demand < 50% of recharge)
l.green	moderate stress (demand > 50% of recharge)
yellow	higher stress (demand > recharge, water taken out of storage and recharged later)

6 Data Gaps

The water balance is described using the best available data, but there are data gaps for each land-use type which would have to be addressed to improve the estimates. The following are uncertainties and assumptions which affect the reliability of the study:

- The number of survey respondents from West Degnen Bay, Northumberland, and Mudge Island is very low. To acquire more representative information for these sub-regions, further work needs to be done.
- There are insufficient data to calculate the amount of drainage from surface runoff and groundwater discharge. Welyk and Baldwin (1994) estimate the mean monthly discharge of eleven not gauged streams on Gabriola Island by relating the mean annual discharge and median drainage elevation of Goodhue Creek with those of 8 other creeks and rivers in southwest British Columbia. The volume of groundwater recharge to the bedrock aquifers from surface water needs to be quantified. Applying the runoff estimates from Welyk and Baldwin (1994) results in year-long negative water balances for many of the sub-regions. For more accurate calculations, drainage basins should be gauged at each of the creeks. Estimates of recharge from surface waters should be estimated or modeled numerically. For this study, the contribution of surface water recharging the groundwater system through stream leakage is assumed to be zero.
- Surface water use is not considered in this study.
- Water usages for many commercial establishments are unknown, and are estimated. There are no reporting commercial establishments from DeCourcy and South Descanso Bay, so commercial water demand from these sub-regions is presumed to be zero. Further study needs to be undertaken to target specific commercial establishments to acquire reasonable water use estimates.
- There are no reporting farming establishments from within Northumberland, Descanso and DeCourcy sub-regions, so the water demand from farming from these sub-regions is presumed to be zero. Further study needs to be undertaken to target more farms to acquire reasonable water use estimates.

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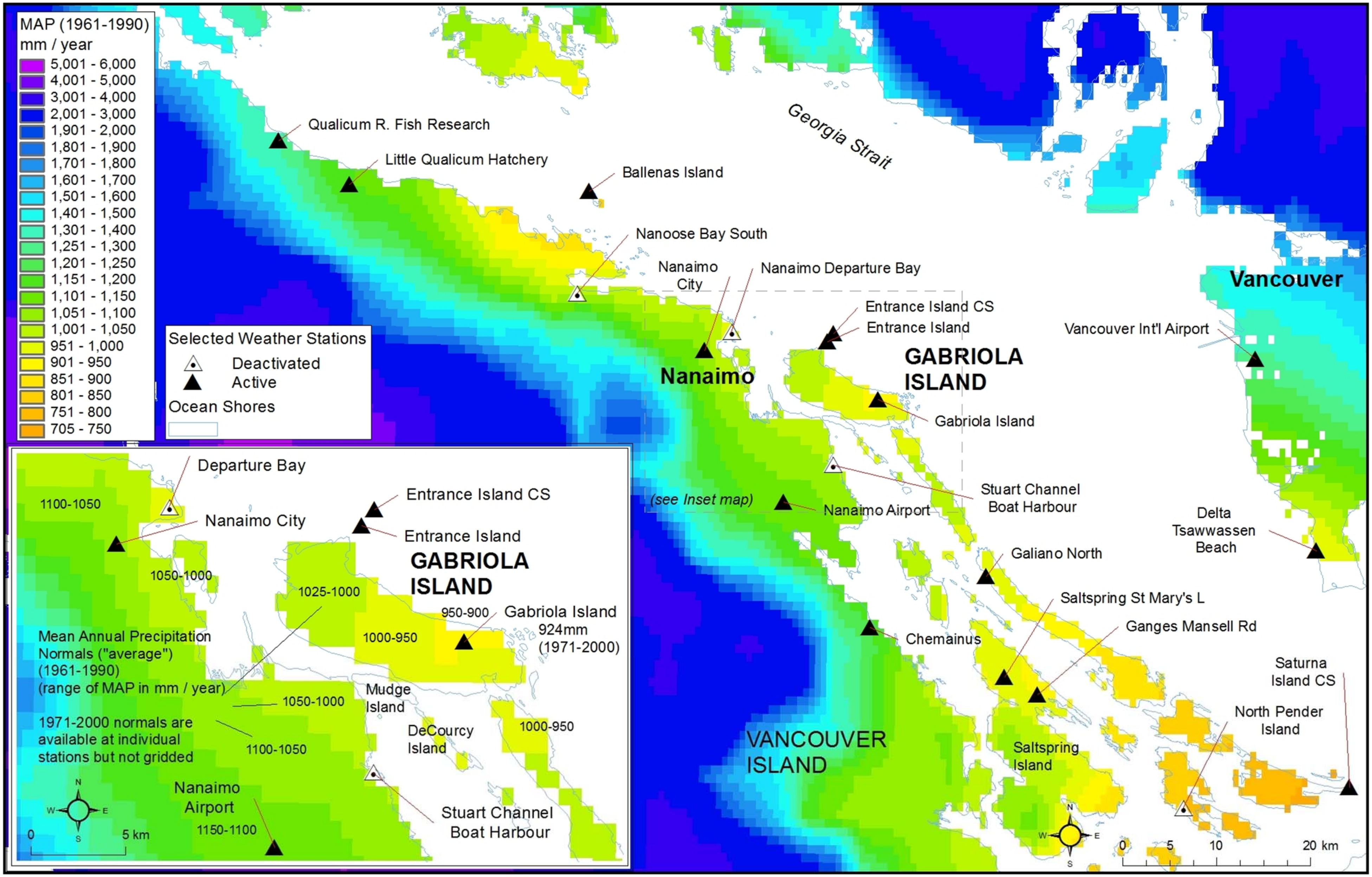

Date Source:
Mean Annual Precipitation Normals 1961-1990 (ClimateBC) (1971-2000 gridded data not available)

Not all weather stations are shown away from Gabriola Island and Nanaimo. Refer to Environment Canada for complete list.

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REGIONAL DISTRICT OF NANAIMO

Gabriola Island

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, and Mudge Islands)

Mean Annual Precipitation Normals (1961-1990) and Weather Stations near Gabriola Island

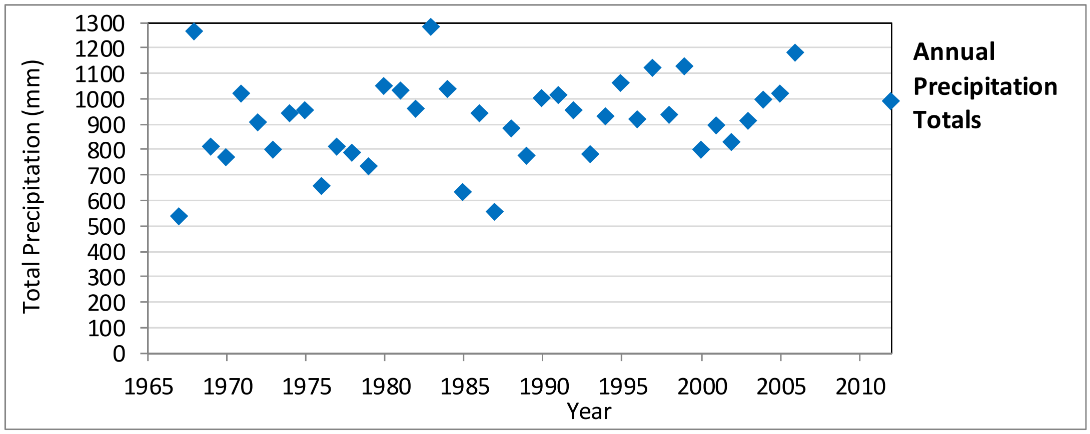
Date:	Approved:	Figure:
April 2013	JS	D-1

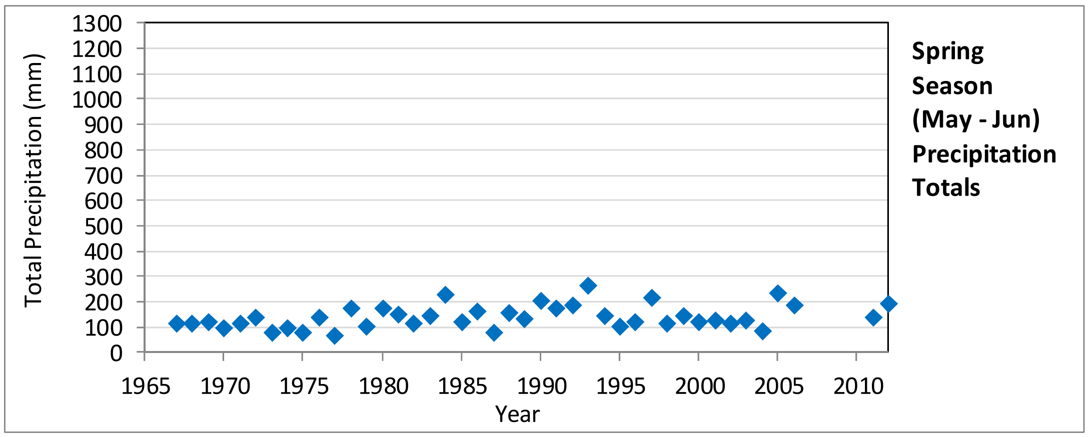
Precipitation at Gabriola Island Weather Station (1023042) 1967 to 2012. Annual and Seasonal Totals.

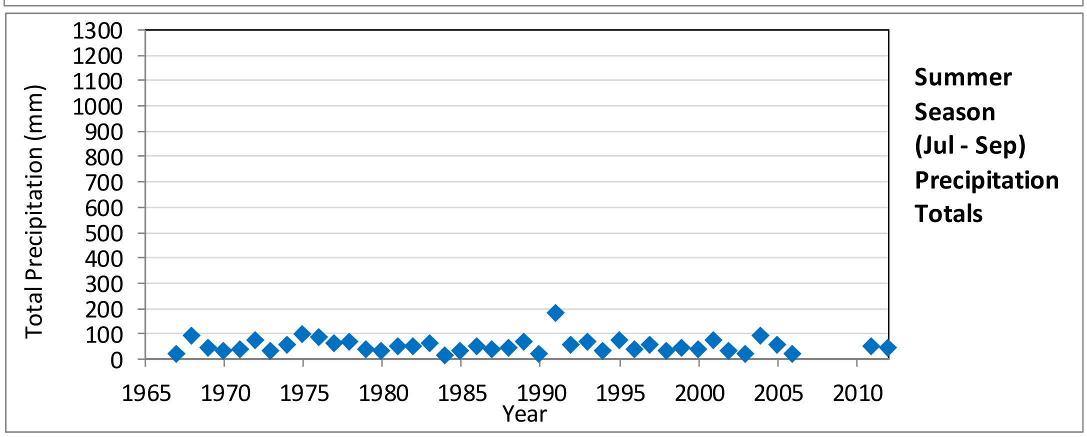
Notes:

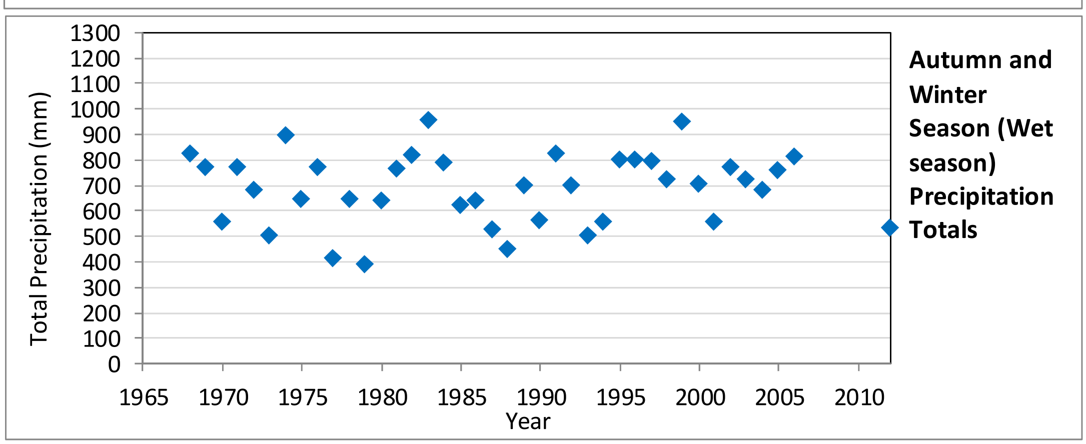
Estimated Annual and Seasonal Precipitation Totals from Published Monthly Data 1967 - 2007

Totals from Daily Data 2011-2012 (Monthly & Annual Totals unconfirmed by Environment Canada – Preliminary)









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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands

Total Annual and Seasonal Precipitation at Gabriola Island

Job No: 1CR010.000

Filename: Figures C2-C16 tides in wells.pptx

Gabriola Island

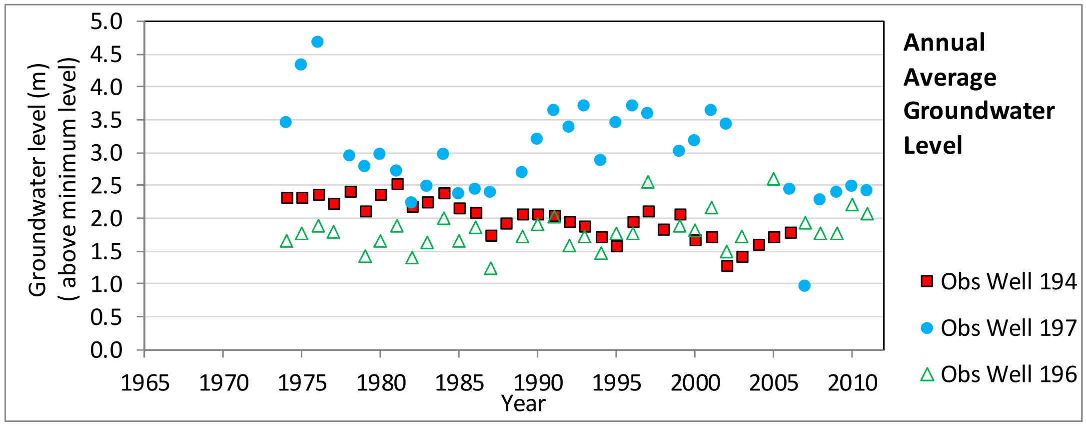
Date:	Approved:	Figure:
April 2013	JS	D-2

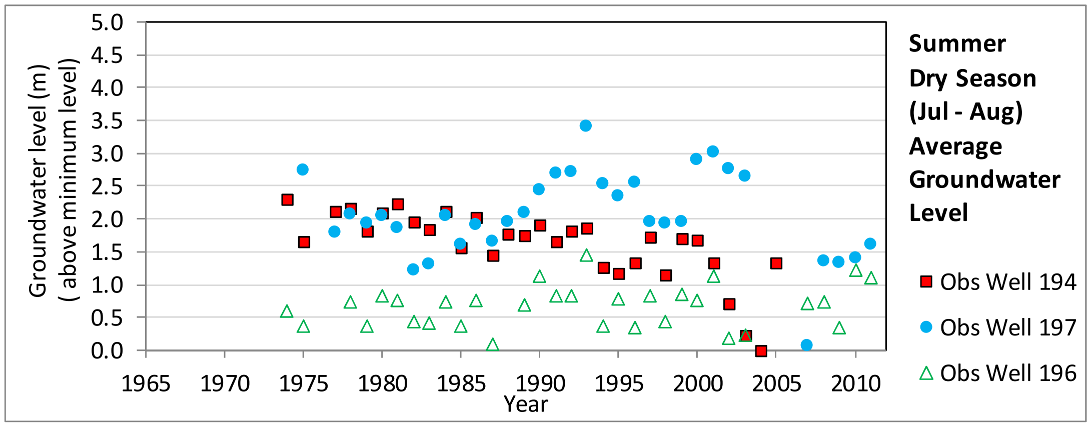
2012 - Gab Water Budget - Resid Consumption Final Calcs_JS review.xlsx

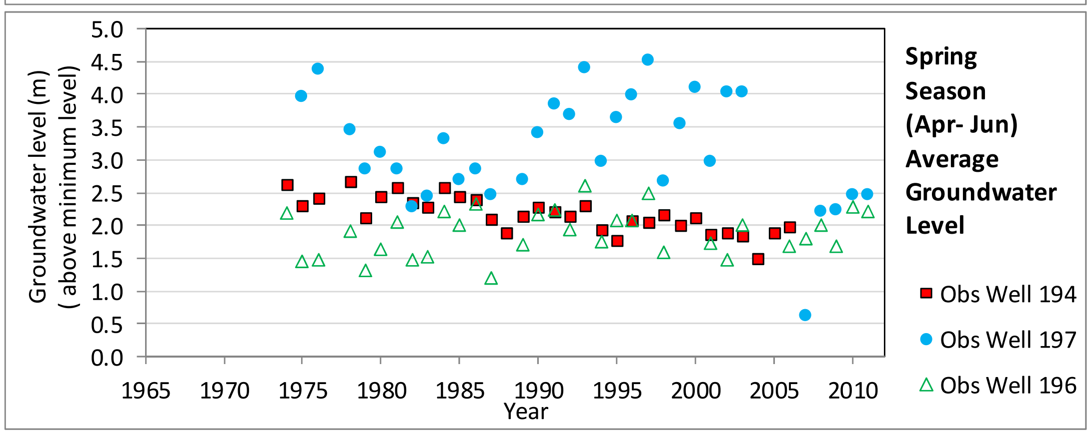
Average Groundwater Level in Provincial Observation Wells 194, 196, 197 on Gabriola Island

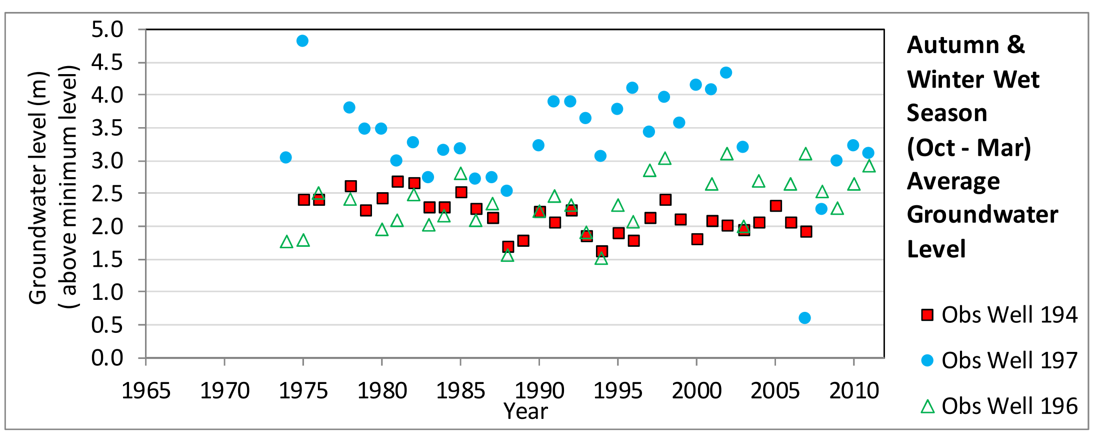
Notes:

Average groundwater levels are calculated from available groundwater levels. Depth to water was converted to water level above local datum to compare different wells on the same time series graphs.









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Job No: 1CR010.000

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Regional District of Nanaimo

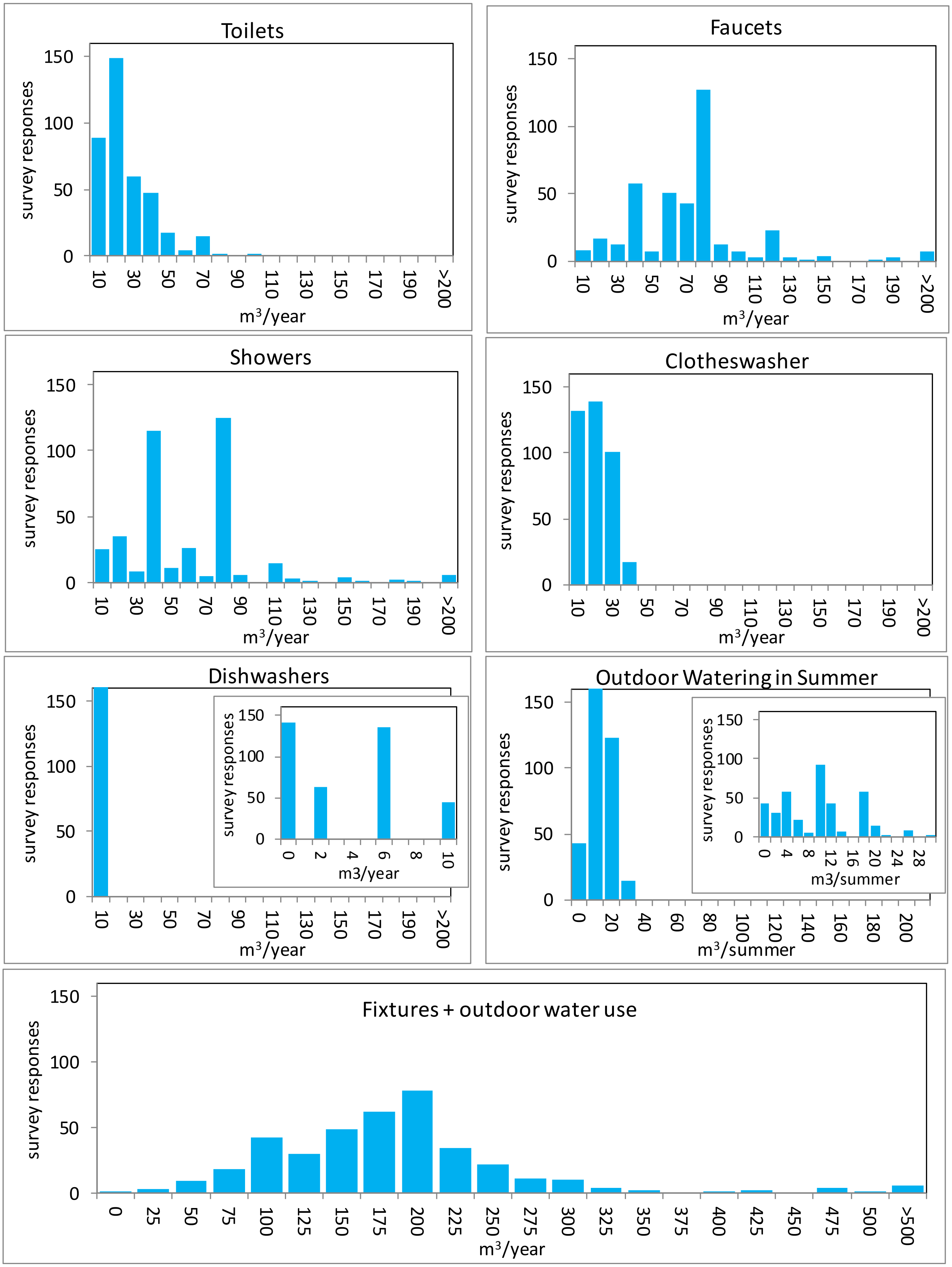
Gabriola Island

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands

Average Annual and Seasonal Groundwater Level in Provincial Observation Wells

Date:	Approved:	Figure:
April 2013	JS	D-3

2012 - Gab Water Budget - Resid Consumption Final Calcs_JS review.xlsx



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REGIONAL DISTRICT OF NANAIMO

Water Budget Project: RDN Phase One (Gabriola, DeCourcy, & Mudge Islands

Histograms of Total Annual Water Use Per Residence for Household Fixtures

Job No: 1CR010.000

Filename: Figures C2-C16 tides in wells.pptx

Gabriola Island

Date:	Approved:	Figure:
April 2013	JS	D-4

2012 - Gab Water Budget - Resid Consumption Final Calcs_JS review.xlsx