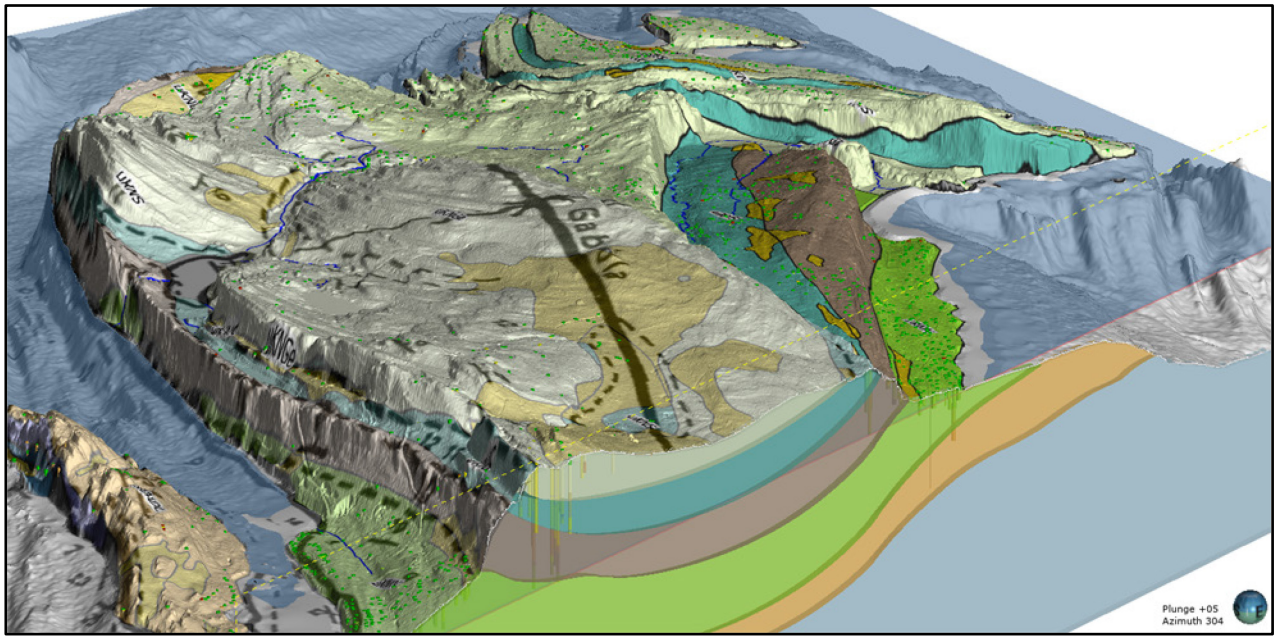
GW SOLUTIONS
ASSESSMENT & PROTECTION OF GROUNDWATER

July 23, 2021
Project No. 20-18

Islands Trust Area Aquifer Conceptualization Models



Prepared for: Islands Trust

Prepared by: GW Solutions Inc.

July 2021

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1 BACKGROUND AND OBJECTIVES

1.1 Background

GW Solutions was retained by the Islands Trust Council (TC) to conceptualize existing aquifers across the Islands Trust Area as part of the *Groundwater Sustainability Science* project. In fiscal year 2020/21 the Study Islands comprised the Northern Gulf Islands, Denman, Hornby, and Gabriola islands and in fiscal year 2019/20 the Study Islands comprised the Southern Gulf Islands of Galiano, Mayne, North Pender, South Pender, Saturna, and Prevost islands. Saltspring Island is included partially herein, however, aquifer mapping was recently updated there (Golder Associates, 2019). Islands Trust intends to complete groundwater recharge and updated aquifer conceptualization in fiscal year 2021/22 on Saltspring, Lasqueti, Valdez, and Thetis islands. A central component of this work is to develop three dimensional (3D) geological models that encapsulate the geology, groundwater and structured well data for the Study Islands.

1.2 Objectives and Scope

The objectives of the Aquifer Conceptualization across the Study Islands are as following:

1) Provide a classified geo-spatial data inventory of the Study Islands to Islands Trust in a format that can be included in the Islands Trust Freshwater Atlas, and other online mapping services including:
    a. Compiled geology mapping for all Study Islands;
    b. Hydrogeological Units;
    c. Groundwater Regions and Aquifers;
    d. Well Yields and Producing Factures (from GWELLS);
    e. Groundwater Levels (from GWELLS); and
    f. Seasonal Groundwater Level Variation.
2) Develop 3D conceptual models for the Study Islands, and:
    a. Provide 3D models in the current version of Leapfrog 3D, including meshes, surfaces, and volumes to be used later for hydrogeological modelling;
    b. Provide generalized and stylized models in Leapfrog 3D Viewer to be shared publicly; and
    c. Provide complete models in Island Trust's Seequent Central, where Leapfrog models and data can be visualised and managed in a centralised environment.

2 AQUIFER CONCEPTUALIZATION

2.1 Well Yields, Fractures, and Data Standardization.

The province maintains the GWELLS database where groundwater well information is stored. GWELLS is a rich source of information on groundwater and geology, yet it requires a significant amount of effort to restructure and refine when a sizeable population of wells is studied (e.g., hundreds to thousands of wells). The database is composed of four main tables as shown in Figure 1. The lithology table is mostly useful for unconsolidated (sand and gravel) wells, whereby the various units encountered during drilling help define aquifers and aquitards. Bedrock lithologies are lumped together regardless of bedrock type since groundwater is hosted in bedrock fractures and voids irrespective of rock type. A table defining productive fractures becomes important when dealing with bedrock wells which is the case for all Study Islands.

GW Solutions has extracted, cleaned, and standardized fracture and yield information extracted from GWELLS. The standardized table is attached in Appendix 2. Over 3000 wells are listed within the Study Islands with approximately 1710 providing information on both fracture depth and estimated yield per fracture.

The estimated yield reported by drillers and/or estimated from pumping tests was extracted for 83% of the wells (see Appendix 3). Most wells in the Study Islands have reported yields less than 15 USgpm (US gallons per minute):

- 40% of wells report yields of less than 2 USgpm ;
- 40% of wells report yields between 2 to 15 USgpm; and
- 10 % greater than 15 USgpm.

Water well drillers typically advance wells through one or more water-bearing bedrock fractures, until the cumulative water produced is deemed satisfactory in terms of quantity and quality. The completed well depth indicates at what depth sufficient, cumulative yield was reached. From a population of over 3000 wells, approximately 95% recorded total depth. Of these, approximately,

- 14% are less than 100 feet (30 m) deep;
- 32% are between 100 and 200 feet (61 m) deep;
- 23% are between 200 and 300 feet (91 m) deep; and
- 20% are greater than 300 feet (91 m) deep.

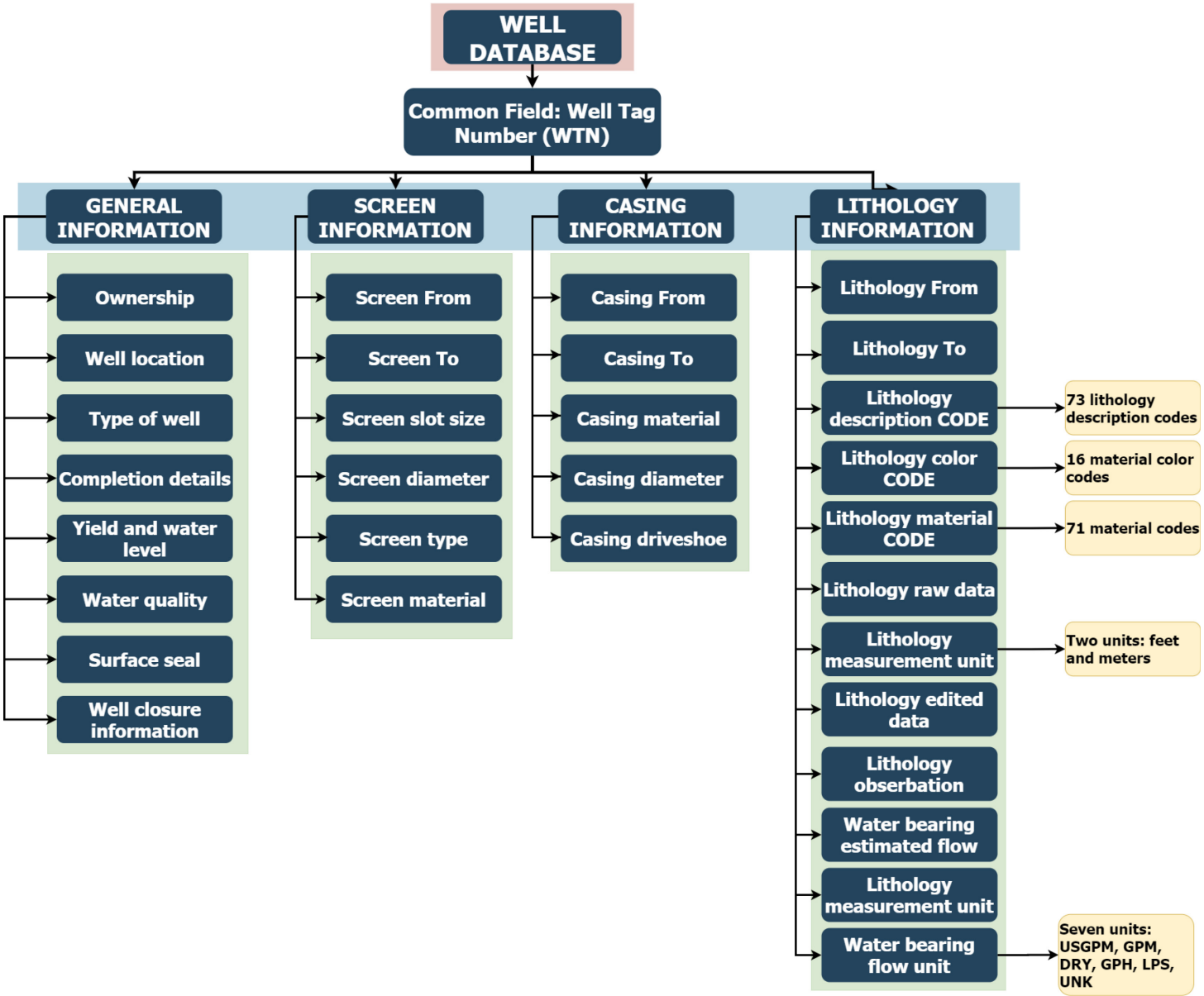


Figure 1 : BC Well Database (GWELLS) tables

2.2 Mapped aquifers, observation wells and groundwater fluctuations

Throughout the Study Islands, many shallow, dug wells rely on groundwater resources from the surficial veneer of glacial sediments. There are a several overburden aquifers mapped throughout the Study Islands: north Denman Island (Aquifer #739), Mayne Island (Aquifer #750), and Saltspring Island (Aquifer #'s 155, 156, 157, and 1048). However, apart from Aquifer 739 on Denman Island, these overburden aquifers are not aerially extensive.

Bedrock is the most widespread source of groundwater throughout the Study Islands. Most of the mapped bedrock aquifers for the Study Islands comprise sedimentary rocks of the Nanaimo Group. The Provincial mapped aquifers for the Study Islands are shown in Figure 2.

Figure 2 shows the surface water and groundwater monitoring stations. Many hydrometric stations were formerly operating throughout the study islands. Currently, water levels of St Mary's and Maxwell Lake on Saltspring Islands are recorded[1]. There are 23 provincial groundwater observation network (PGOWN) wells. Water level plots for each observation well are presented in Appendix 4. Key findings are summarized below:

- Generally, groundwater level minima occur in the summer to early fall, usually August and September, depending on the well type and depth (deep or shallow). Aquifer recharge typically starts in October.
- Groundwater level maxima occur in the winter months where precipitation is predominantly rain.
- Decreasing trends in groundwater elevation indicate aquifer discharge is greater than recharge. This may be attributed to cumulative impacts of climate change, pumping, land use change and development. Decreasing trends are noted for the following observation wells:
    - OW258 Galiano Island from 1980 to present.
    - OW125 Mayne Island from 1972 to present.
    - OW283 North Pender from 1983 to present.
    - OW 284 North Pender from 2004 to present.
- The largest seasonal groundwater fluctuation is observed for the observation wells on Galiano (9 to 11 m), followed by wells on Saturna (1.4 to 2.0 m) and North Pender (1.1 to 2.0 m). The smallest groundwater fluctuation is noted from observation wells on Mayne (0.5 to 1.4 m).

[1] https://northsaltspringwaterworks.ca/water/lake-levels/

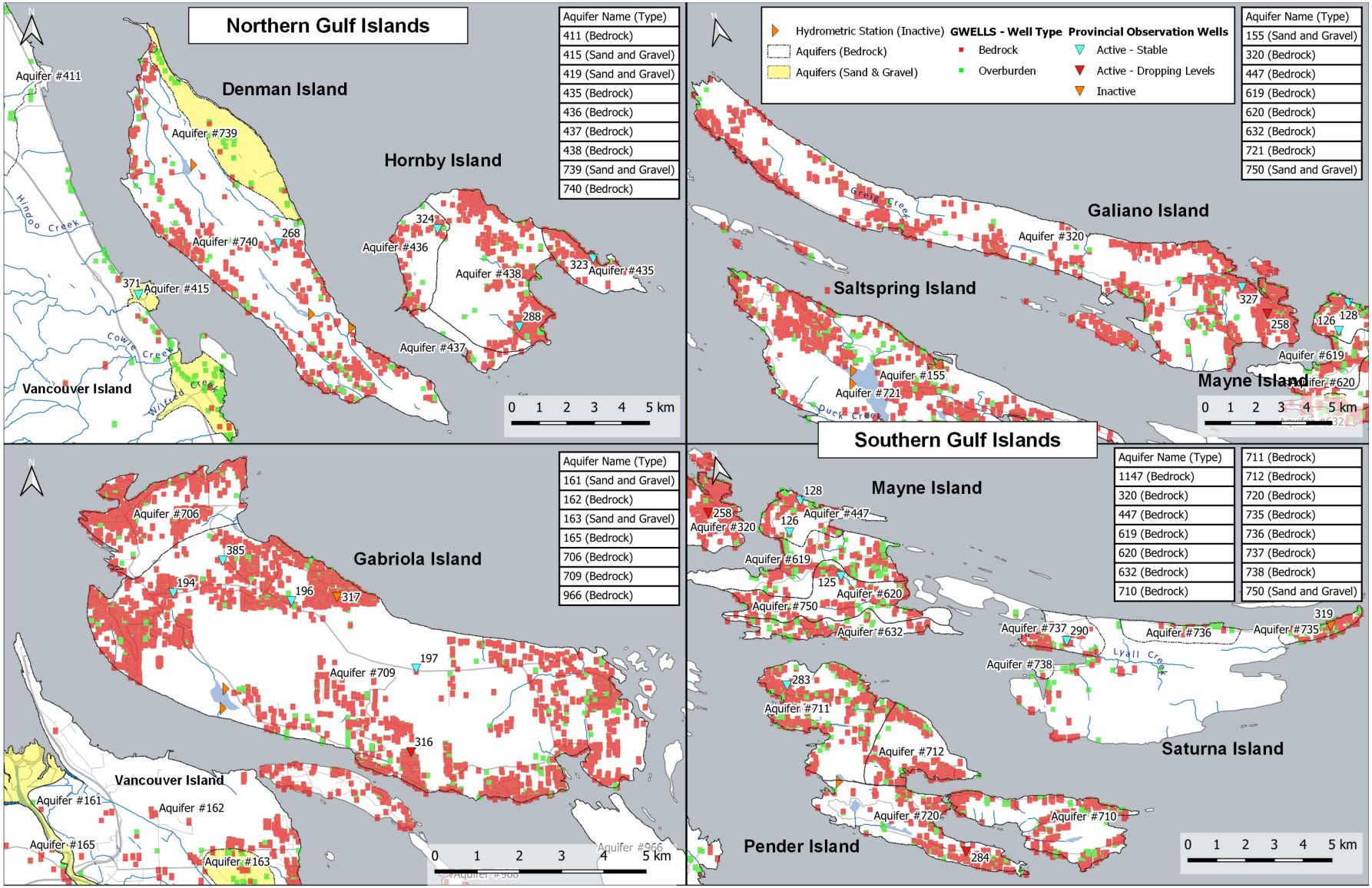


Figure 2. BC Mapped Aquifers and provincial observation wells (PGOWN)

2.3 3D Geological Conceptual Models

GW Solutions built 3D geological conceptual models for the Study Islands using Leapfrog (Seequent Ltd.) software (Figure 3). Model inputs include:

- LiDAR Bare Earth Topography (2 m resolution);
- Standardized GWELLS;
- Borehole Producing Fractures;
- Reported Well Yields; and
- Bedrock Geology.

The Study Islands are predominantly comprised of folded, faulted, and dipping bedrock strata of the Nanaimo Group formations of sandstone, conglomerate, and mudstone/shale (Figure 4 and Figure 5). Groundwater in bedrock aquifers is mostly stored and transmitted in fractures and faults, however, tracing these in the subsurface is rarely feasible. Instead, GW Solutions focused on modelling the broad-scale geology and structure of the Nanaimo Group across the islands, together with the wells, water levels and recorded fractures (Figure 6).

LiDAR topography revealed subtle structures such as bedrock contacts, bedding planes and lineaments that are not visible from traditional, ground-based geology mapping. To interpret the 3D geological structures of the islands, LiDAR topography was overlain by geology mapping for each Study Island (Table 1). GW Solutions has used the geological contacts mapped at ground surface, together with strike and dip information from the maps to interpret the subsurface structure of strata in Leapfrog. In some cases, the stratigraphy of the standardized bedrock lithologies could be interpreted from a sizeable population of the wells (e.g., Hornby, Denman, Gabriola). Stratigraphic contacts interpreted in GWELLS records were added to the models, where possible.

Each island is comprised of different suite of rocks from the sequence of Nanaimo Group formations (Table 2). Structural character varies across the islands in terms of bedrock bedding plane orientations (strike and dip), folds and faulting. All islands, however, display a characteristic pattern of topographically prominent coarse-grained strata (e.g., conglomerate or sandstone), with intervening low areas of fine-grained rocks (e.g., mudstone or shale). The interplay of bedrock type, structure and topography likely controls the relative amounts of surface runoff versus recharge.

Table 1. Geology maps used in the development of the 3D models.

Island	Information Sources
Hornby	(Bain, 2016), Katnick & Mustard (2001)
Denman	(Bain, 2016), Katnick & Mustard (2001)
Gabriola	England (1989), ITC (2020)
Galiano	England (1989), Carter (1976), ITC (2020)
Pender	England (1989), ITC (2020)
Mayne	England (1989), ITC (2020), Rutter & Blyth (1993)
Saturna	England (1989), ITC (2020)
Salt Spring	England (1989), Greenwood & Mihalynuk (2009), ITC (2020)

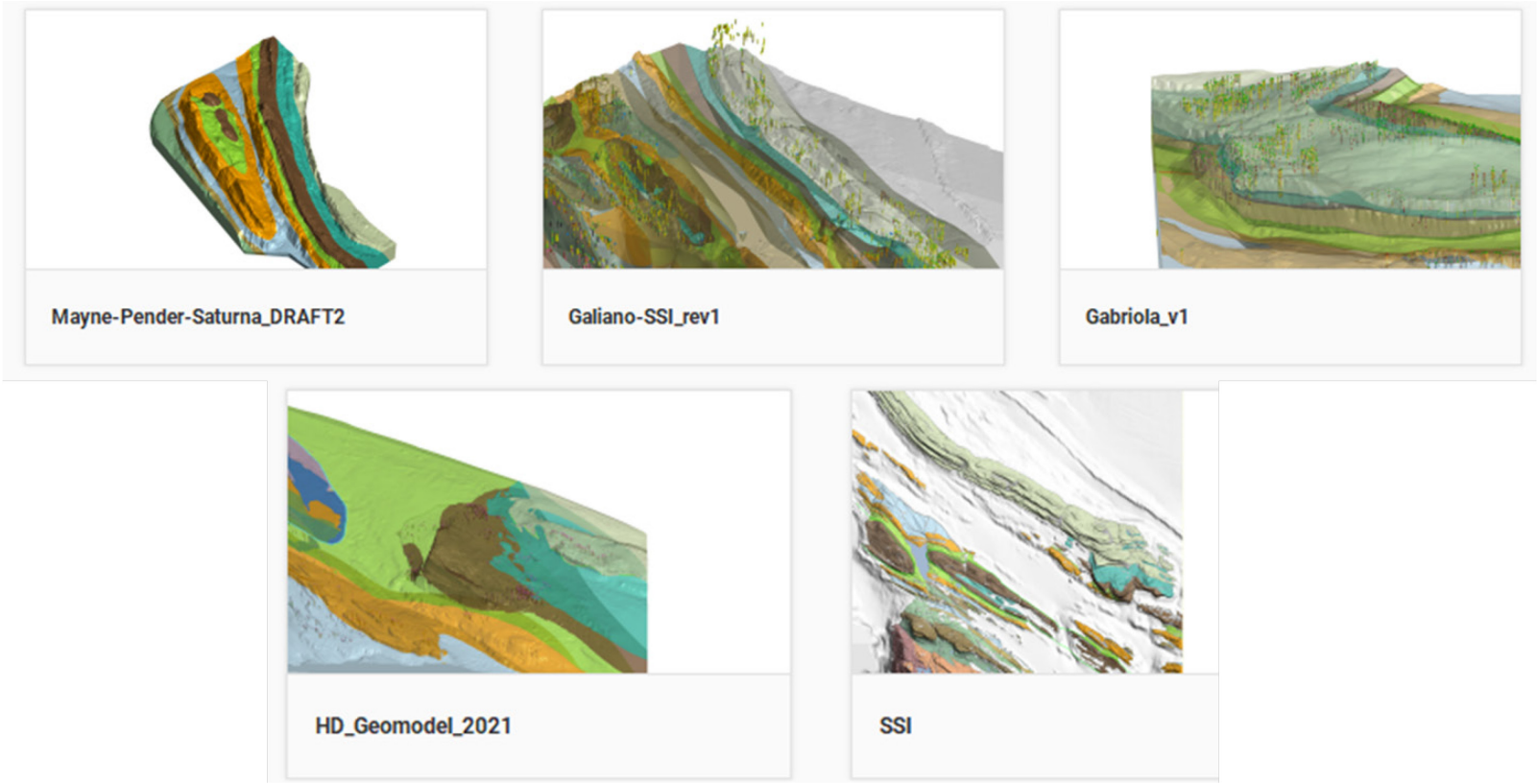


Figure 3. Seequent Central thumbnail scenes of the 3D geological conceptual models of the Study Islands

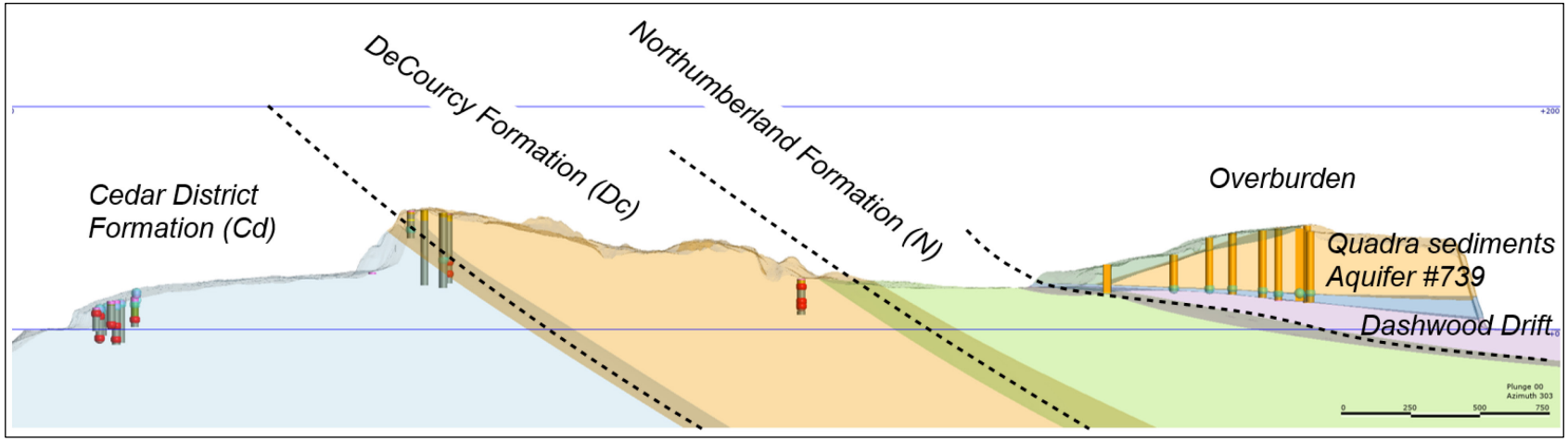


Figure 4. 3D model slice through geological conceptual model of north Denman Island

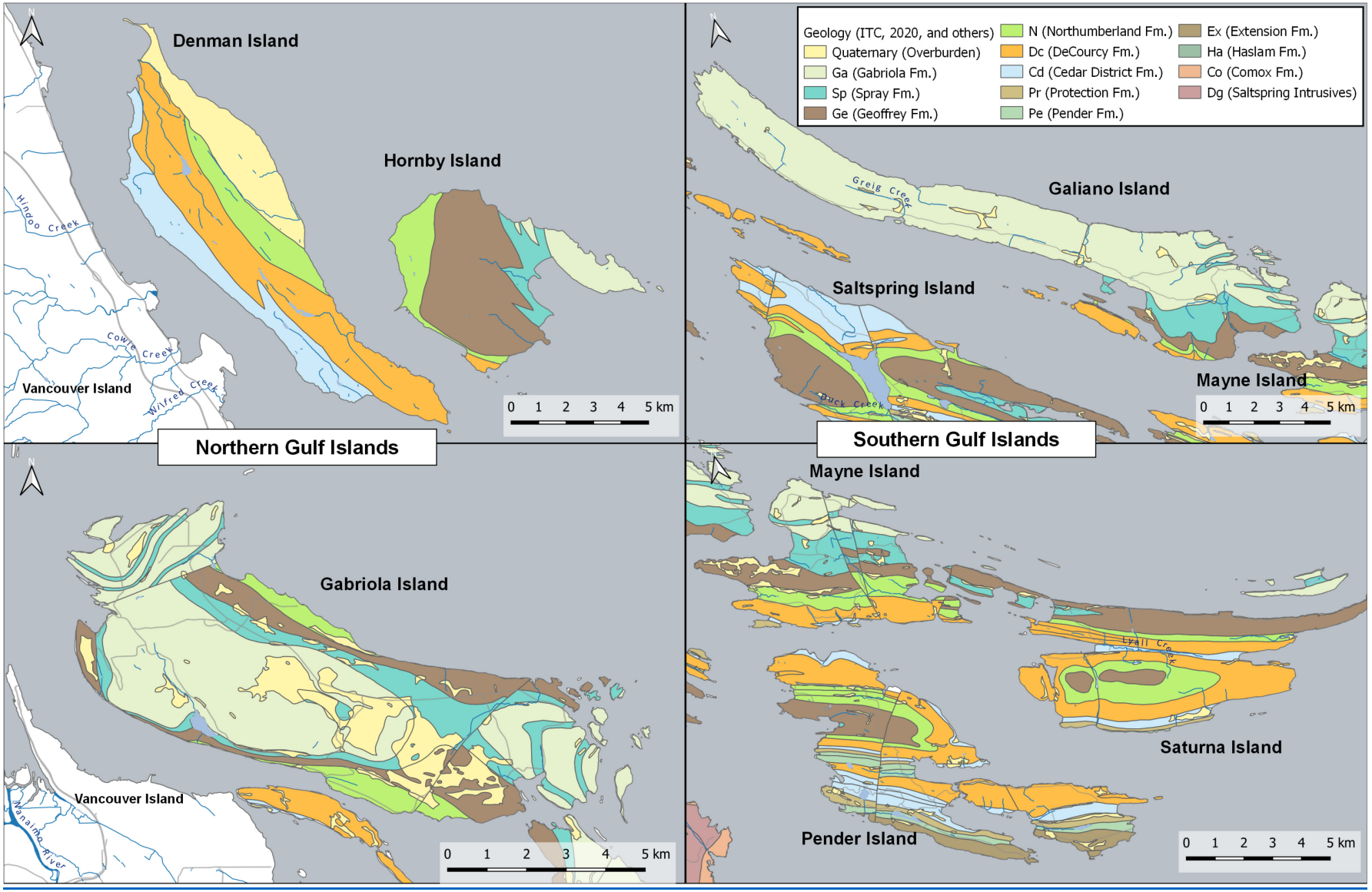


Figure 5. Overview of Gulf Island geology mapping.

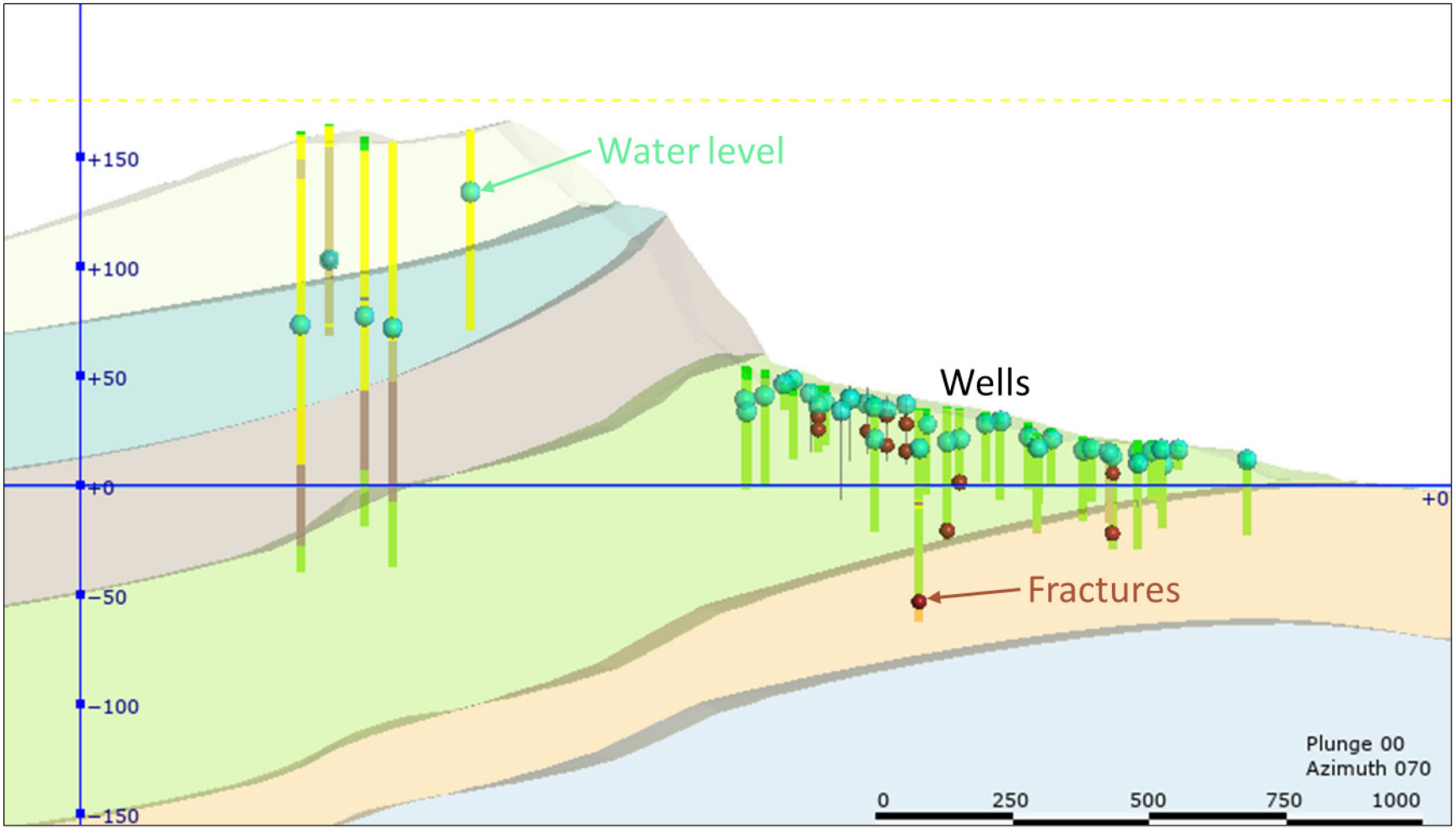
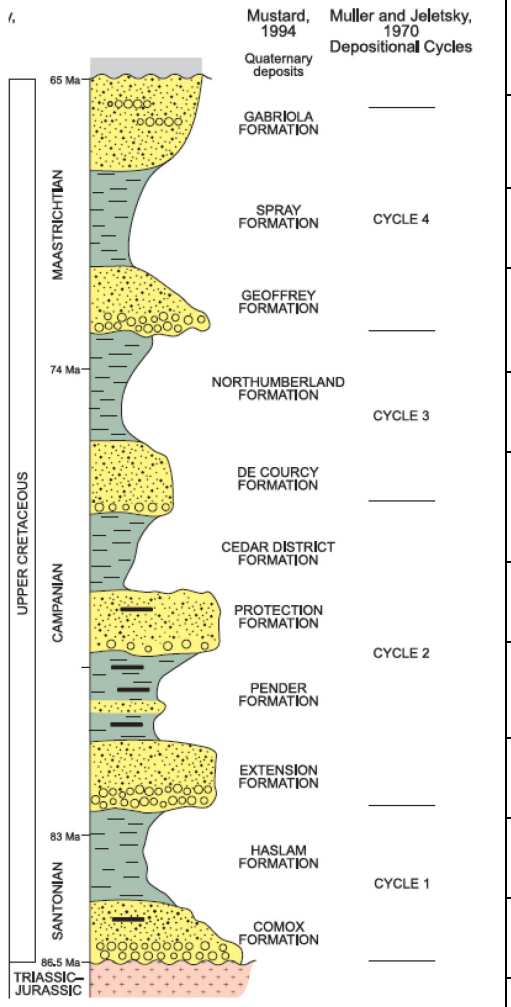


Figure 6. 3D Geological model components: topography, bedrock geology, wells, water levels, and fractures.

Table 2. Formations of the Nanaimo Group mapped on each island.



Map Code	Hornby	Denman	Gabriola	Galiano	Mayne/ Saturna	Pender	Saltspring
Ga							
Sp							
Ge							
N							
Dc							
Cd							
Pr							
Pe							
Ex							
Ha							
Co							

The Study Island conceptual models allow the user to slice through the study islands at any location to visually correlate, for example, wells and productive fractures to geological units and structures. The conceptual models comprise the following geological units:

1. **Quaternary Sediments – Q:** Several overburden sand and gravel aquifers have been mapped in the study islands. Aquifer #739, located on north Denman Island, is the largest (Figure 2). Aquifer #739 was identified from water well records and is the saturated portion of the Quadra sediments (sand, silty sand, and minor gravel). The aquifer is exposed at ground surface or is overlain by glacial till (Vashon Drift) and underlain by silt, stony clay, or till of the Dashwood Drift, or by bedrock.

2. **Gabriola Formation - Ga**: Thick-bedded, channelized conglomerate interbedded with sandstone. The unit forms the prominent ridges along the south coast of Gabriola Island.

    - Although a prominent topographic feature, the main source of groundwater for wells drilled through this unit is likely the underlying Spray Formation.

    - The Gabriola Fm. is a major source of groundwater for most of Galiano Island.

3. **Spray Formation - Sp**: Massive, olive-grey mudstone interbedded with thin-bedded (or locally thick-bedded), massive sandstone.
    - The Spray Fm. is a heterogenous unit (in contrast to the overlying Gabriola Formation) and is notable for its mixed interbedding of sandstone and shale in driller's logs. This unit is a major source of groundwater in the more densely developed areas of southern and northeastern Hornby Island.
    - The Spray Fm. is a significant source of groundwater on Gabriola and Mayne islands, and likely the source for many wells along southeast Galiano Island.
4. **Geoffrey Formation - Ge**: Thick-bedded, channelized conglomerate interbedded with massive, olive-grey sandstone, and minor mudstone. The Geoffrey Formation conglomerate is the resistive capstone of Mt Geoffrey (Hornby Island), the most prominent topographic feature of Hornby Island.
    - The unit is identified as conglomerate, sandstone/conglomerate, and massive sandstone from driller's logs. The conglomerate and sandstone are likely not major water-bearing units, however, the inclined bedding planes may direct runoff to areas where infiltration to the subsurface can occur.

5. **Northumberland Formation - N**: This dominantly fine-grained unit is characterized by massive dark grey mudstone, locally interbedded with siltstone and sandstone. In well logs, this unit is typically described as shale or mixed sandstone/shale.
    - The Northumberland is interpreted as the dominant source of groundwater for north and northwestern Denman Island, and significant areas of Gabriola Island, especially along the coast.
6. **De Courcy Formation - Dc**: The De Courcy Formation is characterized by massive, light grey, thick-bedded sandstone, locally interbedded with thick-bedded conglomerate. This unit forms topographic ridges and the intervening valleys are dominated by shale units of the overlying Northumberland Fm or underlying Cedar District Fm. The shale units have preferentially eroded to form small surface water catchments.
    - The De Courcy Formation is a prominent ridge-forming unit on Pender, Mayne, Saturna, and Saltspring islands. Many wells are drilled through the massive sandstone/conglomerate of the ridge tops and terminate in underlying fine-grained Cedar District Formation.
7. **Cedar District Formation – Cd**: Massive dark grey mudstone (shale), locally interbedded with siltstone and sandstone.
    - The unit is likely the dominant source of groundwater for wells drilled along the central axis of Denman Island.
    - The Cedar District Fm. is a locally important groundwater source on Pender Island and north Saltspring Island.
8. **Protection, Pender, Extension, Haslam & Comox Formations – Pr, Pe, Ex, Ha, Co**: These formations represent a sequence of alternating coarse- or fine-grained rocks. The resistive sandstone/conglomerate formations (Protection, Extension, and Comox formations) make up topographic ridges and the intervening valleys are dominated by mudstone/shale units (Pender and Haslam formations).
    - The mudstone-dominant units are important sources of groundwater on Pender and central Saltspring islands. Many wells were drilled through the massive sandstone/conglomerate of the ridge tops and terminate in underlying fine-grained units.

3 CONCLUSIONS

Based on the completed work, GW Solutions draws the following conclusions:

1. 3D aquifer conceptual models have been developed for the following islands: Hornby, Denman, Gabriola, Galiano, Mayne, Saturna, Pender, and Saltspring.
2. 3D Models compiled available geology and groundwater data, including standardized wells, lithologies, producing fractures, and water levels.
3. The Leapfrog3D models have been packaged for use in the free Leapfrog3D viewer and are available on the Islands Trust Seequent Central server.
4. Geospatial datasets generated from this work include:
    - Compiled geology mapping for all Study Islands;
    - Hydrogeological Units;
    - Groundwater Regions and Aquifers;
    - Well Yields and Producing Factures (from GWELLS);
    - Groundwater Levels (from GWELLS); and
    - Seasonal Groundwater Level Variation.

4 RECOMMENDATIONS

GW Solutions makes the following recommendations:

1. Review, expand and update the Leapfrog models as new information becomes available.
2. Develop a comprehensive model of the saltwater lenses and risk of saltwater intrusion using the 3D models as a framework to model the spatial variability of groundwater chemistry data across the islands.
3. Increase the number of community groundwater monitoring locations on each Study Islands to better understand the seasonal and inter-annual fluctuations in groundwater. This could be achieved through a community-based network of

privately-owned wells that are equipped with devices that measure water level and electrical conductivity (a proxy for salinity). The Regional District of Nanaimo's Volunteer Observation Well Network includes private wells on Gabriola Island and could provide a good model for the other islands.

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5 STUDY LIMITATIONS

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The findings and conclusions documented in this document have been prepared for the specific application to this project, and have been developed in a manner consistent with that level of care normally exercised by hydrogeologists currently practicing under similar conditions in the jurisdiction.

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If new information is discovered during future work, including excavations, sampling, soil boring, water sampling and monitoring, predictive geochemistry or other investigations, GW Solutions should be requested to re-evaluate the conclusions of this document and to provide amendments, as required, prior to any reliance upon the information presented herein. The validity of this document is affected by any change of site conditions, purpose, development plans or significant delay from the date of this document in initiating or completing the project.

The produced graphs, images, and maps have been generated to visualize results and assist in presenting information in a spatial and temporal context. The conclusions and recommendations presented in this document are based on the review of information available at the time the work was completed, and within the time and budget limitations of the scope of work.

The Islands Trust may rely on the information contained in this report subject to the above limitations.

6 CLOSURE

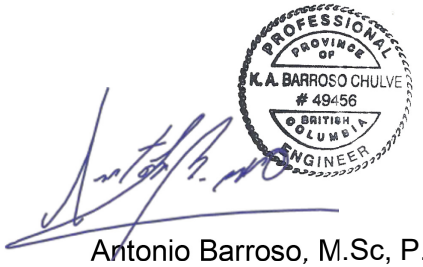
Conclusions and recommendations presented herein are based on available information at the time of the study. The work has been carried out in accordance with generally accepted engineering practice. No other warranty is made, either expressed or implied. Engineering judgement has been applied in producing this letter-report.

This letter report was prepared by personnel with professional experience in the fields covered. Reference should be made to the General Conditions and Limitations attached in Appendix 1.

GW Solutions was pleased to produce this document. If you have any questions, please contact us.

Yours truly,

GW Solutions Inc.



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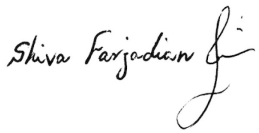

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APPENDIX 1

GW SOLUTIONS INC. GENERAL CONDITIONS AND LIMITATIONS

This report incorporates and is subject to these “General Conditions and Limitations”.

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This report pertains to a specific area, a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment. This report and the assessments and recommendations contained in it are intended for the sole use of GW SOLUTIONS’s client. GW SOLUTIONS does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than GW SOLUTIONS’s client unless otherwise authorized in writing by GW SOLUTIONS. Any unauthorized use of the report is at the sole risk of the user. This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of GW SOLUTIONS. Additional copies of the report, if required, may be obtained upon request.

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During the performance of the work and the preparation of this report, GW SOLUTIONS may have relied on information provided by persons other than the client. While GW SOLUTIONS endeavours to verify the accuracy of such information when instructed to do so by the client, GW SOLUTIONS accepts no responsibility for the accuracy or the reliability of such information which may affect the report.

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The client recognizes that property containing contaminants and hazardous wastes creates a high risk of claims brought by third parties arising out of the presence of those materials. In consideration of these risks, and in consideration of GW SOLUTIONS providing the services requested, the client agrees that GW SOLUTIONS’s liability to the client, with respect to any issues relating to contaminants or other hazardous wastes located on the subject site shall be limited as follows:

(1) With respect to any claims brought against GW SOLUTIONS by the client arising out of the provision or failure to provide services hereunder shall be limited to $10,000, whether the action is based on breach of contract or tort;

(2) With respect to claims brought by third parties arising out of the presence of contaminants or hazardous wastes on the subject site, the client agrees to indemnify, defend and hold harmless GW SOLUTIONS from and against any and all claim or claims, action or actions, demands, damages, penalties, fines, losses, costs and expenses of every nature and kind whatsoever, including solicitor-client costs, arising or alleged to arise either in whole or part out of services provided by GW SOLUTIONS, whether the claim be brought against GW SOLUTIONS for breach of contract or tort.

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GW SOLUTIONS is only responsible for the activities of its employees on the job site and is not responsible for the supervision of any other persons whatsoever. The presence of GW SOLUTIONS personnel on site shall not be construed in any way to relieve the client or any other persons on site from their responsibility for job site safety.

5.0 DISCLOSURE OF INFORMATION BY CLIENT

The client agrees to fully cooperate with GW SOLUTIONS with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The client acknowledges that in order for GW SOLUTIONS to properly provide the service, GW SOLUTIONS is relying upon the full disclosure and accuracy of any such information.

6.0 STANDARD OF CARE

Services performed by GW SOLUTIONS for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Engineering judgement has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of this report.

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The client undertakes to inform GW SOLUTIONS of all hazardous conditions, or possible hazardous conditions which are known to it. The client recognizes that the activities of GW SOLUTIONS may uncover previously unknown hazardous materials or conditions and that such discovery may result in the necessity to undertake emergency procedures to protect GW SOLUTIONS employees, other persons and the environment. These procedures may involve additional costs outside of any budgets previously agreed upon. The client agrees to pay GW SOLUTIONS for any expenses incurred as a result of such discoveries and to compensate GW SOLUTIONS through payment of additional fees and expenses for time spent by GW SOLUTIONS to deal with the consequences of such discoveries.

8.0 NOTIFICATION OF AUTHORITIES

The client acknowledges that in certain instances the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by GW SOLUTIONS in its reasonably exercised discretion.

9.0 OWNERSHIP OF INSTRUMENTS OF SERVICE

The client acknowledges that all reports, plans, and data generated by GW SOLUTIONS during the performance of the work and other documents prepared by GW SOLUTIONS are considered its professional work product and shall remain the copyright property of GW SOLUTIONS.

10.0 ALTERNATE REPORT FORMAT

Where GW SOLUTIONS submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed GW SOLUTIONS's instruments of professional service), the Client agrees that only the signed and sealed hard copy versions shall be considered final and legally binding. The hard copy versions submitted by GW SOLUTIONS shall be the original documents for record and working purposes, and, in the event of a dispute or discrepancies, the hard copy versions shall govern over the electronic versions. Furthermore, the Client agrees and waives all future right of dispute that the original hard copy signed version archived by GW SOLUTIONS shall be deemed to be the overall original for the Project. The Client agrees that both electronic file and hard copy versions of GW SOLUTIONS's instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except GW SOLUTIONS. The Client warrants that GW SOLUTIONS's instruments of professional service will be used only and exactly as submitted by GW SOLUTIONS. The Client recognizes and agrees that electronic files submitted by GW SOLUTIONS have been prepared and submitted using specific software and hardware systems. GW SOLUTIONS makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.