Islands Trust Area
Groundwater Recharge Potential Mapping

Prepared for: Islands Trust

Prepared by GW Solutions Inc.

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GW Solutions Inc.

Unit 24 – 4800 Island Hwy, Nanaimo, BC, V9T 1W6

Tel. (250) 756-4538 * abarroso@gwsolutions.ca

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1 BACKGROUND AND OBJECTIVES

1.1 Background

GW Solutions was retained by the Islands Trust Council (TC) to assess the spatial variability of groundwater recharge potential across Northern Gulf Islands including Denman and Hornby islands, and Southern Gulf Islands including Gabriola, Galiano, Mayne, North Pender, South Pender, and Saturna Islands and some neighboring islands including Prevost Island, Parker Island and Samuel Island, as a part of the *Southern Gulf Islands Groundwater Sustainability Strategy* project. In this report, we use "Study Islands" to refer to the five major islands as well as the neighbouring three small islands.

This study covers an area of 294.53 km^2 and forms part of the *Gulf Islands Groundwater Sustainability Science* project. Location maps of the Study Islands for Northern Gulf Islands and Southern Gulf Islands are presented in Figure 1 and Figure 2, respectively.

1.2 Objectives and Scope

The steps to achieve the Groundwater Recharge Potential Mapping across the Study Islands are as following:

1) Review the previous hydrogeology, hydrology, and geology studies across the Study Islands.
2) Compile existing datasets that are required to assess the spatial variability of groundwater recharge across the Study Islands;
3) Identify data gaps required to improve our understanding of groundwater recharge across the Islands;
4) Provide TC with full and open access to the geospatial model input and output results for incorporation into TC's TAPIS and MapIT mapping services.
5) Provide Islands Trust staff and public with the means to assess the relative degree to which a given land parcel or area may contribute to recharging groundwater; and
6) Uphold the Islands Trust mandate to preserve and protect the water resources on the Study Islands for sustainable water use through an improved understanding of the spatial variability of groundwater recharge potential.

   It is anticipated that this research and mapping will support TC staff with assessment of the potential impacts of density or intensity of land use (e.g., at build-out) on aquifer recharge. Ultimately, this work has potential to support the TC to deliver on their mandate to ensure the sustainability of water resources

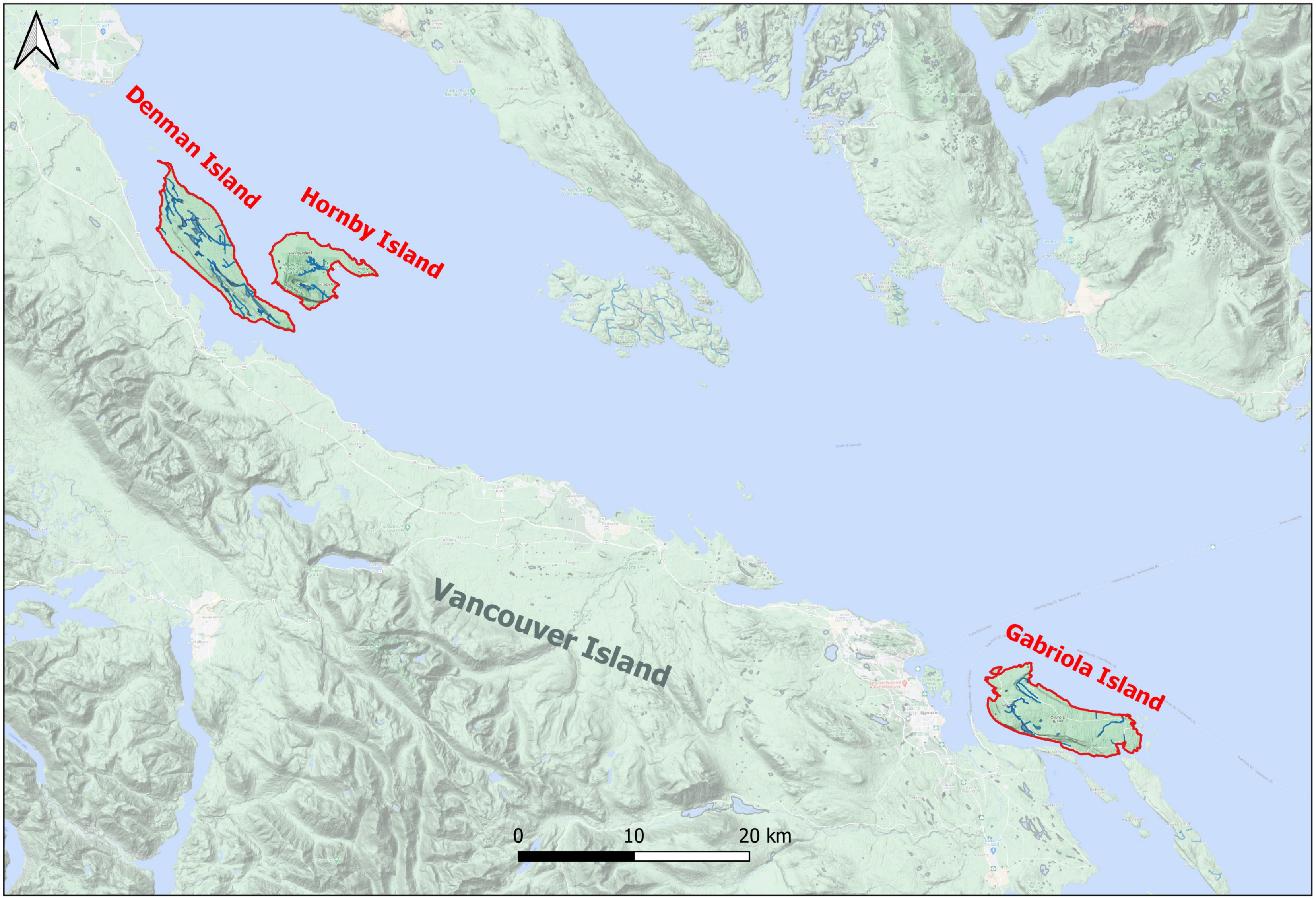

Figure 1: Northern Gulf Islands (Denman and Hornby) and Southern Gulf Island (Gabriola) - Study Islands

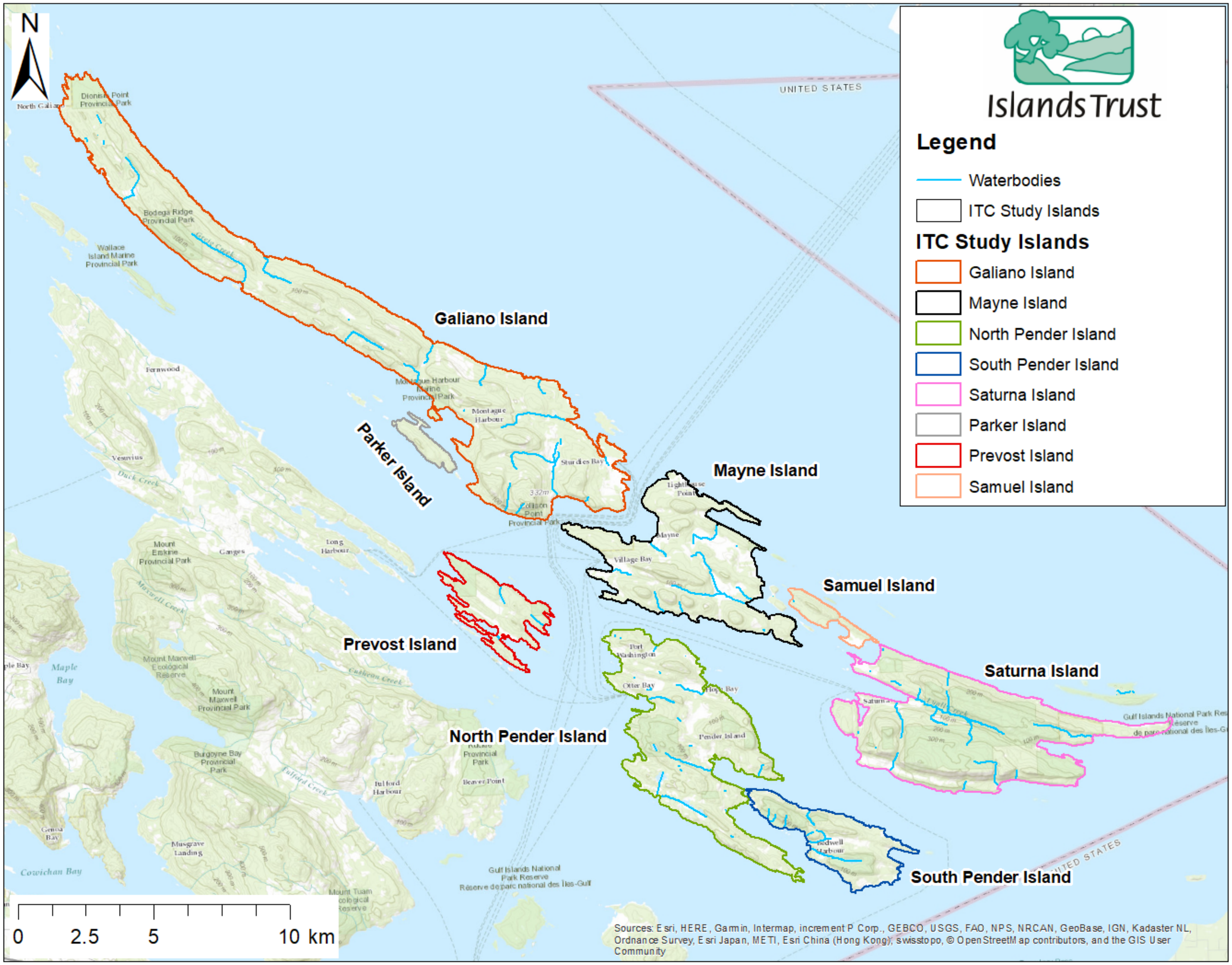

Figure 2: Southern Gulf Islands - Study Islands

2 DATA COMPILATION

A significant amount of research and scientific inquiry has been done over the previous decades to assess water resources across the Study Islands. The most relevant studies that have been reviewed are listed in references. To complete this study, GW Solutions compiled the following information sources (Table 1).

Table 1. Data type and source of information

Data Type	Data Source	Provided by
Groundwater levels	Provincial Groundwater Observation Wells Network (PGOWN water levels)	BC Ministry of Environment and Climate Change Strategy
Climate	Pacific Climate Impacts Consortium (gridded meteorological information and precipitation data)	Pacific Climate Impacts Consortium
	Current and Historical precipitation and temperature information	Environment and Natural Resources Canada (NRCan)
Watersheds	Freshwater Atlas Watershed boundary	Islands Trust (CRD Boundaries)
Waterbodies	Lakes and wetlands	Islands Trust (CRD Boundaries)
Surface water levels and flows	Provincial and Federal Government	Environment and Natural Resources Canada (NRCAN)
Parcel information	Parcel assessment and rezoning type	Islands Trust
Elevation	30 m x 30 m digital elevation model (DEM)	Natural Resources Canada - NRCan
	2 m contour	Islands Trust
	16 m x 16 m Digital Elevation Model	Islands Trust
	LiDAR data 1m resolution	Islands Trust
Soil and land Cover	BC Soil Information Tool (regional and local geology and soils information)	BC Soil Information Finder Tool and Islands Trust
	BC Land cover	BC Data Catalogue
	Bedrock Geology	Islands Trust
Geology	Geology Survey of Canada, Department of Energy, Mines and Resources	Islands Trust
	BC Faults	BC Data Catalogue
TEM Ecosystem mapping	Terrestrial Ecosystem Mapping	Islands Trust
Vegetation Inventory Index	Island Trust	Island Trust
Water usage/demand data	VIHA	GW Solutions
Wells, aquifer properties and mapped aquifers	BC GWELLS database	BC Province
	Aquifer boundaries and map sheets	BC Province
	Aquifer properties and mapped aquifers	EcoCat Ecological Reports Catalogue

3 DELINEATION OF GROUNDWATER MANAGEMENT REGIONS

The concept of a “groundwater region” encompasses both the surface catchment and subsurface media of water bearing materials. The scale of a groundwater region is determined based on the goal of the study and the resolution of available information.

Groundwater regions help synthesize the potentially complex conditions in a way that facilitates planning and sustainable management of water resources and is considered a Management Unit. The existing groundwater regions devised for Denman, Hornby, and Gabriola islands were mainly based on topography, catchment areas, management systems and the density/extent of groundwater development.

GW Solutions has revised the groundwater regions for the Study Islands based on the following data sets:

- Previous groundwater regions mapping.
- Watershed/ sub-watershed mapping.
- Topography relief and surface catchments.
- Water wells (i.e., spatial density and productivity).
- Subsurface geology.
- Structural geology such as faults.
- Mapped aquifers or recently delineated aquifer(s).

Groundwater regions were revised and delineated in a Geographic Information System (GIS). Maps and information on groundwater regions for all the Study Islands are provided in Appendix 2. Figure 3 presents the groundwater regions for Denman and Hornby Islands.

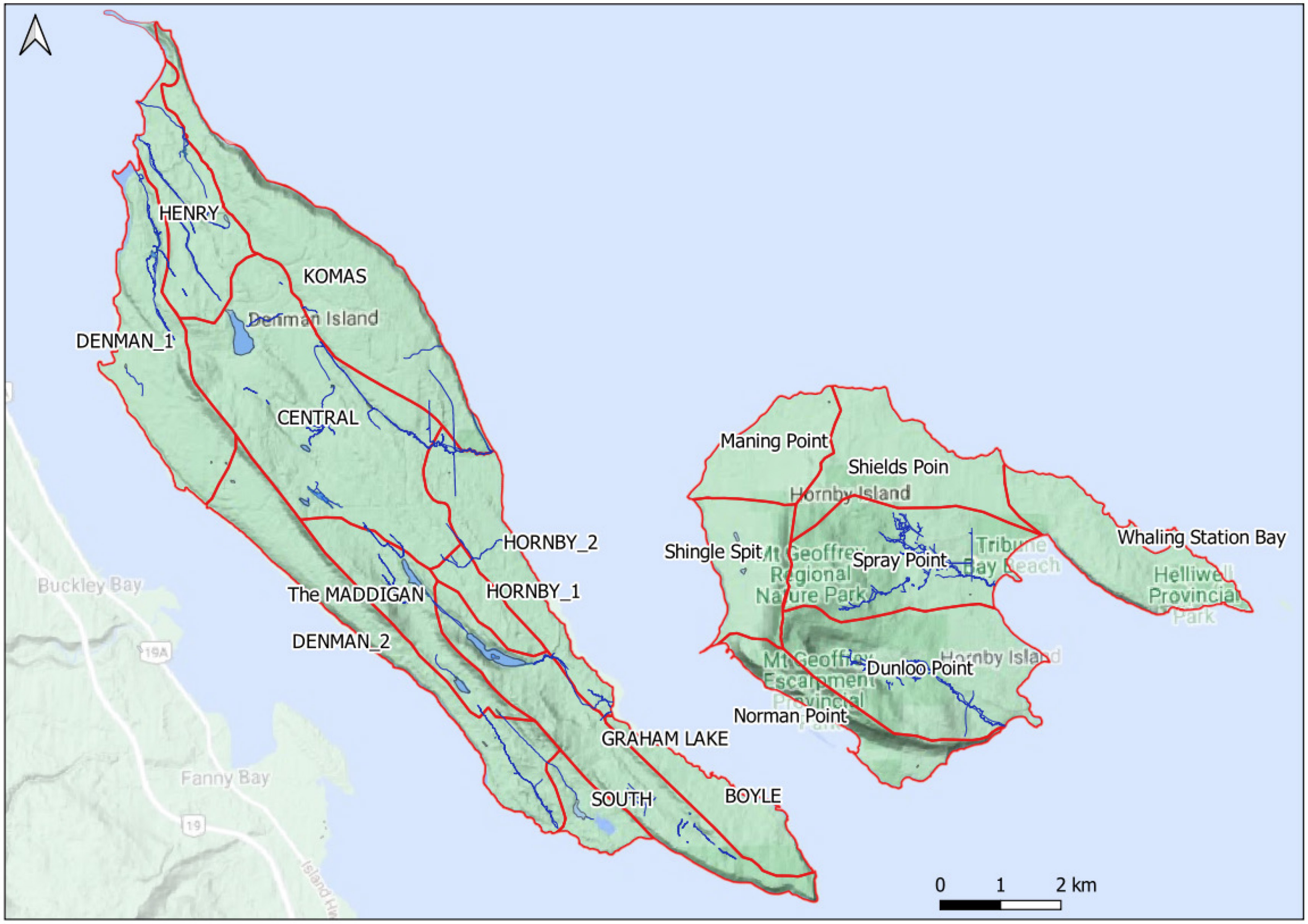

Figure 3. Groundwater regions for Denman and Hornby Islands

4 DEFINITION OF BEDROCK LINEAMENTS

Bedrock on the Study Islands is predominantly comprised folded, faulted, and dipping bedrock strata of the Nanaimo Group formations of sandstone, conglomerate, and mudstone/shale. Groundwater in bedrock aquifers is mostly stored and transmitted in fractures and faults, which are largely controlled by regional bedrock lineaments. While it is thus intuitively obvious that groundwater is also preferentially recharged via bedrock lineaments quantifying the role of each lineament is highly complex.

Bedrock fracturing can be enhanced in friable or easily breakable rock types (e.g., mudstone, shale) or by geologic structures (e.g., faulting, folding). Glaciation and weathering of heavily fractured areas can leave behind topographic depressions due to preferential erosion and dipping strata direct surface runoff towards topographic lows, enhancing recharge in these areas. In the subsurface, large faults may also be barriers to groundwater flow as they can fill with silt and clay (“fault gauge”). Folded strata may have enhanced permeability – and hence recharge, at the apex of syncline/anticline structures due to tension cracking of the rock.

Detailed mapping of the landscape is now possible due to the availability of LiDAR imagery of the Study Islands. The LiDAR imagery is processed to derive a “bare earth” model of the landscape, which can reveal subtle structures (bedrock faults, bedding planes and lineaments) not visible from the ground. We have delineated fracture zones using the following sources of information:

1- LiDAR with 2m resolution provided by Island Trust; Bedrock lineaments were digitized from a high-resolution hillshade (derived from a bare earth LiDAR DEM).

2- Bedrock geology maps of formation contacts and large-scale structural geology (faults and folds).

3- Previous geological studies on the Study Island: Bedrock Lithology and Structure from Foweraker (1973), Carter (1976) and Muller (1980).

4- Lineament maps produced by NRCan, which have been reviewed and revised based on the LiDAR-2m.

Figure 4 shows the delineated structural geology features inferred from the above-mentioned information sources for Denman and Hornby Islands. The lineaments for all the Study Islands are presented in Appendix 3. These lineations are considered to be potential groundwater recharge pathways in the recharge zones and groundwater discharge pathways in the discharge zones.

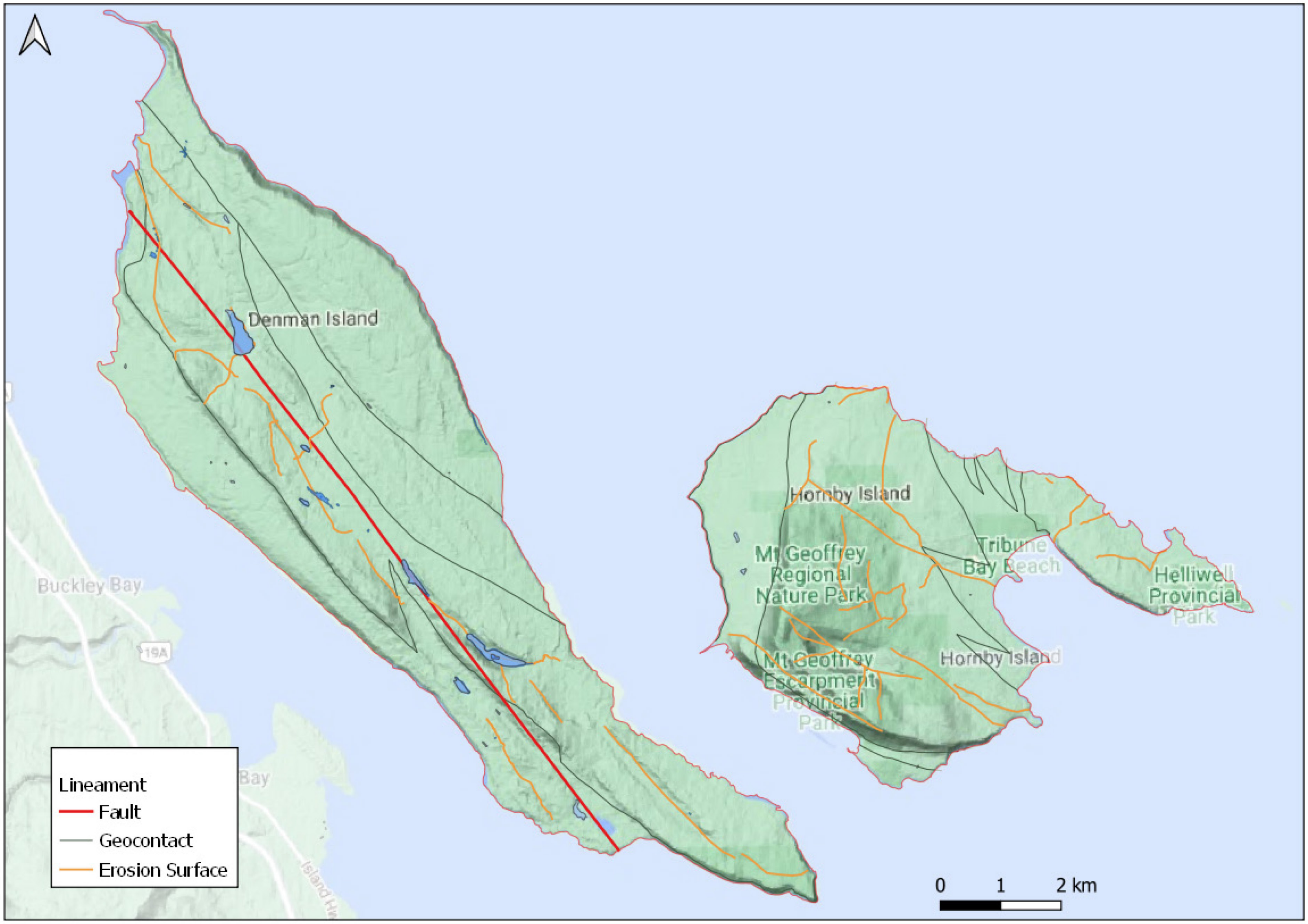

Figure 4. Denman and Hornby Islands lineaments (faults, erosion surface, and geological contacts)

5 TOPOGRAPHIC WETNESS INDEX

The interplay of surface runoff and topography can be qualitatively assessed using the Topographic Wetness Index (TWI). TWI is a mapping product based on a gridded (raster) Digital Elevation Model (DEM). TWI is a function of the size and slope of the upstream contributing area associated with each grid cell of a raster DEM. Large values of TWI are typically associated with lowlands having a larger contributing catchment area and indicate groundwater discharge areas where the water table intersects the land surface. At higher elevations in a watershed, where groundwater is recharged, high TWI values can indicate either a local water table perched above the main water table, or it can indicate locations where surface water is funnelled into depressions which will focus high amounts of recharge. To incorporate this dynamic in the recharge assessment, we calculated TWI for the Study Islands using SAGA[1] tools and the 2m resolution LiDAR DEM.

The generated TWI mapping across the Study Islands is provided in Appendix 4.

6 DELINEATION OF GROUNDWATER RECHARGE AND DISCHARGE AREAS

The geochemistry of groundwater in the area is similar to that of rainwater indicating the groundwater is recharged predominantly by the infiltration of precipitation through soils and geologic formations to the water table (Allen and Suchy, 2001). Groundwater recharge thus mainly occurs where the water table is below the land surface and the soils are sufficiently permeable or “well-drained” to allow infiltration. The areas where the water table meets the land surface are known as groundwater discharge areas.

Groundwater recharge is defined by the downward movement of groundwater while groundwater discharge is defined as the upward movement of groundwater to the land surface.

Groundwater discharge can have an apparent vertical upward component as they emerge at the land surface. Groundwater discharge areas are typically located in topographic lows such as stream valleys providing seasonal or year-round baseflow to streams, underground discharge to lakes, wetlands and estuaries.

In contrast, groundwater recharge typically occurs in upland areas where the unsaturated/vadose zone is thick and the water table is deep enough to allow water percolate underground and replenish the saturated zone.

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[1] System for Automated Geoscientific Analysis. Downloaded from http://www.saga-gis.org/en/index.html.

Several approaches have been proposed for estimating the presence of preferential areas for groundwater discharge and recharge, using a variety of data sources. GW solutions reviewed several academic and public-sector methodologies to select (a) method(s) for defining and delineating groundwater discharge and recharge potential areas that could be applied to the Study Islands.

Two approaches were selected; one based on hydraulic head and the thickness of the unsaturated zone; the other based on remote sensing and multispectral image analysis.

6.1 Depth to Water Methodology

The depth of groundwater is a dominant control of groundwater recharge across the Study Islands. Previous studies of the hydrogeology and groundwater recharge for Gabriola and Hornby islands have showed that the depth of water table or the thickness of unsaturated zone has a significant role in controlling groundwater recharge rate across the Study Islands (Allen & Matsuo, 2002, SRK, 2013). Despite surficial conditions that are suitable for groundwater infiltration, a shallow water table limits the amount of water that can infiltrate underground.

When highly dense water level measurements are available, the depth of water table is derived from the differentiation of elevation of the ground surface and groundwater elevation surface. However, in BC water depth from wells are available from GWELLS which have inherent inaccuracies; water levels measured at the end of drilling may not accurately represent the true water table and water levels measured at different seasons over many decades can fluctuate by several meters. Additionally, wells intercepting different fractures with likely different piezometric levels. However, in our experience, these vertical inaccuracies average out *at the watershed scale* with a large number or data points. Therefore, we use the terminology average interpreted groundwater elevation and depth to water to describe the average potential for groundwater to allow recharge. For instance, if groundwater level is above ground surface, it will limit groundwater recharge and allow mostly groundwater discharge. The opposite condition will occur when the groundwater level is below ground and allow mostly groundwater recharge.

Average interpreted depth to water = Ground Surface Elevation – Average Interpreted Groundwater Elevation

Average interpreted groundwater elevation surfaces were interpolated from classified groundwater elevation points derived from the average interpreted depth to water from GWELLS and locations of known springs from surface water licenses. Springs are locations where groundwater discharges at the land surface.

Using Leapfrog (*see GW Solution, 2021, Report 1: Aquifer Conceptualization*) a surface of groundwater elevation (Groundwater elevation grids) was created then exported into QGIS as a raster file for each Study Island. The average interpreted piezometric level is a measurement that averages the water level at different depths (fractures) taking from water wells, springs, and water level surveys. The average interpreted depth to water over the study areas was generated by subtracting the average interpreted groundwater surface elevation from the land surface elevation (DEM) in QGIS.

According to historical and active monitoring wells, the water table elevation can fluctuate by several meters over the year; high in late winter/early spring and low in late summer/early fall. This leads to areas with temporary groundwater discharge in the spring yet they are groundwater recharge areas for the remainder of the year. For this study, all areas with either permanent or temporary groundwater discharge were classified as groundwater discharge areas. Areas where the range of groundwater fluctuations is always above the water table were classified as groundwater recharge areas.

Maps of preferential recharge and discharge areas determined for the study areas based on the average interpreted depth to water method are presented in Appendix 5.

6.2 Remote Sensing/ Satellite Multispectral Image Analysis Methodology

The approach of using satellite multispectral image analysis includes application of two methods: 1) A Normalized Difference Vegetation Index - Normalized Difference Moisture Index, and 2) Thermal Data Method. These methods were chosen due to their ease of implementation, reliance on free and publicly available data, and accuracy in identifying soil moisture levels on the landscape. Soil moisture level is then used as a proxy for groundwater discharge potential.

Appendix 6 describes the methodological review process for different methods of remote sensing approach and the final discharge mapping process.

6.2.1 Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) method

This method focuses on identifying areas of potential groundwater discharge areas by using the image signatures of relative soil moisture and vegetation types. Soil moisture signatures created by detection of “darkening” or “greening” of imagery pixels. High perennial soil moisture can darken soils or encourages green vegetation to flourish in otherwise dry conditions. Such indications of landscape “wetness” and “greenness” can be detected using satellite imagery, by relying on satellite based spectral indices. A spectral index can be understood as a mathematical manipulation on certain wavelengths of detectable light that are designed to highlight certain characteristics of the landscape, such as greenness or wetness, while minimizing other confounding effects.

A vast number of spectral indices have been defined for various use cases. Here we rely on the NDVI (Normalized Difference Vegetation Index) and the NDMI (Normalized Difference Moisture Index). Both are well-known and widely used image analysis methods.

NDVI is designed to highlight the presence of dense, green vegetation, or “greenness”, while the NDMI is designed to highlight the level of moisture within vegetation or soil, defined as “wetness”. By comparing landscape “greenness” and “wetness” between the wet season and the dry, it is possible to observe which parts of the landscape *preserve* their wetness and greenness between the wet and the dry season. Areas on the landscape that continue to be “green” and “wet” in the dry season indicate groundwater discharge, as groundwater would be the primary source for continued oisture supply to the surface in the dry season (excluding irrigation).

Implementing this method required multispectral satellite images for the wet and dry season over the study area. These images were available free of charge from both the Landsat and the Sentinel satellite missions. This methodology is discussed in greater detail in Appendix 6.

Appendix 7 presents the generated groundwater discharge probability maps for the Study Islands based on NDVI and NDMI method.

6.2.2 **Thermal data method**

Thermal remote sensing mapping can provide regional scale information on groundwater discharge zones (Sass et al., 2014). This technique hinges on the phenomenon that depending on the time of the year, groundwater discharges at a temperature that differs from the land surface. Using thermal imagery taken by the Landsat mission during winter, discharging groundwater will register as warmer than a land surface covered by frost or snow. This approach is untenable on Vancouver Island and the Gulf Islands as temperatures rarely fall below freezing long enough for groundwater discharge zones to stand out as thermal anomalies.

A method was tested using summer-time satellite imagery, with the goal of identifying thermal anomalies with a cool temperature signature. During the dry season, groundwater discharge zones are likely to be distinctly cooler than the surrounding landscape, (about 10-12 degrees). Known discharge zones such as wetlands were identified to examine whether such a signature was present. Unfortunately, the applicability of this method was limited by the fact that thermal satellite imagery for the study area was taken at 7pm, due to the satellite’s orbital trajectory. Unlike for a winter-time scenario, the time of day of temperature retrieval is critical for detection of a summer-time cool temperature anomaly, as the landscape cools each evening. The thermal imagery method was not used in this study, however, we present it here for future investigation, should appropriately timed Landsat imagery become available.

7 GROUNDWATER RECHARGE POTENTIAL

GW Solutions has developed a GIS-based methodology that incorporates diffuse and localized recharge pathways to estimate the spatial variability of recharge potential. The method uses infiltration/groundwater recharge coefficients for each of the spatial variables controlling recharge. Figure 5 is a flowchart for the integration of data inputs to estimate the groundwater recharge potential.

Groundwater recharge is the process whereby water moves from precipitation to the subsurface and consequently to replenish aquifers. Groundwater recharge is dependent upon factors such as the amount of precipitation (snow/rain), land surface slope (topography), the amount of water interception by plants (water retention or water used by plants), evaporation of open water or water on the land surface, and the permeability of the soil and subsurface geologic formations. Each of these factors is assigned an appropriate weighting factor in the calculation of recharge potential. Weighting factors were determined based on previous studies and predominant factors influencing groundwater recharged observed across Vancouver Island.

Recharge to bedrock aquifers can be understood as being *diffuse* or *localized*. Diffuse recharge is due to the widespread movement of water from land surface to the water table that varies spatially and seasonally. The percentage of precipitation that becomes diffuse recharge is dependent on soil, vegetation, local topography, and depth to the water table. Localized recharge occurs along discrete, bedrock lineaments (fractures, faults and geologic bedding planes and contacts). The magnitude of a localized contribution to recharge depends on the size of the catchment area and the ability of the lineaments to transmit water.

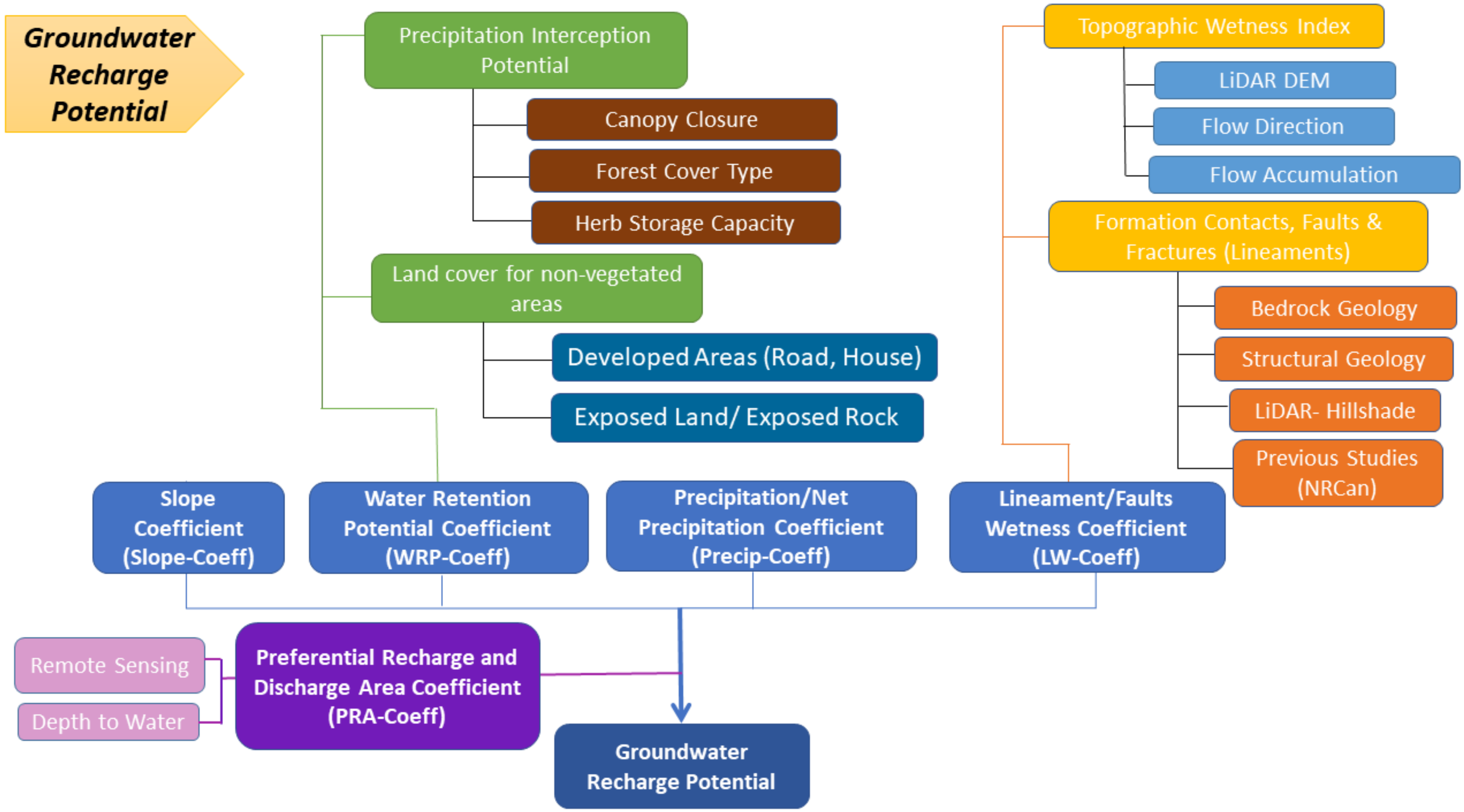

Figure 5: Flowchart illustrating the methodology used to estimate the groundwater recharge potential.

7.1 Estimation of Recharge Coefficients

7.1.1 Slope Coefficient

Topography greatly influences the potential for water infiltration to the subsurface. In groundwater recharge areas, low slopes promote infiltration whereas steep slopes promote runoff and decreased infiltration. Table 5 summarizes the slope infiltration factors and Figure 8 shows the resulting slope infiltration factor map.

LiDAR at 1-m resolution as well as a 5-m Digital Elevation Model (DEM) were made available to GW Solutions through the Island Trust from the LiDAR project inventory for British Columbia. Slope was derived from the 5-m DEM processed from LiDAR.

The maps of spatial slope coefficient across the Study Islands are presented in Appendix 8, Section1.

Table 2. Slope infiltration coefficient and groundwater recharge potential based on the slope degrees.

Groundwater recharge Potential	Slope degree	Infiltration coefficient
Lowest	> 24	0.03
Poor	12 - 24	0.06
Moderate	5.1 - 12	0.1
Good	2.7 – 5.1	0.15
Very good	0.3-2.7	0.18
High	< 0.3	0.2

7.1.2 Water Retention Potential (WRP) Coefficient

We combine vegetation and land cover data into a Water Retention Potential coefficient.

The maps of spatial WRP coefficient across the Study Islands are presented in Appendix 8, Section 2.

Precipitation Interception Potential

Vegetation effects groundwater recharge through the interception of precipitation by the foliage (i.e. evapotranspiration); Greater foliage interception leads to longer exposure to the atmosphere and increased evaporation. Islands Trust recently investigated the role of soil and vegetation on precipitation, producing a precipitation interception potential map. The map has been developed as follows:

1- A literature review to determine which vegetation characteristics contribute significantly to precipitation interception.

2- The Vegetation Resource Inventory (VRI) available for the Islands Trust region was correlated with vegetation interception characteristics.

3- A weighting scheme was developed, based on the literature review, that assigns a relative importance of relevant VRI attributes that impact precipitation interception.

4- The variables that have been considered for quantifying and mapping of precipitation interception include 1) Canopy Closure, 2) Forest Cover Type, and 3) Herb Storage Capacity. Each of the variables of interception were assigned a weight describing their relative importance to rainfall interception.

5- VRI attributes were processed in GIS; assigned weighting values were used to create a surface representing precipitation interception potential for the Islands Trust area.

The Island Trust VRI Precipitation Interception Potential Manual describing the developed methodology is in Appendix 9.

Land Cover/Land Surface

For non vegetated areas (exposed rock and developed areas), GW Solutions used NRCAN circa 2000 Land Cover vector polygons to derive land cover classes.

Table 4 summarizes the WRP coefficients based on the precipitation interception potential and Table 5 shows the coefficients based on the land use/cover for non vegetated areas.

Table 3: Recharge potential coefficients for Precipitation Interception Potential

Groundwater Recharge potential	Precipitation Interception Potential	Precipitation Interception Potential	Infiltration coefficient
Minimum	Very High	> 0.6	0.1
Low	High	0.5-0.6	0.2
Moderated	Moderate	0.4-0.5	0.25
good	Low	0.2-0.4	0.28
Very good	Very Low	0-0.2	0.3

Table 4. Recharge potential coefficients for non-vegetated areas.

Groundwater Recharge Potential	Land Use in None Vegetated Areas	Infiltration coefficient
Minimum	developed area: pavement, building, road	0.1
good	exposed bedrock and soil	0.28

7.1.3 Precipitation Coefficient

Precipitation variability is the main driver in groundwater recharge. Gridded annual total precipitation data were obtained from the Pacific Climate Impact Consortium (PCIC) corresponding to climate normals for the 1981-2010 period. The precipitation coefficient across the Study Islands is shown in in Appendix 8, Section 3 and the values area summarized in Table 6.

Table 5. Recharge potential coefficients for precipitation.

Groundwater Recharge Potential	Precipitation range (mm)	Infiltration coefficient
Low	< 960	0.1
Poor	960 - 1010	0.15
Moderate	1010 - 1060	0.18
Good	1060- 1110	0.22
Very good	> 1110	0.25

7.1.4 Bedrock Lineaments Coefficient

Bedrock lineaments and Topographic Wetness Index (TWI) were combined to estimate discrete recharge potential in the bedrock. Values with high TWI suggest a higher possibility for groundwater recharge at the location of lineaments.

The recharge potential values corresponding to the combined TWI and bedrock contacts/lineaments are listed in Table 7.

TWI coefficient along the lineaments for the Study Islands is presented in Appendix 8, Section 4.

Table 6: Bedrock Lineament Coefficient and groundwater recharge potential based on TWI ranges.

Groundwater Recharge Potential	TWI Range	Bedrock Lineament Infiltration Coefficient
Low	< 3	0.1
Moderate	3 - 6	0.15
High	6 - 9	0.2
Very High	> 9	0.25

7.1.5 Preferential recharge/discharge areas (PRDA)

The *Depth to Water* and *NDVI-NDMI* methods were selected as inputs to estimate the spatial variability of recharge/discharge potential. Both these methods could be implemented with the available data, and their respective results matched well.

Based on the groundwater discharge probability maps, an attribute ratings system has been developed to assign specific values to each groundwater discharge probability group.

PRDA coefficient across the Study Islands is presented in Appendix 8, Section 5.

Table 7: Groundwater recharge potential coefficient based on the probability of groundwater discharge spatially.

Groundwater Recharge Potential	Probability of Groundwater Discharge Area	Groundwater Recharge coefficient
Minimum	Very High probability	0.05
Low	High probability	0.1
Moderate	Medium probability	0.3
Good	Low-Medium probability	0.7
Very good	Low probability	0.9
High	Very Low probability	1

7.2 Recharge Potential

Across the study Islands, the recharge potential was determined using the following equation:

$$RP = R_{PRDA}\,[(R_{WRP}) + (R_{LW}) + (R_{Slope}) + (R_{Precipitation})]$$

Where:

RP = Recharge potential (0-1)

R_{PRDA} = Preferential Recharge/Discharge Areas Factor (0.05-1)

R_{WRP} = Water Retention Potential Factor (0.1-0.3); Influence ranges up to 30%

R_{LW} = Bedrock Lineament Wetness Factor (0.1 – 0.25); Influence ranges up to 25%

R_{Slope} = Slope Factor (0.03-0.2); Influence ranges up to 20%

$R_{Precipitation}$ = Precipitation Factor (0.1-0.25); Influence ranges up to 25%

A recharge potential of 1 suggests high potential of recharge, and this is present in open fractures found within areas with a high preferential of recharge (PRDA). The lowest recharge potential values are typical of paved land.

The resulting groundwater recharge potential map for Hornby and Denman Islands is presented in Figure 6 as an example. Appendix 10 provides groundwater recharge potential maps for all Study Islands.

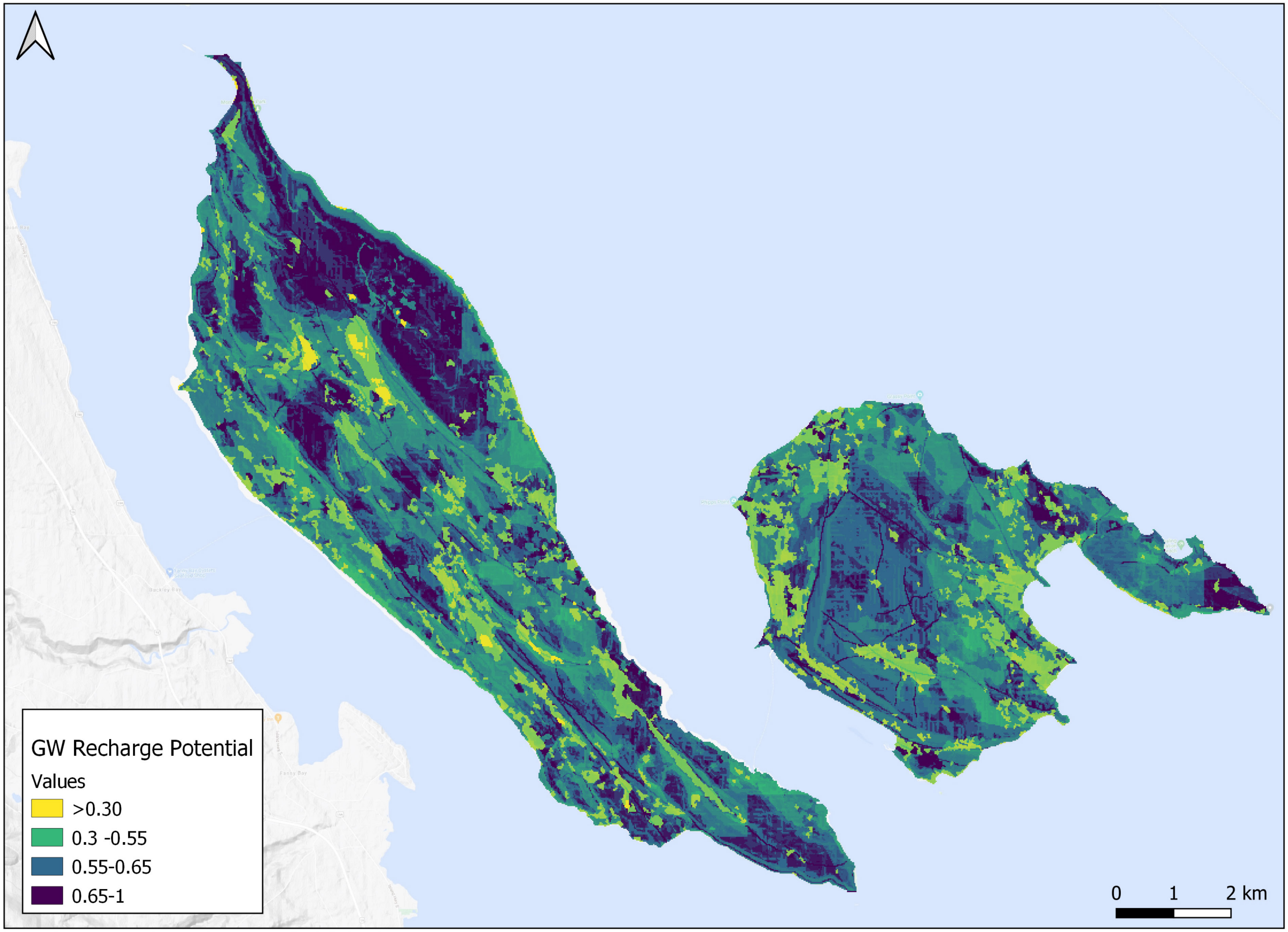

Figure 6: Estimated groundwater recharge potential across Denman and Hornby Islands

8 CONCLUSIONS

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

1. A new approach has been developed to determine the infiltration capacity or groundwater recharge potential for the Islands Trust Area. This method considers spatial variability of slope, lineaments (such as faults and contacts between bedrock strata), vegetation precipitation interception inferred from Vegetation Inventory Index, land cover/land use and recharge-discharge preferential areas.

2. Analysis of available high-resolution, LiDAR-derived, bare-earth topography has revealed previously unmapped bedrock lineaments. These discrete features were incorporated in the recharge potential mapping.

3. Based on the availability of data/information and conceivability of data for the Study Islands, two approaches were chosen to delineate the groundwater discharge and recharge preferential areas:

    - Remote sensing, satellite-based multispectral image analysis (from Sentinel satellite 10x10 meters resolution), and

    - Depth to groundwater (inferred from GWELLS database, water level monitoring network, and Leapfrog model)

4. The spatial variability of aquifer recharge potential has been estimated from combined infiltration coefficients. These coefficients account for precipitation, land cover/land use, soil characteristics and vegetation, the bedrock structures (lineaments), and slope. Maps illustrating recharge potential have been produced at a 20 m x 20 m grid scale, revealing areas with low (less than 0.30), moderate (0.30-0.55), good (0.55 – 0.65) and high (greater than 0.65) recharge potential.

5. A total of 75 groundwater regions have been delineated to facilitate sustainable groundwater management and planning across the Study Islands. The regions are based on catchment areas, mapped aquifers, structural geology and the distribution and characteristics of water wells.

9 DATA GAPS AND RECOMMENDATIONS

GW Solutions makes the following recommendations:

1. Engage with island communities with the objectives of better characterizing, monitoring, protecting, and enhancing groundwater resources. Some of the tasks to be completed through this engagement should include:

    a. Monitor groundwater level fluctuations in groundwater regions with the highest stress or risk of saltwater intrusion. This should be achieved through the deployment of monitoring wells, either dedicated wells, or privately-owned wells that are equipped with devices that measure water level and electrical conductivity (a proxy for salinity). Early detection and mitigation of the risks of salt-water intrusion should be a particular focus of these monitoring efforts.

    b. Define local environmental flow needs for surface water bodies and implement measures to preserve them.

    c. Envision water management scenarios that address environmental needs and minimize or prevent water conflicts.

    d. Better define the relationship between land development and groundwater use and availability to make land development and land management decisions that do not jeopardize the water resource.

2. The effects of climate change on aquifer recharge and groundwater availability should be monitored through data collection. Several climate stations should be installed, including at higher elevations, which play an important role in recharge. Significant changes in temperature and precipitation are expected in the coming decades, which will likely have an impact on aquifer recharge and groundwater availability.

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11 STUDY LIMITATIONS

This document was prepared for the exclusive use of Islands Trust (the client). The inferences concerning the data, site and receiving environment conditions contained in this document are based on information obtained during investigations conducted at the site by GW Solutions and others and are based solely on the condition of the site at the time of the site studies. Soil, surface water and groundwater conditions may vary with location, depth, time, sampling methodology, analytical techniques and other factors.

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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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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.

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12 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 is pleased to produce this document. If you have any questions, please contact us.

Yours truly,

GW Solutions Inc.

PROFESSIONAL PROVINCE OF K.A. BARROSO CHULVE # 49456 BRITISH COLUMBIA ENGINEER

PROFESSIONAL PROVINCE OF Dr. D. N. BETHUNE # 53150 BRITISH COLUMBIA GEOSCIENTIST

Antonio Barroso, M.Sc, P.Eng
Project Hydrogeologist

Shiva Farjadian, Msc
Project Hydrogeologist

Matt Vardal, M.Sc.
Geologist and GIS

David Bethune, Ph.D., P.Geo.
Senior Hydrogeologist

Saeesh Mangwani, B.Sc
GIS Analyst

APPENDIX 1

GW SOLUTIONS INC. GENERAL CONDITIONS AND LIMITATIONS

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

1.0 USE OF REPORT

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.

2.0 LIMITATIONS OF REPORT

This report is based solely on the conditions which existed within the study area or on site at the time of GW SOLUTIONS's investigation. The client, and any other parties using this report with the express written consent of the client and GW SOLUTIONS, acknowledge that conditions affecting the environmental assessment of the site can vary with time and that the conclusions and recommendations set out in this report are time sensitive. The client, and any other party using this report with the express written consent of the client and GW SOLUTIONS, also acknowledge that the conclusions and recommendations set out in this report are based on limited observations and testing on the area or subject site and that conditions may vary across the site which, in turn, could affect the conclusions and recommendations made. The client acknowledges that GW SOLUTIONS is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the client.

2.1 INFORMATION PROVIDED TO GW SOLUTIONS BY OTHERS

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.

3.0 LIMITATION OF LIABILITY

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.

4.0 JOB SITE SAFETY

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.

7.0 EMERGENCY PROCEDURES

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.