

Islands Trust Area Groundwater Recharge Potential Mapping

Prepared for: Islands Trust

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1 BACKGROUND AND OBJECTIVES

1.1 Background

GW Solutions was retained by the Islands Trust Council (ITC) to assess the spatial variability of groundwater recharge potential across twelve of the Gulf Islands. The study islands, highlighted in Figure 1, include Anvil Island, Bowen Island, Gambier Island, James Island, Keats Island, Lasqueti Island, Reid Island, Salt Spring Island, Sidney Island, Thetis Island, Thormanby Island, and Valdes Island, as a part of the *Gulf Islands Groundwater Sustainability Strategy* project. In this report, we use “Study Islands” to refer to the twelve islands.

The ITC requires a comprehensive study to qualitatively determine groundwater recharge to establish a balance between the values of all water users and the environment across the Study Islands. The purpose of this study is to map the spatial distribution of groundwater recharge and assess the effects future climate change is predicted to have on groundwater recharge.

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 Map IT 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 groundwater recharge; 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 mapping will support ITC staff with the assessment of the potential impacts of increased settlement density or intensity of land use on areas with high aquifer recharge. This work also supports the ITC to deliver on their mandate to ensure the sustainability of water resources for future generations.

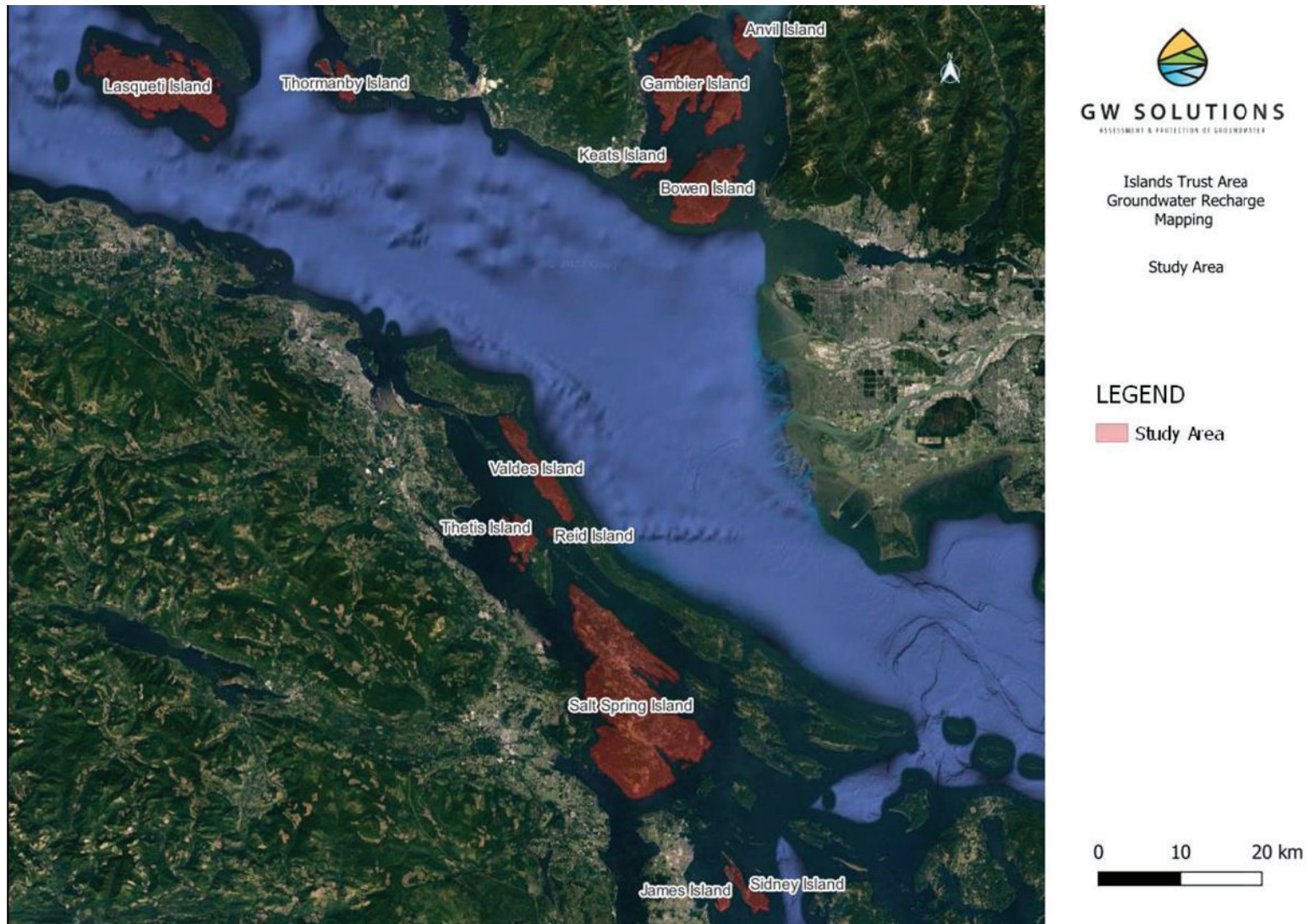


Figure 1: Study Islands

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
Precipitation Interception Potential	Precipitation Potential Interception Mapping	Islands Trust
Vegetation Inventory Index	Island Trust	Island Trust
Water usage/demand data	VIHA	GW Solutions

Data Type	Data Source	Provided by
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 the subsurface water-bearing materials. The size of a groundwater region is based on the scale of the study and the resolution of available information.

Groundwater regions help synthesize complex hydrogeologic conditions in a way that facilitates planning and sustainable management of water resources and are often considered “Management Units”. The groundwater regions are devised for Anvil, Bowen, Lasqueti, Keats, Reid, Sidney, Thormanby and Thetis Islands 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 delineated in a Geographic Information System (GIS). Maps and information on groundwater regions for all the Study Islands are provided in Appendix 2. Figure 2 presents the groundwater regions for Bowen Island. Considering the limited extent of James Island and minimal topographic change as well as the unity of surficial geology, only one groundwater regions has been defined for this island.

4 METHODOLOGY: 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 groundwater recharge coefficients for each of the spatial variables controlling recharge. Figure 3 is a flowchart for the integration of data inputs to estimate the groundwater recharge potential.

Recharge 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 localized recharge depends on the size of the catchment area and the ability of the lineaments to transmit water.

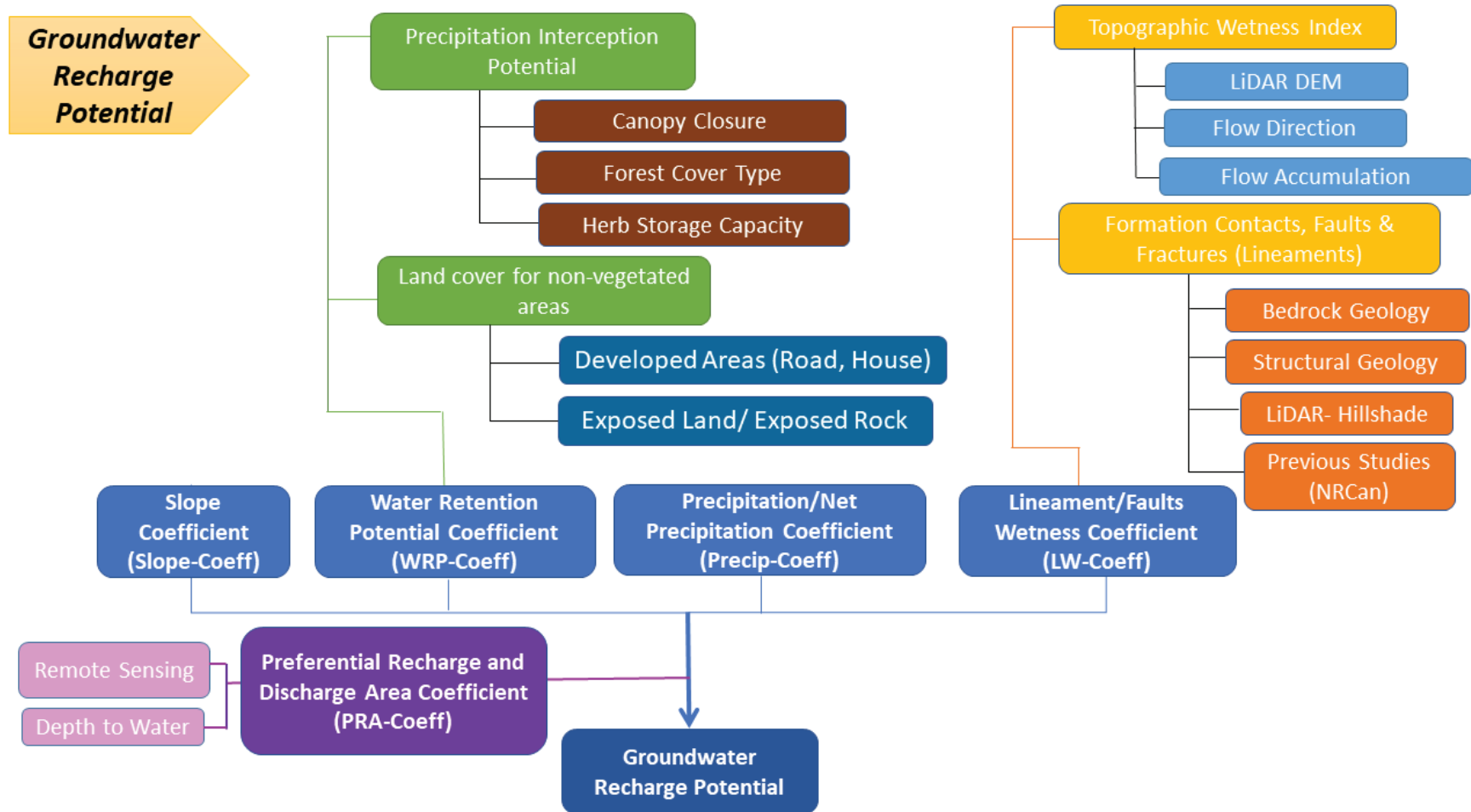


Figure 3: Flowchart illustrating the methodology used to estimate the groundwater recharge potential.

4.1 Definition of Bedrock Lineaments

Bedrock on the Study Islands is predominantly comprised of folded, faulted, and dipping bedrock strata of the various Nanaimo Group, Bowen Island Group, Buttle Lake Group and Gambier Group formations of sandstone, conglomerate, and mudstone/shale, volcanic rocks of Sicker Group and Vancouver Group as well as intrusive rocks of Salt Spring Plutonic Suite and Mount Hall Gabbro. 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.

The interpretation of bedrock lineaments depends on the hydrogeologic context of the lineament location specifically whether the lineament is in a groundwater recharge or discharge area. In groundwater recharge areas, lineaments are pathways for preferential collection and infiltration of rainwater. This contrasts with groundwater discharge areas, where lineaments are pathways for the upward flow of groundwater.

Detailed mapping of the landscape is now possible due to the availability of LiDAR (*light detection and ranging*) imagery of the Study Islands. The LiDAR imagery provides 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.

4.2 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. The interpretation of TWI requires knowledge of the hydrogeologic context specifically the identification of groundwater recharge and discharge areas. 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 SAGA¹ tools and the 2m resolution LiDAR DEM.

4.3 Delineation of groundwater recharge and discharge areas

Groundwater recharge 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 groundwater discharge areas.

Groundwater recharge is defined as water added to an aquifer through the unsaturated zone after infiltration and percolation following a rainfall event. Groundwater recharge is typically associated with the downward movement of groundwater. Groundwater discharge is the outflow of groundwater from aquifers which can occur diffusely across the landscape, such as when vegetation is reliant on groundwater. Discharge also occurs at point-source areas, such as natural springs or along rivers and lakeshores.

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.

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 methods 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 the depth to groundwater (i.e. thickness of the unsaturated zone); the other based on remote sensing and multispectral image analysis to inspect variations in vegetation and soil moisture.

4.3.1 Depth to Water Methodology

The depth of groundwater below the land surface is directly related to the amount 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 the unsaturated zone has a significant role in controlling groundwater recharge rate across the Study Islands (Allen & Matsuo, 2002, SRK, 2013). A deep-water table or thick unsaturated zone is associated with higher elevations where rainfall is often higher. Despite surficial conditions that are often suitable for groundwater infiltration (i.e. a flat area fed by a large catchment), a shallow water table limits the amount of water that can infiltrate underground.

When a dense network of water level measurements from wells are available, the depth of water table is derived from the difference between the ground surface elevation of the well and water level elevation in the well. In BC, water levels in wells are available from GWELLS although it is noted there are 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, nearby wells can intercept different fractures with different water pressures. However, in our experience, these inaccuracies average out *at the watershed scale* with a large number of 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.

$$\text{Average Interpreted Depth to Water} = \text{Ground Surface Elevation} - \text{Average Interpreted Groundwater Elevation}$$

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.

A *groundwater elevation surface* was created in 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 taken 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 4.

4.3.2 Remote Sensing/ Satellite Multispectral Image Analysis Methodology

The approach of using satellite multispectral image analysis includes the application of two methods: 1) A Normalized Difference Vegetation Index (NDVI) - Normalized Difference Moisture Index (NDMI), 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. However, the applicability of thermal remote sensing mapping method was limited by the fact that thermal satellite imagery for the Study Islands was taken at 7pm when the landscape cools each evening, and the time of day of temperature retrieval is critical for detection of a summer-time cool temperature anomaly as a signature of groundwater discharge. Therefore, the NDVI and NDMI method have been applied.

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 is a mathematical manipulation of 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 applications. In this study we rely on the NDVI and the NDMI. 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 moisture 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.

4.4 Estimation of Recharge Coefficients

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/coefficient in the calculation of recharge potential. Weighting factors were determined based on previous studies and the predominant factors influencing groundwater recharged observed across Vancouver Island.

4.4.1 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 2 summarizes the slope infiltration factors.

LiDAR at 1-m resolution as well as a 5-m Digital Elevation Model (DEM) were made available to GW Solutions through the ITC 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 5, Section 4.

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	12.0-24.0	0.06
Moderate	6.0-12.0	0.1
Good	4.0-6.0	0.15
Very good	2.0-4.0	0.18
High	<2	0.2

4.4.2 **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 5, 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. The ITC has 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 ICT area.

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 3 summarizes the WRP coefficients based on the precipitation interception potential and Table 4 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 Potential2	Infiltration coefficient
Minimum	Very High	> 0.65	0.1
Low	High	0.55-0.65	0.15
Moderated low	Moderated high	0.35-0.45	0.22
Moderated high	Moderate low	0.25-0.35	0.25
good	Low	0.2-0.4	0.27
Very good	Very Low	0-0.25	0.3

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

Groundwater Recharge Potential	Land Use in None Vegetated Areas	Infiltration coefficient
Low	developed area: pavement, building, road	0.15
good	exposed bedrock and soil	0.27
Good	water	0.27

4.4.3 Precipitation Coefficient

Precipitation is the source of all groundwater recharge; however, precipitation amounts can vary spatially even on the scale of the Study Islands with higher levels on land directly exposed to the prevailing winds and at higher elevations. 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 5, Section 5 and the assumed values are summarized in Table 5.

Table 5. Recharge potential coefficients for precipitation.

Groundwater Recharge Potential	Precipitation range (mm)	Infiltration coefficient
Lowest	<813	0.2
Poor	813-1191	0.21
Moderate	1191-1571	0.22
Good	1571-1951	0.23
Very good	1951-2331	0.24
High	2331- 2711	0.25

4.4.4 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 if they are within groundwater recharge areas.

The recharge potential values corresponding to the combined TWI and bedrock contacts/lineaments are listed in Table 6.

TWI coefficient along the lineaments for the Study Islands is presented in Appendix 5, Section 3.

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

Groundwater Recharge Potential	TWI Range	Bedrock Lineament Infiltration Coefficient
Low	<10	0.15
Moderate	10.0-12.0	0.2
High	12.0-14.0	0.22
Very High	> 14	0.25

4.4.5 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, see Table 7.

PRDA coefficient across the Study Islands is presented in Appendix 5, Section 1.

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

Groundwater Recharge Potential	Probability of Groundwater Preferential Discharge Area	Groundwater Recharge coefficient
Minimum	Very High probability	0.1
Low	High probability	0.3
Moderate	Medium probability	0.6
Good	Low probability	0.9
High	Very Low probability	1

4.4.6 Result: 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 in fact groundwater discharge areas.

The resulting groundwater recharge potential map for Bowen Island is presented in Figure 5 as an example. Appendix 6 provides groundwater recharge potential maps for all the Study Islands.

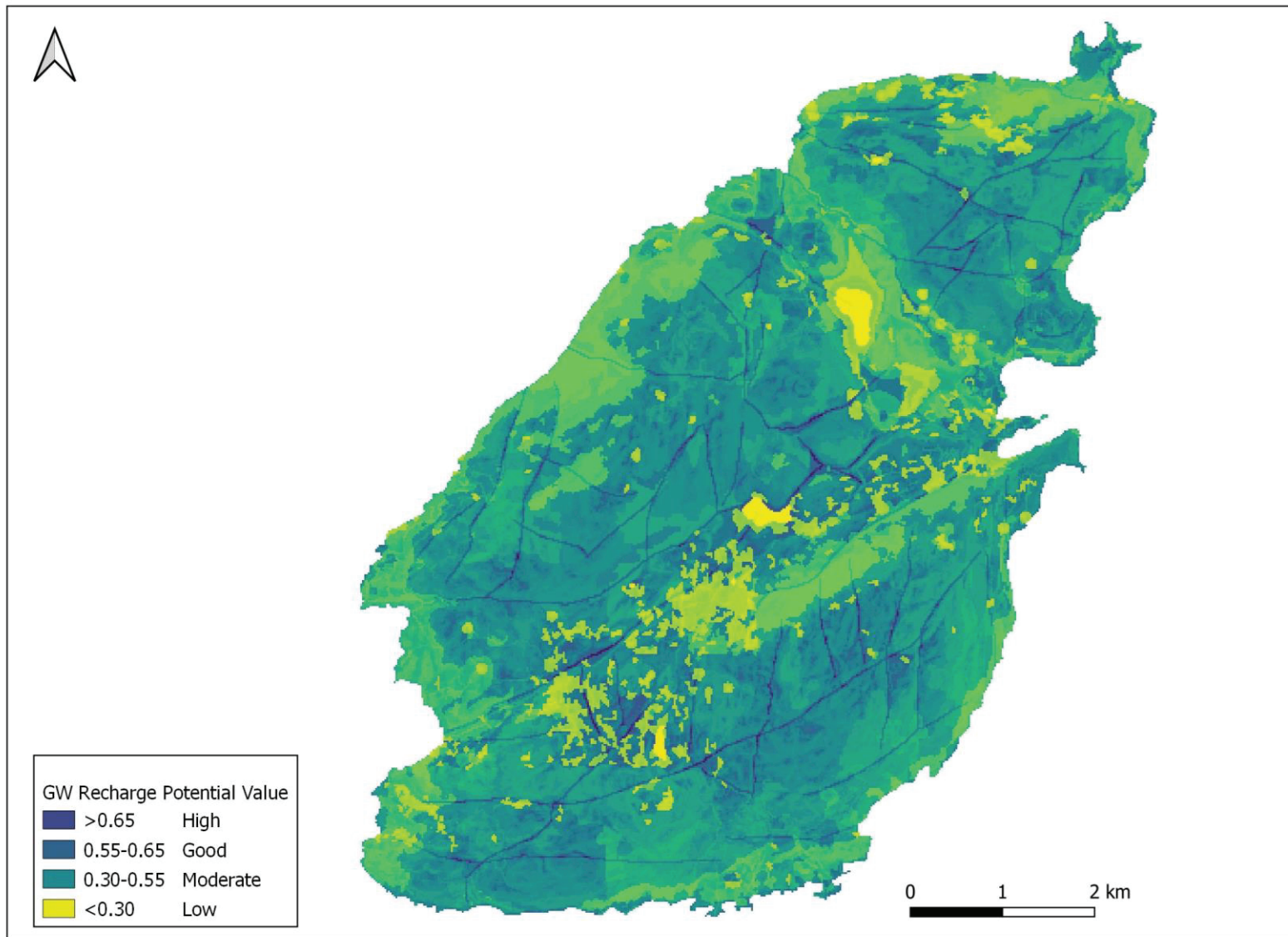


Figure 5: Estimated groundwater recharge potential across Bowen Island

5 SENSITIVITY AND SUSTAINABILITY ANALYSIS

The estimation of groundwater recharge potential (RP) requires several input variables that are expected to change over time, due to climate change, population and land use changes. To estimate the potential impact of such temporal changes on recharge potential, GW Solutions conducted a sensitivity analysis, which analyzed the magnitude of impact projected changes in precipitation and land use would have on our estimations of recharge potential.

Since reliable estimates of current rates of land use change were not available, the sensitivity analysis for land use change was based on hypothetical scenarios, using Bowen Island as a case study due to it being one of the fastest developing islands in the study region. Known urban boundaries on the island were expanded by five amounts: 100 meters, 150 meters, 200 meters, 250 meters, 500 meters and 1000 meters. This was aimed to simulate urban expansion foreseeable over the next few decades, under the assumption that new built-up land would most likely occur close to existing settlements.

The sensitivity analysis for precipitation was done in two ways. The first relied on hypothetical precipitation change scenarios, where precipitation across the island was increased by 10%, 20%, 30% and 50% and decreased by 10%, 20%, 30% and 50%. This analysis aimed to simulate the impact of more extreme precipitation variations on RP. This analysis was also conducted using Bowen Island as a case study.

In addition to the above sensitivity analysis on Bowen Island, sensitivity of RP based on projected climate change was also estimated for all the islands. In this case, projected precipitation for the years 2030, 2050, 2070 and 2090 under the SSP 8.5 climate scenario were obtained from ClimateBC (Wang et al., 2016, updated version 2022). SSP 8.5 represents the most extreme case of climate change, and thus simulates the largest potential impact that may occur across the islands, based on estimates from the most recent Climate Model Intercomparison Project (CMIP6) (Riahi et al. 2017). An ensemble of 13 of the best models, available already aggregated from ClimateBC, were used to gather projected precipitation data for each of these scenarios. .

Table 8 summarises the developed scenarios for sensitivity analysis for Bowen Island and the climate change analysis for all the Study Islands.

Table 8: Designed Scenarios for Sensitivity Analysis

Variables	Scenarios
Changes in Average Annual Precipitation (Case Study- Bowen Island)	-10% Change in Annual Average Precipitation
	-20% Change in Annual Average Precipitation
	-30% Change in Annual Average Precipitation
	-50% Change in Annual Average Precipitation
	+10% Change in Annual Average Precipitation
	+20% Change in Annual Average Precipitation
	+30% Change in Annual Average Precipitation
	+50% Change in Annual Average Precipitation
Water Retention Potential by Land Modification (Case Study – Bowen Island)	Landcover modification assuming land development around the exiting developed area with 100m-buffer
	Landcover modification assuming land development around the exiting developed area with 150m-buffer
	Landcover modification assuming land development around the exiting developed area with 200m-buffer
	Landcover modification assuming land development around the exiting developed area with 250m-buffer
	Landcover modification assuming land development around the exiting developed area with 500m-buffer
	Landcover modification assuming land development around the exiting developed area with 1000m-buffer
Climate Change effects (RCP 8.5)- For all Study Islands	For future period 2030s
	For future period 2050s
	For future period 2070s
	For future period 2090s

5.1 Sensitivity Analysis for Bowen Island Case Study

The results from each of the land use and precipitation scenarios run for Bowen Island are summarized in Table 9.

For precipitation, it has been assumed if the average annual precipitation increases (+) and decreases (-) by 10%, 20%, 30% and 50% of Normals (30 years average annual), how much would affect on groundwater recharge potential and what would be the extent of influenced areas.

The sensitivity analysis of landcover consists of six scenarios, assuming that the developed/urban areas are expanded by 100-, 150-, 200-, 250-, 500- and 1000- meter buffers around the existing developed areas. Then the Water Retention Potential (WRP) coefficient was estimated assuming changes in land cover under these six scenarios. Each scenario estimates the change in groundwater recharge potential within a range of possible affected areas.

In Table 9, the first column, beside the scenarios' definition, shows the average percent change in island-wide recharge potential under each scenario. The next two columns show the amount of area where changes occurred, as an absolute amount and as a proportion of the total island area. The last two columns measure changes considering only the area affected. The first is the average change in recharge potential within the area affected. The second the maximum change value that occurred in this scenario, indicating the upper limit of the impact. Note that values in both these columns show absolute changes in recharge potential values (measured on a scale from 0 to 1), not percent changes relative to the base scenario.

Table 9: Summary of sensitivity analysis – Bowen Island case study

Scenario	Mean % change in RP (whole island)	Total area affected (square km)	Proportion of island area affected (%)	Mean change in RP value (area affected)	Maximum change in RP value (area affected)
Precipitation decreased by 10%	-0.8%	18.354	36.8%	-0.009	-0.01
Precipitation decreased by 20%	-1.5%	38.07	76.4%	-0.008	-0.01
Precipitation decreased by 30%	-2.5%	49.431	99.2%	-0.01	-0.02
Precipitation decreased by 50%	-4.2%	49.836	100%	-0.017	-0.03
Precipitation increased by 10%	0.8%	20.795	41.7%	0.008	0.01
Precipitation increased by 20%	1.6%	40.013	80.3%	0.008	0.01
Precipitation increased by 30%	2.2%	49.362	99%	0.009	0.02
Precipitation increased by 50%	3.8%	49.836	100%	0.016	0.02
Built-up area buffered by 100m	-0.9%	2.828	5.7%	-0.07	-0.15
Built-up area buffered by 150m	-1.4%	4.173	8.4%	-0.069	-0.15
Built-up area buffered by 200m	-1.7%	5.316	10.7%	-0.069	-0.15
Built-up area buffered by 250m	-2.1%	6.565	13.2%	-0.068	-0.15
Built-up area buffered by 500m	-3.7%	12.035	24.1%	-0.066	-0.15
Built-up area buffered by 1000m	-6.3%	21.711	43.6%	-0.066	-0.15

Figure 6 and Figure 7 show the distribution of percent change in RP under each sensitivity scenario. The X-axis shows the percentage change in RP relative to the original, or “base” RP scenario. The Y-axis shows the amount of area affected by the change as well as the amount of area with zero change. Bars to the right of the red line show the amount of area where RP increased, whereas those to the left show the amount of area where RP decreased.

Figure 8 shows the polygons of existing developed areas, and a 200m buffer zone around these areas as an example.

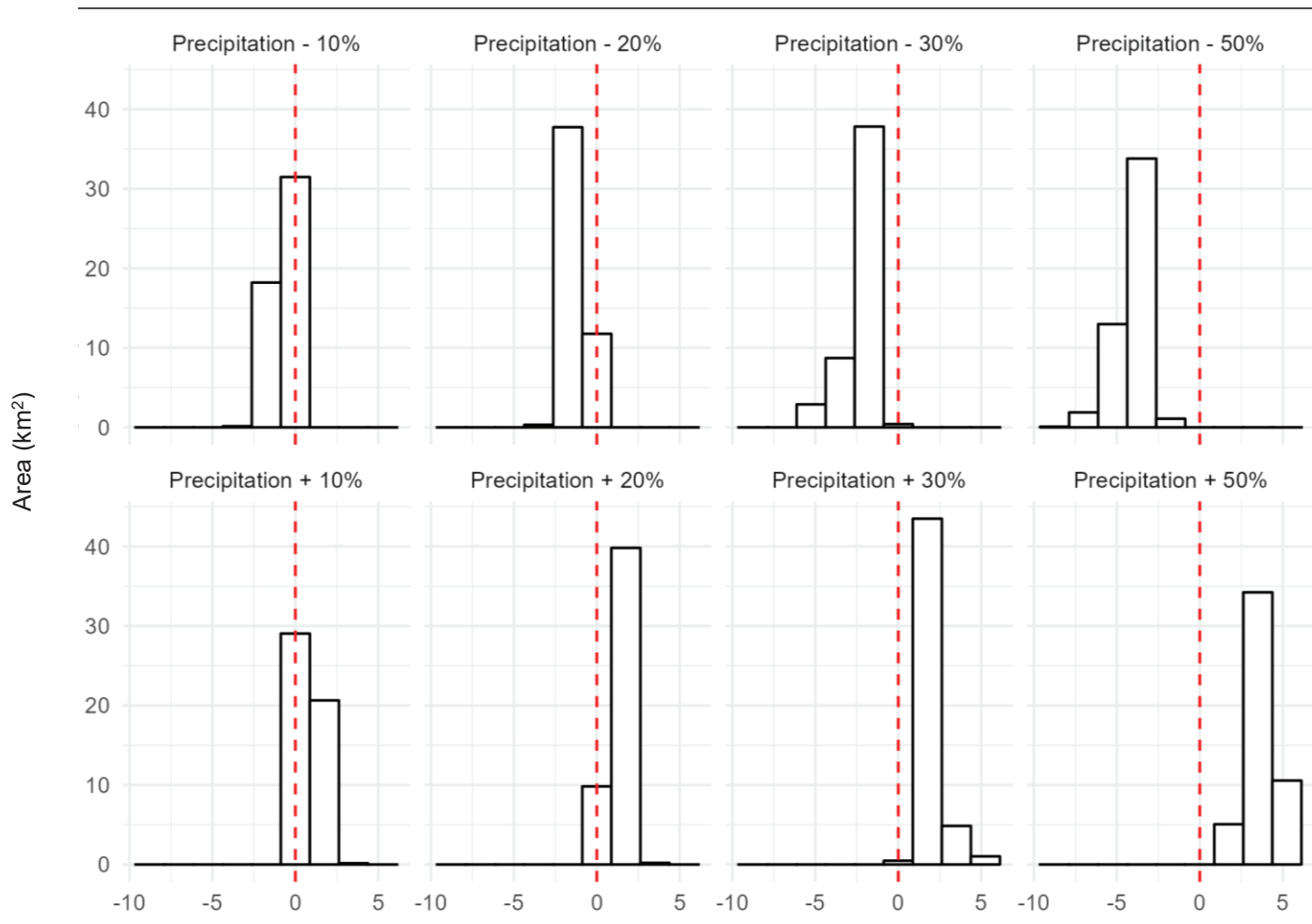


Figure 6: Distribution of percent changes to RP under each precipitation scenario for the Bowen Island case study. X-axis shows the percent change relative to the base case. The red-dotted line at 0 indicates the area with no change.

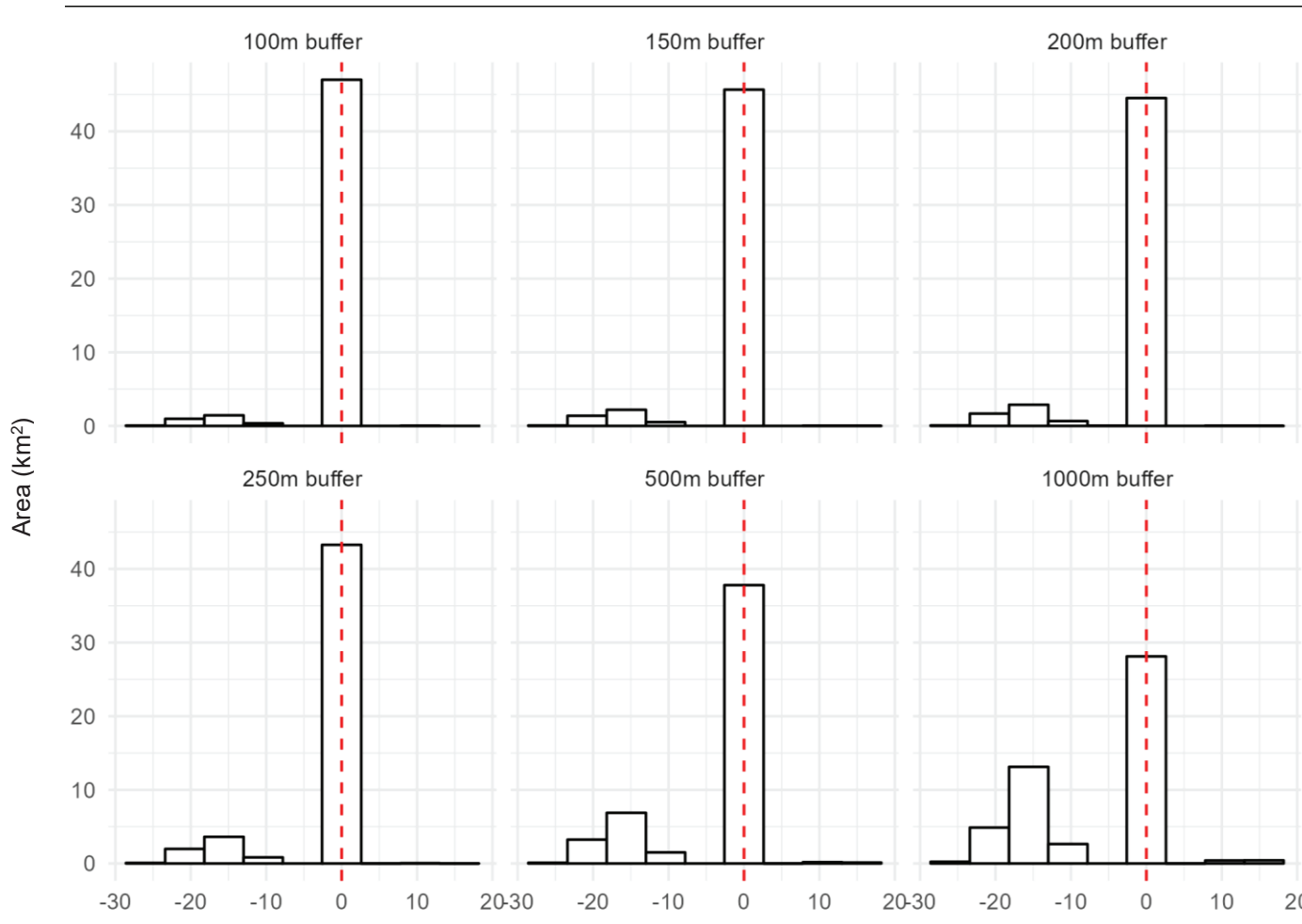


Figure 7: Distribution of percent changes to RP under each land cover scenario for the Bowen Island case study. X-axis shows the percent change relative to the base case. The red-dotted line at 0 indicates the area with no change.

The results indicate that RP across most of the island is not very sensitive to changes in land use and precipitation. Under the precipitation scenarios, the spatial extent of impact can be extensive, however the magnitude of the change under these scenarios was small. Even in the most extreme scenario of 50% decrease in precipitation, the average decrease in island-wide RP was only 4.2%.

The land use scenarios showed a higher sensitivity than precipitation, although the area affected was significantly smaller than for the precipitation scenarios. The most extreme case of built-up areas growing by 1000 meters showed a 6.4% decrease in RP. The maximum observed change was, however, much larger in the landcover scenarios, as all scenarios showed a maximum reduction of 0.15. So, while the magnitude of RP reduction was overall small, this may be driven mainly by the limited spatial extent of these scenarios. Thus, it can be seen that the increase in built-up, non-permeable land uses can significantly alter RP.

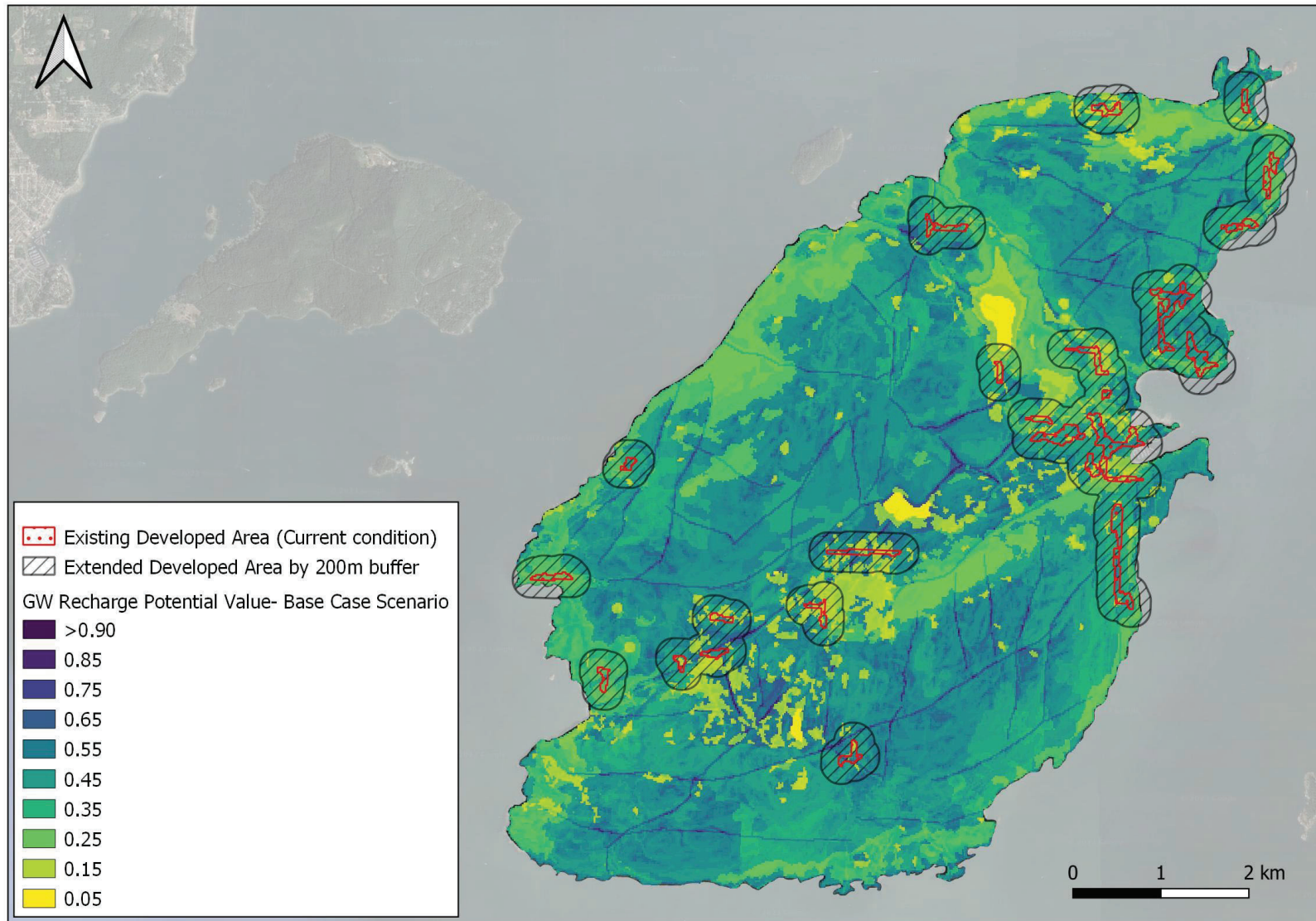


Figure 8: Estimated GW recharge potential map with existing developed areas and assumed land use changes for a-200m buffer around the current developed areas.

5.2 Sensitivity Analysis for Projected Climate Change under SSP 8.5

Precipitation is the only climatic parameter that is used as an input in determination of “Recharge Potential”, therefore initially the climate change model was run to estimate the amount of precipitation for future periods (2030s, 2050s, 2070s and 2090s), then the modelled output, precipitation, was inserted into the “Recharge Potential” equation.

The results of the sensitivity analysis of climate change scenarios are summarized in Table 10. These contain the same information as described for Table 9 (Bowen Island only), but for all Study Islands. The results are very similar to the patterns found for Bowen Island above, with several islands indeed showing no change in their recharge potential under any climate change scenario.

Table 10: Summary of sensitivity analysis – Projected precipitation under climate change (SSP 8.5)

Island	Scenario	Mean % change in RP (whole island)	Total area affected (square km)	Proportion of island area affected (%)	Mean change in RP value (area affected)	Maximum change in RP value (area affected)
Anvil	Precipitation in 2030 (SSP 8.5)	1%	4.604	50.7%	0.008	0.01
	Precipitation in 2050 (SSP 8.5)	1.2%	5.516	60.8%	0.008	0.01
	Precipitation in 2070 (SSP 8.5)	1.3%	5.824	64.2%	0.008	0.01
	Precipitation in 2090 (SSP 8.5)	1.5%	6.518	71.8%	0.008	0.01
Bowen	Precipitation in 2030 (SSP 8.5)	0.6%	15.492	31.1%	0.008	0.01
	Precipitation in 2050 (SSP 8.5)	0.8%	21.173	42.5%	0.008	0.01
	Precipitation in 2070 (SSP 8.5)	0.9%	23.23	46.7%	0.008	0.01
	Precipitation in 2090 (SSP 8.5)	1.2%	28.883	58%	0.008	0.01
Gambier	Precipitation in 2030 (SSP 8.5)	0.5%	19.037	28%	0.008	0.02
	Precipitation in 2050 (SSP 8.5)	0.7%	24.368	35.8%	0.009	0.02

	Precipitation in 2070 (SSP 8.5)	0.8%	27.222	40%	0.009	0.02
	Precipitation in 2090 (SSP 8.5)	1.2%	36.977	54.3%	0.009	0.02
James	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		
Keats	Precipitation in 2030 (SSP 8.5)	0.7%	1.916	31.8%	0.008	0.01
	Precipitation in 2050 (SSP 8.5)	0.9%	2.548	42.3%	0.008	0.01
	Precipitation in 2070 (SSP 8.5)	1%	2.851	47.3%	0.008	0.01
	Precipitation in 2090 (SSP 8.5)	1.4%	3.93	65.2%	0.008	0.01
Lasqueti	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		
Reid	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		
Salt Spring	Precipitation in 2030 (SSP 8.5)	-0.2%	16.315	8.9%	-0.009	-0.001
	Precipitation in 2050 (SSP 8.5)	-0.1%	11.722	6.4%	-0.009	0.01
	Precipitation in 2070 (SSP 8.5)	-0.1%	10.279	5.6%	-0.009	0.01
	Precipitation in 2090 (SSP 8.5)	0%	8.096	4.4%	0.004	0.01

Sidney	Precipitation in 2030 (SSP 8.5)	-0.3%	1.383	16%	-0.009	-0.003
	Precipitation in 2050 (SSP 8.5)	0.5%	2.311	26.7%	0.007	0.01
	Precipitation in 2070 (SSP 8.5)	0.7%	3.236	37.4%	0.007	0.01
	Precipitation in 2090 (SSP 8.5)	1.3%	6.334	73.3%	0.008	0.01
Thetis	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		
Thormanby	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		
Valdes	Precipitation in 2030 (SSP 8.5)	0%	0	0%		
	Precipitation in 2050 (SSP 8.5)	0%	0	0%		
	Precipitation in 2070 (SSP 8.5)	0%	0	0%		
	Precipitation in 2090 (SSP 8.5)	0%	0	0%		

Figure 9 shows the distribution of projected changes to precipitation under climate change, for each island. This graph thus summarizes the input variability, to which we measured the sensitivity of RP. For each island. even though this is the most extreme climate scenario, the results show more reasonable levels of precipitation variability than what we observed for Bowen Island. It is also clear that patterns across islands are far from consistent, as some islands appear to show almost no changes in average annual precipitation across all climate change years.

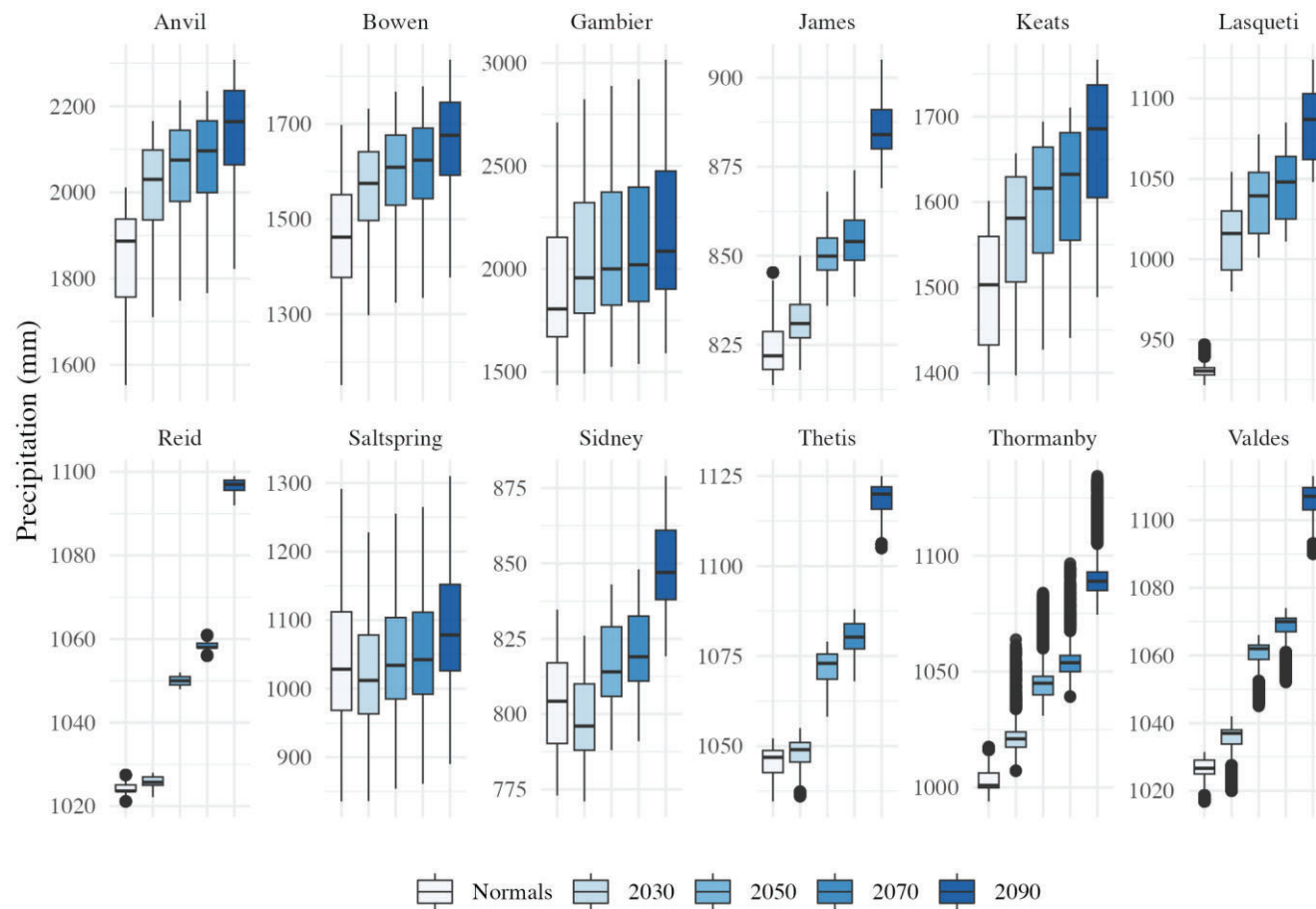


Figure 9: Distribution of island-wide precipitation in each climate time period, compared to climate normals (1980-2010 based on the SSP 8.5 scenario. the climate change projection year is shown on the X-axis, and the Y-axis shows the percent changes. Boxplots for each year show the overall distribution of percent changes in precipitation across the entire island.

Appendix 7 presents the maps of spatial distribution of changes to RP, for each island under each climate change scenario. Since the overall magnitude of change was small, the maps only indicate areas of increase, decrease and no-change. The

spatial extent of impact was highly variable across the islands. Some islands, like Anvil and Gambier, show a large area affected whereas other islands were entirely unaffected in a precipitation scenario.

5.3 Sensitivity Analysis: Result

Considering that RP measures not the actual water flux, but the *potential* for infiltration irrespective of the magnitude of input, GW solutions expected that sensitivity would be low for both land use and precipitation. This is indeed what the results confirmed, as our analysis across all scenarios showed a very low amount of change in groundwater recharge potential. It should be noted, however, that in some cases the spatial extent of impact was large, even if the magnitude of change in these areas was small. Considering that the potential for recharge is the result of several components, some of which can be invariant on decade-to-century timescales, this result is not unsurprising.

The estimated groundwater recharge potential is a relative value and is not known with an absolute certainty. Therefore, it is logical that groundwater recharge potential mapping does not show high sensitivity in changing one coefficient such as WRP or annual average precipitation coefficient.

6 CONCLUSIONS

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

1. The developed approach from the previous groundwater recharge potential mapping studies for southern and northern Gulf Islands have been used to determine the infiltration capacity or groundwater recharge potential for the rest of ITC Study Islands. 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. The 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.
 6. Several scenarios have been designed for groundwater recharge potential sensitivity analysis. The scenarios include the change in climatic variables, precipitation, and the land use modifications. The results indicate that the recharge potential across most of the island is not very sensitive to changes in land use and precipitation. Under the precipitation scenarios, the spatial extent of impact can be extensive, however the magnitude of the change under these scenarios was small, which is logical as the estimated groundwater recharge potential is a relative and qualitative value.

7 DATA GAPS, STUDY LIMITATIONS AND RECOMMENDATIONS

GW Solutions makes the following recommendations:

1. Engage with the island communities with the goal of better characterizing, monitoring, protecting, and enhancing groundwater resources. Some of the tasks to be completed through this engagement could include:
 - a. Monitor groundwater level fluctuations in groundwater regions with the highest stress (i.e. high usage) or risk of saltwater intrusion due to proximity to the shoreline. This could 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 connected to groundwater systems and implement measures to preserve them.
 - c. Envision water management scenarios that address environmental flow 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 water resources.
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, where recharge rates are higher. 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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9 STUDY LIMITATIONS

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


Yours truly,

GW Solutions Inc.

2023/03/31




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March 31, 2023

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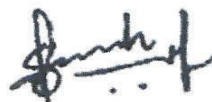
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APPENDIX 1

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- (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.