A Study of Water Balance in Gabriola Island, BC, Canada

By

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Land and Food System

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1. Introduction

Figure 1. The Distribution of Domestic Wells on Gabriola Island

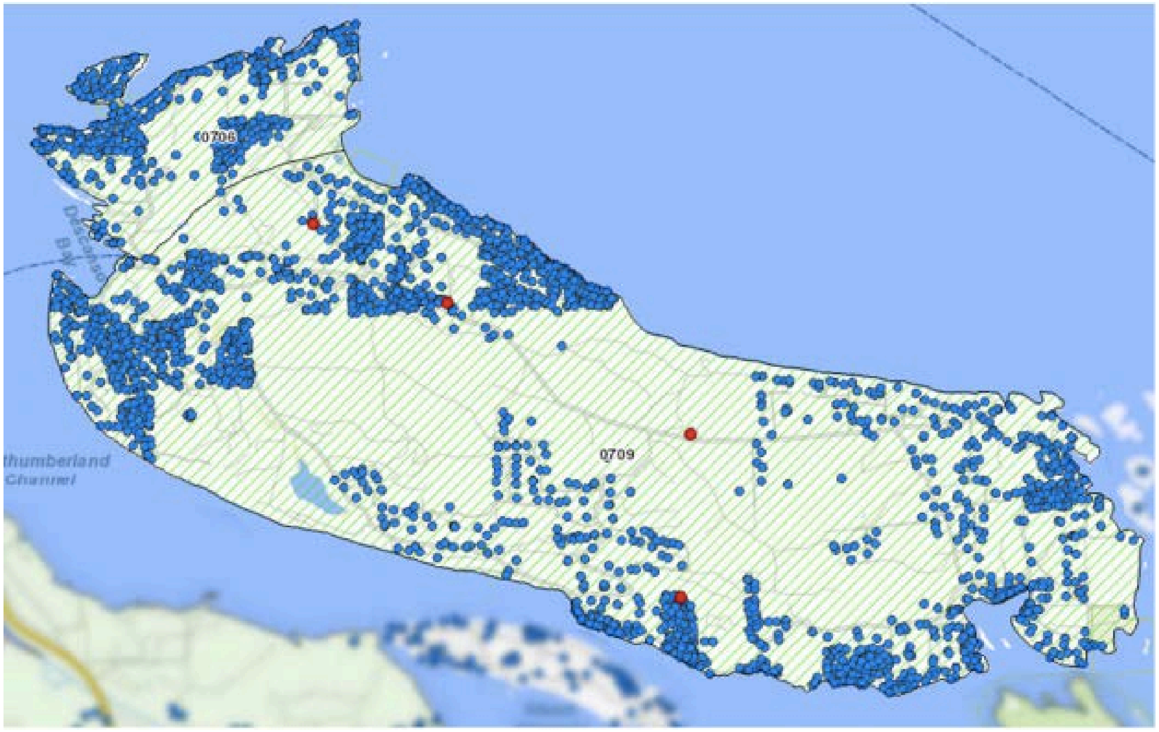

Figure 1 shows the distribution of domestic wells on Gabriola Island (RDN, 2019)

Small islands in the oceanic environment are often vulnerable to sustain secure water supply. A small island usually has small catchment areas; therefore, the majority of the surface rainwater flows quickly into the sea, which limits the recharge of rainfall into the groundwater (Cashman, 2014). With increased human activities, including land-use changes and urban development the natural hydrological balance may be negatively affected, which may also enhance by potential climate change, resulting in water scarcity and saltwater intrusion (Rubenstein, 2011). This is a concern in British Columbia's Gulf Islands on the west coast of Canada, which already are experiencing water scarcity issues. Gabriola Island is the most northerly of the Southern Gulf Islands like many other oceanic islands suffer from lack of surface freshwater during summertime (RDN, 2014). As shown in Figure 1, there are around 300 wells on the island, and concentrated around costal region. Because the majority of water consumed on Gabriola Island are extracted from the groundwater system, only a small portion of consumed water are harvested rainwater. On Gabriola Island, groundwater in the fractured rock aquifers is recharged from rainwater (Island Trust, 2019). Over-pumping from fragile groundwater resources to meet increasing water needs lead to a saltwater intrusion into the potable water supply sources caused by the rapid increase of population during summertime. Water shortages on the Gulf Islands are also exacerbated by other natural and anthropogenic factors such as climate change and further land-use changes and development.

Naturally, the thickness of the freshwater lens under the island is determined by the height of the water table above sea level (SRK Consulting, 2013). As a result of climatic changes, the sea level rises have caused seawater to intrude aquifer more rapidly (SRK Consulting, 2013). Water balance calculations are essential to characterize the water availability for the island and their vulnerability to climatic change. Having access to information at the island scale is critical, therefore the digital elevation models have become an important source of topographical data for the majority of the hydrological studies (d'Ozouville et al, 2008).

The purpose of this project is to provide an assessment the water balance of Gabriola islands as it is being affected by land-use changes, increase seasonal tourist populations and increased climatic variability. The aim of the paper is to conduct a risk assessment of saltwater intrusion resulting from future climate change scenarios.

Figure 2. The location of Gabriola Island

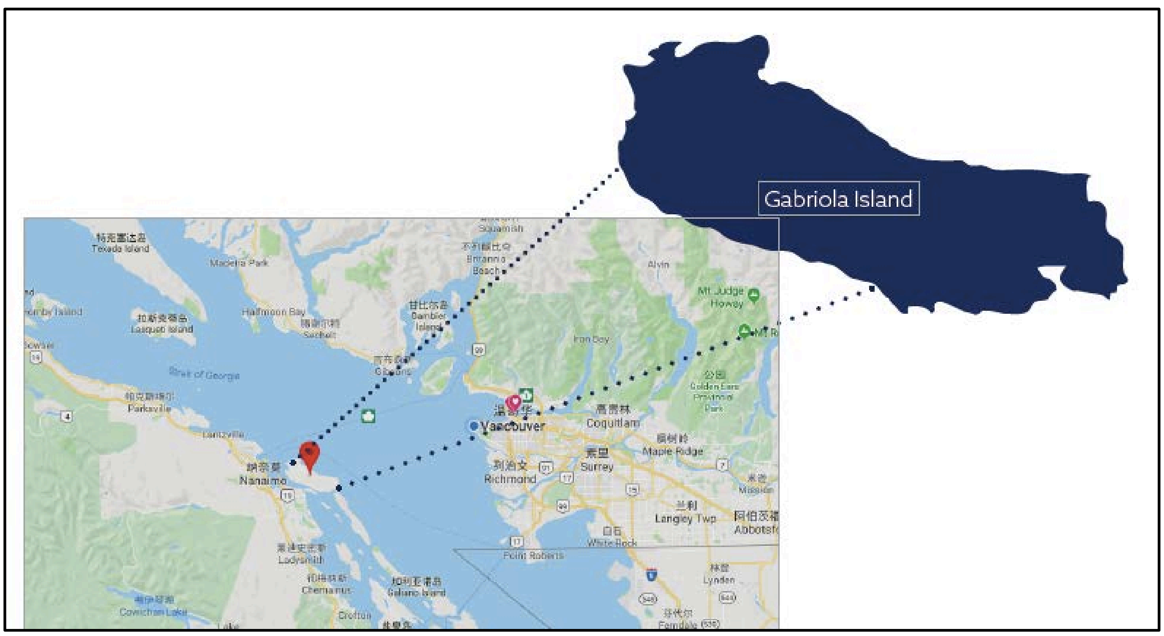

Figure 2 shows the location of Gabriola island that belongs to the Gulf Islands and around the Nanaimo.

1.1 Study Area

The study area, as shown in the figure above, lies in coastal B.C. at 49 9 0 N and 123 43 59 W, is about 5 km east of Nanaimo on Vancouver Island, including a land area of 57.73 km^2, 5 lakes, and 7 wetlands. There are few open water bodies on this island, and the largest lake is Hoggan Lake (SRK Consulting, 2013). Most of the wetlands are seasonal and ephemeral creeks flow only for weeks.

The water table on Gabriola follows the shape of the topography, where the northeast and southwest sides of the island are relatively high in elevation. While the northwest and southeast parts of the island have the lower elevation. The topography of this island is controlled by the bedrocks, which are mainly sandstone and mudstone (Burgess and Allen, 2016). This island is comprised of fractured aquifers, and for the assessment of groundwater, the fractured rocks makes up the bulk of the porous media. The common hydraulic parameters are listed in Table 1. The value of transmissivity and storage capacity are estimated from the pumping test in confined aquifers by SRK Consulting (2013).

Table 1. Hydraulic Properties of Gabriola Island

Porosity	1*10-7 to 3*10-6 m/s
Hydraulic Conductivities	1*10-7 to 1*10-6 m/s
Storativity Coefficient	1*10-4
Transmissivity	6*10-6 to 2*10-5 m^2/s
Storativity	2*10-5 to 3*10-2

Table 1 lists the hydraulic properties of Gabriola island estimated from previous investigations. According to SRK Consulting's report (2013), which assumes the fractures and unfractured rock are an ensemble with equivalent set of hydraulic properties, and the hydraulic tests are conducted in an equivalent porous medium. (Retrieved from SRK, 2013).

The permanent population of this island is about 4033 as recorded in census profile of Statistic Canada (2016), and the only transportation between the Gabriola Island and Vancouver Island is linked by the BC Ferry.

1.2 Climatic

The climate of Gabriola island is oceanic with distinct wet winter and dry summer. Monthly average of precipitation and temperature that recorded from nearby Nanaimo station are shown in Figure 3. There is a significant seasonal variation in precipitation and temperature. The dry season used in this study consisted of April, May, June, July, August, and September, while the rest of months are considered as the wet season. As seen from Figure 4, there is very little indication that the annual precipitation has changed over the 50-year record. However, the mean precipitation of dry season has decreased by 20 mm (Figure 5), and the mean precipitation of wet season has increased by about 80 mm (Figure 6).

Figure 3.

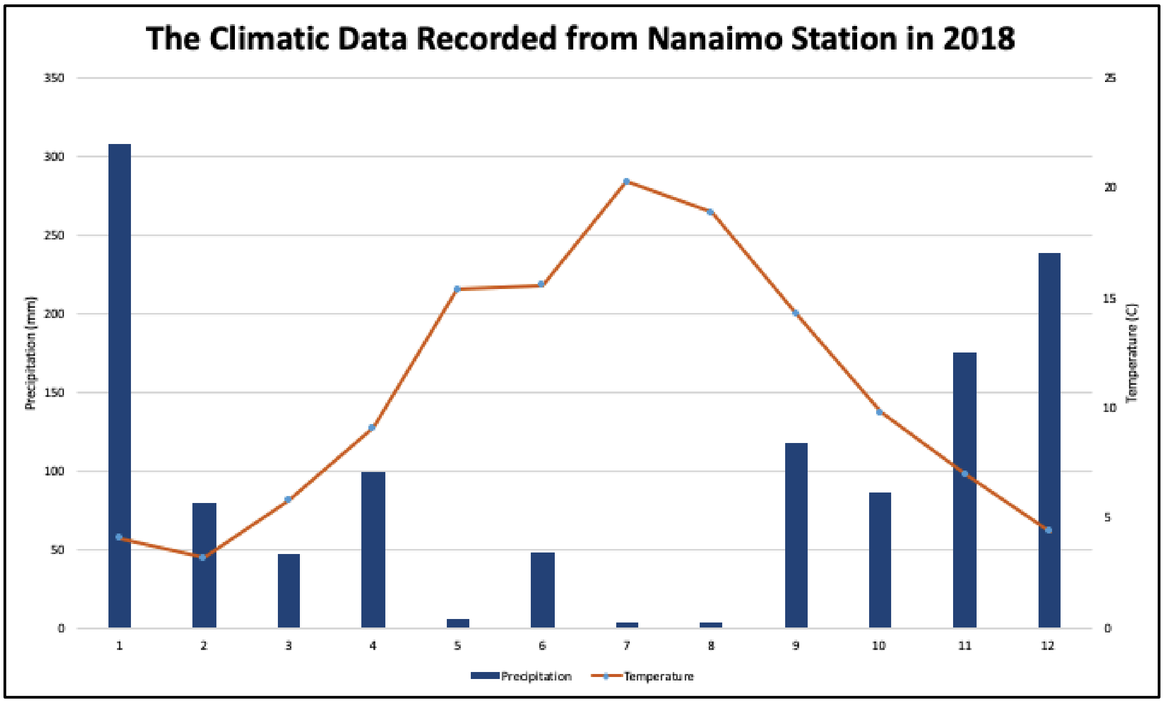

Figure 3 shows the oceanic climate of Gabriola island with wet winter and dry summer.

Figure 4.

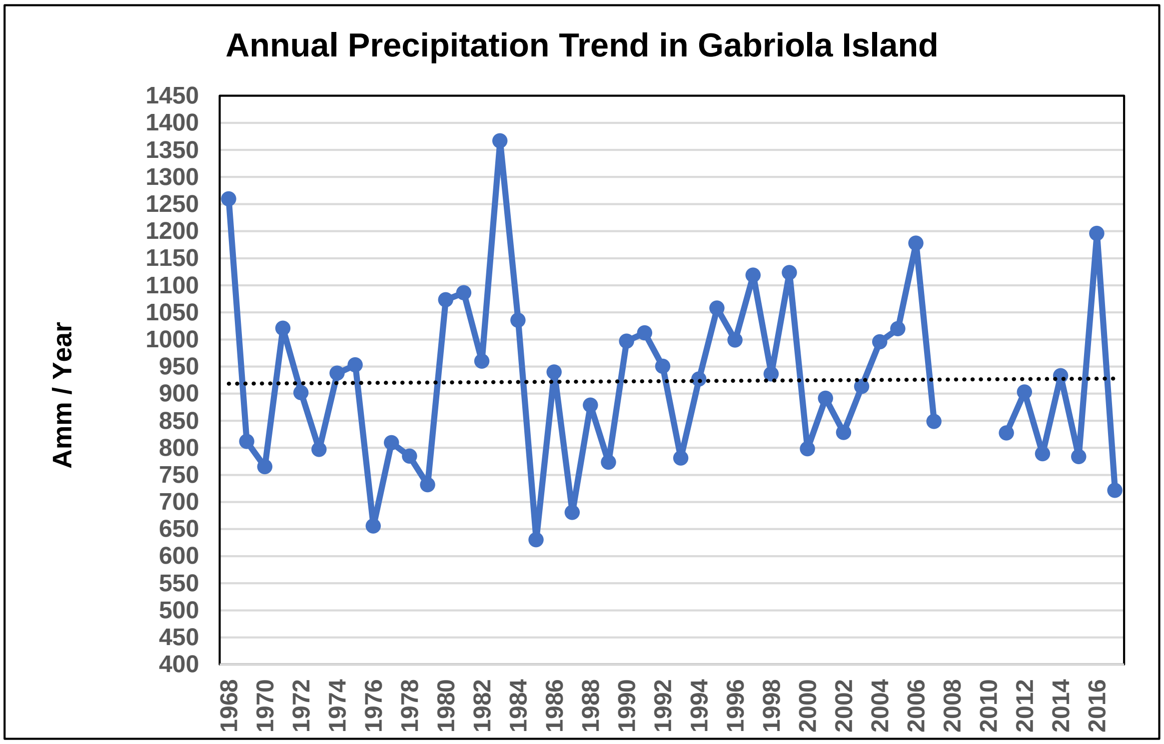

Figure 4 shows the annual precipitation trend in Gabriola Island from 1968 to 2016

Figure 5.

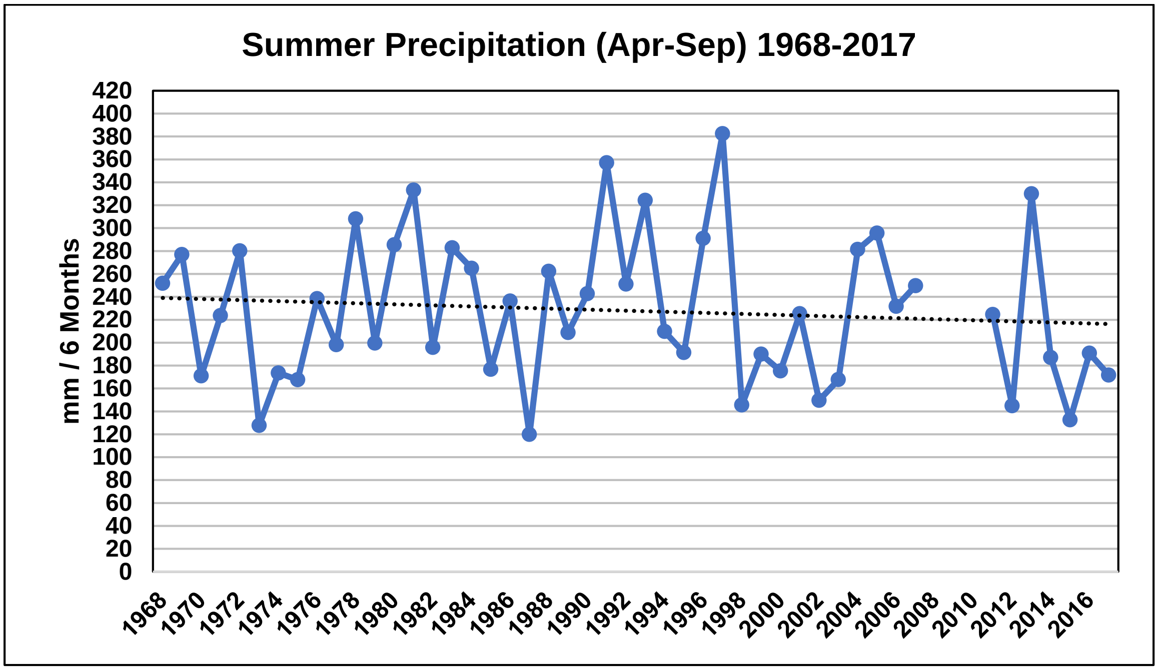

Figure 5 shows the wet season precipitation trend in Gabriola Island from 1968 to 2017.

Figure 6.

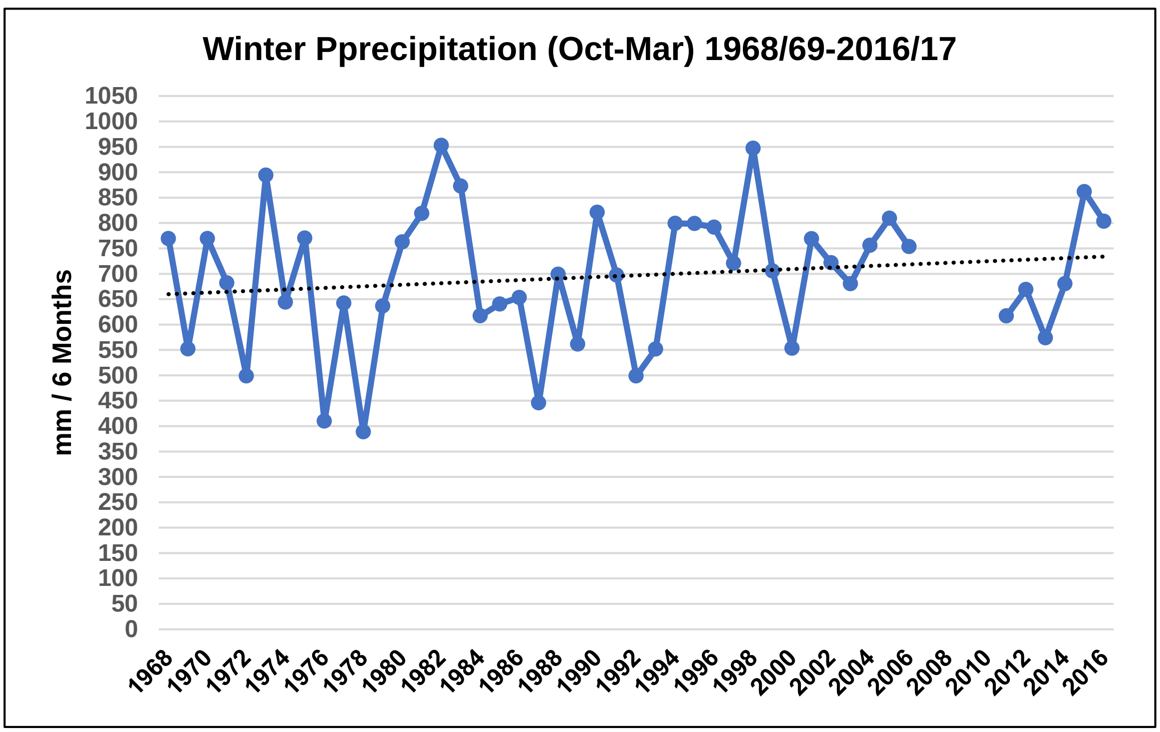

Figure 6 shows the dry season precipitation trend in Gabriola Island from 1968 to 2016.

2. Water Balance on Gabriola Island

Calculating the water balance provides an estimation of the current status and future projections of water resources that is essential for long term resources management. The water balance of Gabriola Island is calculated based on the energy conservation law that is the amount of water flows into the system equals the number of flows out of the system. The water balance equation is shown below. The inflow components is the percentage of precipitation that directly drains into the aquifer and the amount of recharge from the harvested rainfall and the recharge of groundwater used for domestic and outdoor purposes. The amount of rainwater captured is estimated as 5% of the rainfall. The main components of water outflow include groundwater seepage and groundwater extraction for residential and agricultural use.

"Energy Conservation Law" $Water_{in} = Water_{out} + Water_{storage}$

2.1 Seasonal Variation in Recharge to Aquifer

Since the winter precipitation is relatively high and temperatures are low the amount of evapotranspiration is small. This means that a large proportion of the rainfall recharges the aquifer. Therefore, the high-water level is maintained during the winter rainfall period. The method called water level fluctuations is applied in estimating the recharge from intensive rain events on Gabriola Island. After every rain event the water level rises and depending of conditions the groundwater discharge rate might also increase (SRK Consulting, 2013). The aquifer is recharged quickly during the beginning of the rainy season with a large proportion of rainfall draining into groundwater. Therefore, the potential range of recharge on Gabriola is between 20% and 60% of the mean annual precipitation during dry and rainy season respectively (Burgess, 2017).

2.2 Evapotranspiration Estimated for Different Land Use

Evapotranspiration (ET) is an important component in water resources management, which can be determined as potential ET that calculated from climatic variables and is independent of vegetation (Liu et al, 2011). The actual ET is the net result of potential ET and the moisture available (Burgess and Allen, 2016). Though under the same climatic conditions, the actual ET exist significant spatial and seasonal variation with different vegetation covers and various land development (Liu et at, 2010). The potential ET of Gabriola island was calculated using the AWSET software through temperature, humidity, wind speed and solar radiation data (Burgess and Allen, 2016). The potential ET ranges from 182.5 mm/year to 876 mm/year that indicates the seasonal variation as low values occur during winter months and high values occur during summer months (Burgess and Allen, 2016). According to previous studies, the actual ET on Gabriola island is around 36% to 50% of annual precipitation.

As shown in Figure 7, the land uses on Gabriola island mainly consist of forestry, agriculture, residential use, and open water. According to Burgess and Allen (2016), 55% of the island is covered by young forest, followed by 35% covered by urban areas, 7% is agricultural region, 2% is open water, and 1% is recreational areas. Based on the study conducted by BC Ministry of Forests, the Gabriola island falls into the Coastal Douglas-fir zone, where the vegetation is dominated by Douglas-fir, western red cedar, grand fir, arbutus, Gray oak, and red alder. As the actual ET is affected by the climatic variations such as temperature and humidity, the actual ET of each land uses during the dry season are assumed higher in the summer season. As shown in Figure 8, there is a significant water deficiency during the summer months. Based on the study of Liu et al (2011), the actual ET of open water is 55% of annual precipitation and the forest is estimated as 48%, followed by the agricultural area that is 45%, the residential region is 42% and recreation area is 40%. While during the rainy season, the actual ET of open water is assumed as 35% of the annual rainfall, followed by the forestry of 28%, agricultural of 25%, urban of 22%, and recreation of 20%. The comparison of actual ET of each land uses at different seasons is shown in Figure 9.

Figure 7. The Land Uses Distribution on Gabriola Island

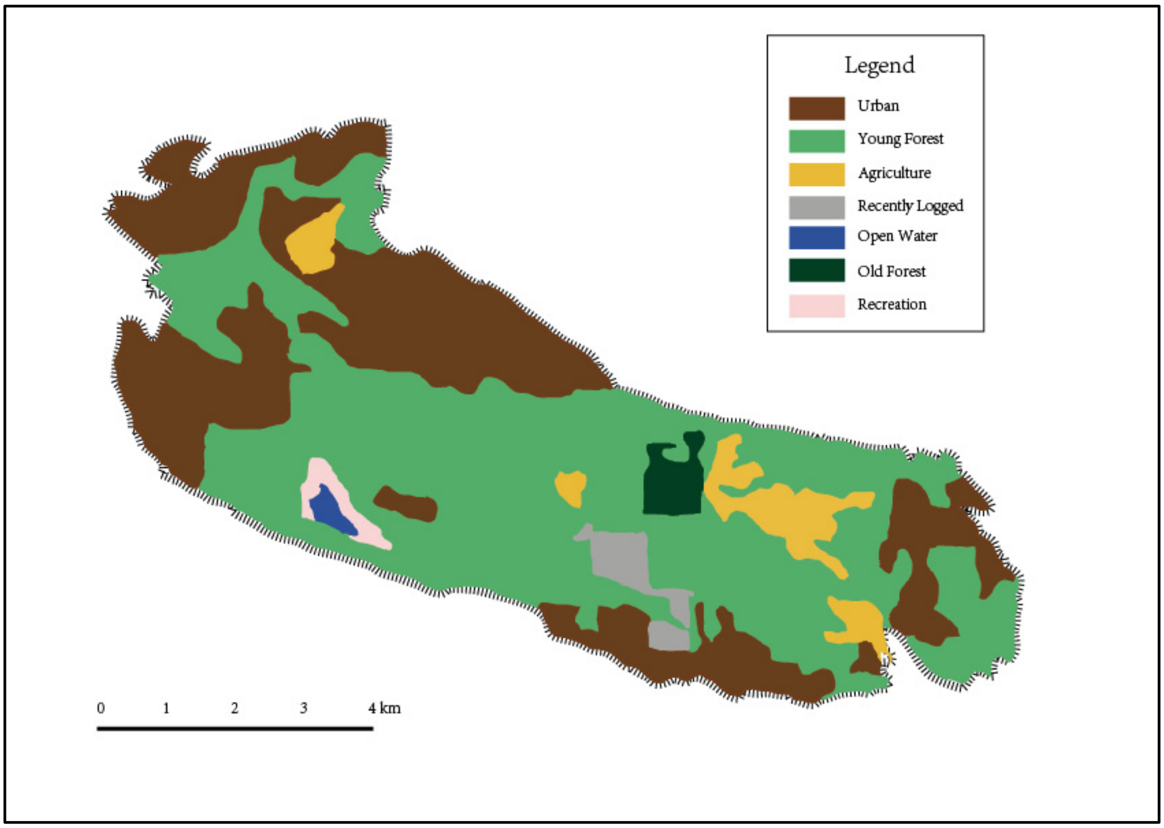

Figure 7 shows the distribution of urban, forest, agriculture, open water, and recreational region on Gabriola (Retrieved from Burgess and Allen, 2016).

Figure 8.

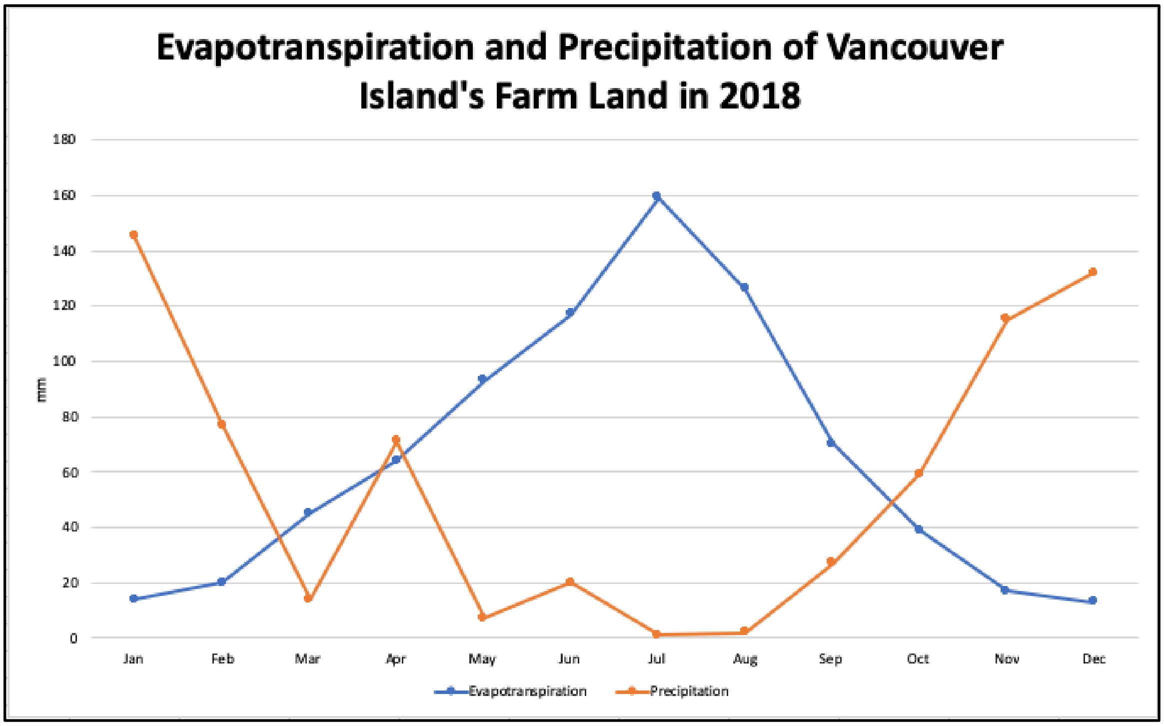

Figure 8 shows the evapotranspiration and precipitation record from Vancouver Island's farm land in 2018 indicate the trend of water deficiency (Retrieved from PFCA, 2019).

Figure 9.

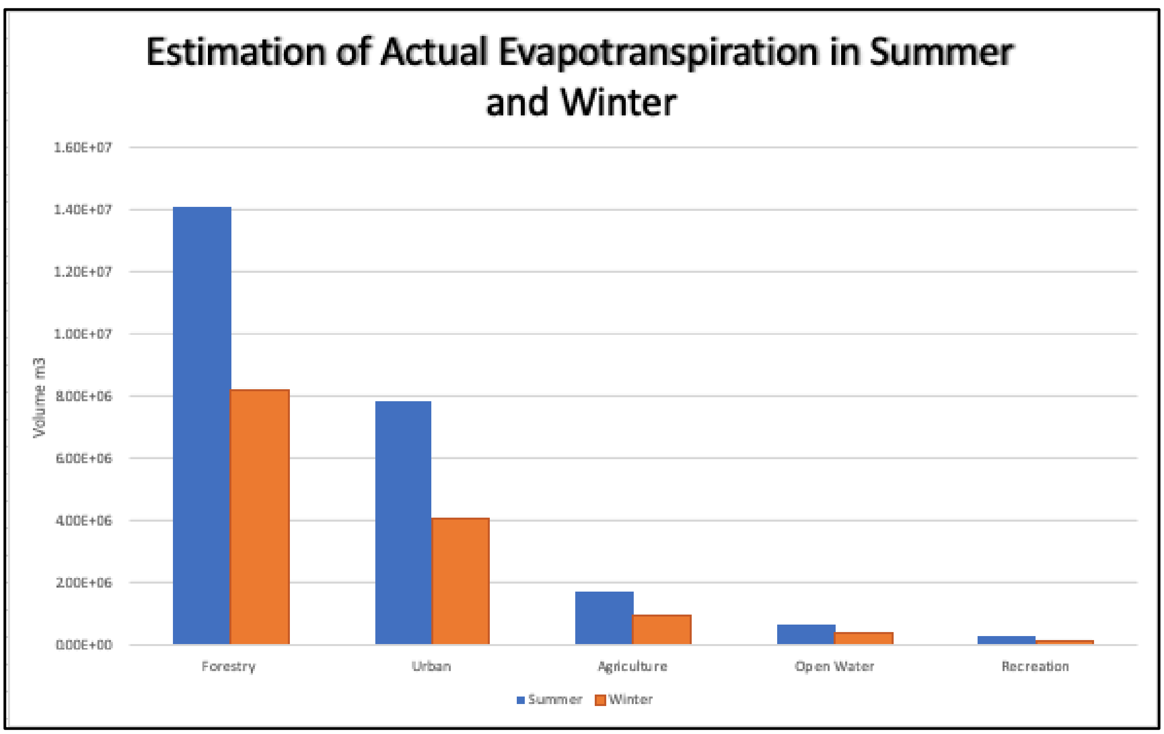

Figure 9 shows the actual ET estimated of various land uses.

2.3 Surface Water Runoff

There are a total of 5 lakes and ephemeral creeks on Gabriola island which indicates surface runoff during the rainy season. Those streams do not flow during the summertime. Some of the small streams originate as springs that follow rock fractures. As mentioned in SRK Consulting's report (2013), the peak discharge hydrograph is about 0.35 m^3/s during the rainy season, followed by a significant reduction in flow in spring, and no flow during a dry period. The average annual discharge is approximately 0.176 m^3/s. Therefore, the annual runoff volume from Gabriola island are estimated as about 30% of average annual precipitation (Burgess, 2017).

2.4 Harvested Rainwater Consumption

Rain harvesting is the measure of collecting and storing rainwater that are comprised of a catchment area, a conveyance system, and a storage tank. Harvested rainwater are mainly used for outdoor irrigation on Gabriola Island (RDN, 2019). As shown in the report, garden and lawn watering consume more water in summer months, which is double than winter water demands. Besides, outdoor cleaning can consume about 4.5 m^3 per month, and using rainwater to flush toilets can save 15% of annual water consumption (2.2 m^3 per month per house).

2.5 Groundwater Contributions to Environmental Flows

The discharge of groundwater into stream provides a supply of water during dry periods and maintain water levels. According to Forstner et al (2018), the fluxes of groundwater’s contribution to environmental flows in the majority of Gabriola island ranges from 0.01 to 0.1 $m^3A^{-1}yr^{-1}$, while the fluxes of groundwater’s contribution to environmental flows in small portion of Northern Gabriola Island varies between 0.1 to 1 $m^3A^{-1}yr^{-1}$, which are based on the low flow zones approach.

2.6 Groundwater Consumption

Groundwater consumption is the volume of groundwater removed from an aquifer, which is usually represented by withdrawal. The groundwater withdrawal of Gabriola Island is only estimated for agricultural, commercial, and domestic sectors. Agricultural water withdrawal was estimated based on farm type. Farms are defined as crops, livestock and mixed of crops and livestock (SRK Consulting, 2013). The annual agricultural water consumption on Gabriola Island is about 469000 m^3. There is a significant seasonal variation in water use for agriculture. The amount of water use in dry season is around 348000 m^3, while in wet season is approximately 121000 m^3 (SRK Consulting, 2013). Commercial establishments have the lowest water withdrawal with slightly seasonal variation. The annual withdrawal is about 46000 m^3. The total consumption in summer months is about 31000 m^3, while the total consumption in winter months is around 15000 m^3 (SRK Consulting, 2013). The residential water use in Gabriola Island is the strongest affected by seasons. The total annual residential water use is estimated based on amount tourists and local citizens, which is around 5840000 m^3. The total consumption in summer months is 4220000 m^3, and in winter months is 1620000 m^3.

2.7 Seasonal Variation of Tourists Numbers

Gabriola Island has many public beaches, forests, a few restaurants, and a museum, which is also known for the Isle of the Arts. Besides, a lot of visitors also have cabbing. Thus, the number of visitors increases significantly during the summer time. As shown in Figure 10, the seasonal variation of visitors as indicated by the record of BC Ferries' traffic statistics (2018). The number of visitors increases significantly from June to August, followed by a dramatical reduction from September to February. Therefore, there are more tourists during summer than winter and this results in more water consumption during the summer. Based on the B.C. Ferry statistics a total of 407095 visitors entered the island in 2018 and this includes the 4033 local citizens that also use the ferry system.

The amount of water extracted from the groundwater system is calculated from the number of people visiting the island and the water consumption per person per day data provided by the BC Municipal Water Survey (2016). The average residential water use in British Columbia is 312 liters per capita per day.

Figure 10.

Figure 10. shows the seasonal fluctuation of traffics on Gabriola island based on statistics from BC Ferries

3. Results

3.1 Annual and Seasonal Water Balance

Each component required in estimating the water balance of Gabriola island listed in Table 2 and shown in Figure 11.

Table 2. Calculated water balance for Gabriola island.

	Precipitation	AET	Runoff	Recharge
Annual (m^3)	5.31E+07	3.80E+07	1.59E+07	2.66E+07

Table 2 lists all the components that included in the water balance equation.

Figure 11. Comparison of Water Balance in Dry Season and Wet Season

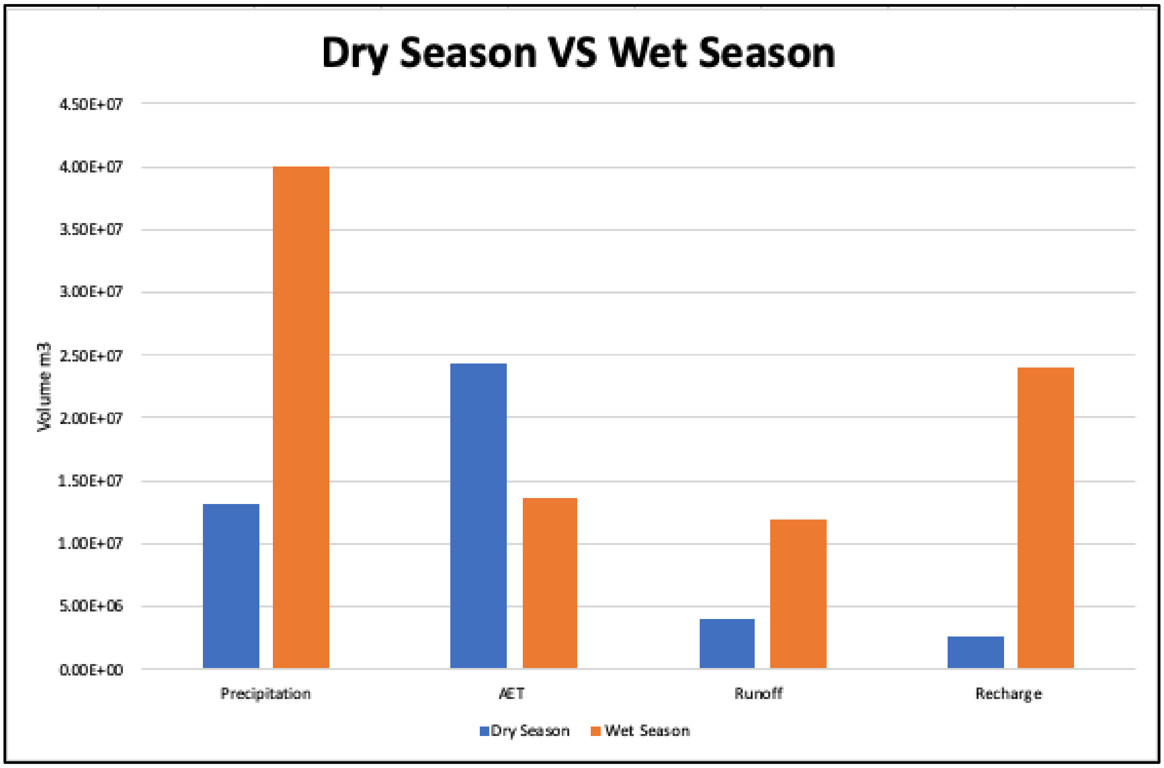

Figure 11 shows the comparison of water balance between dry and wet season on Gabriola Island

3.2 Seasonal Variation of Water Consumption

As listed in Table 3., the amount of water required for domestic sector in dry season is about 4.60E+06 m^3, and the amount of water used for residential purposes in wet season is around 1.76E+06 m^3. The total water withdrawal in summer is around 3 times higher than the amount of water required in winter. The largest amount of water consumed is for residential purpose followed by agricultural and commercial.

According to Burgess (2017) the aquifer stress can be quantified through a ratio of water use to availability. The positive number represent excessive water were be stored in groundwater system, while the negative number indicate more water were either flowing out or extracted out from the groundwater system. The seasonal variation of aquifer stress is shown in Table 4. The groundwater footprint is -1.46 in summer and 0.08 in winter, which indicate the local aquifer is under stress during the summer time.

$$Stress = \frac{Use}{Availability}$$

Table 3. Groundwater Consumption of different land uses.

	Agricultural	Commercial	Residential	Sum
Summer	348000	31000	4220000	4.60E+06
Winter	121000	15000	1620000	1.76E+06

Table 4 Groundwater Footprint estimated for Each Season

	Groundwater Consumption m^3	Recharge m^3	Environmental Streamflow Contributed by Groundwater m^3	Groundwater Footprint
Summer	4600000	2630000	5770000	−1.46
Winter	1760000	24000000	577000	0.08

Table 4 list the groundwater footprint that calculated as groundwater stress indicator.

3.3 Climatic Change Projection of British Columbia

As noted by Moore et al's (UN), the future climatic scenarios of British Columbia are obtained based on the projection of greenhouse gases emission from the Intergovernmental Panel on Climate Change. Climate change will change the pattern of temperature and precipitation, which eventually affect the groundwater resources. According to these projections, British Columbia will have increases in temperature and precipitation, and southern British Columbia are expected to be drier in the summer and wetter during the winter. Besides, the change in extreme events is also important considering the water resource management. As shown in future climatic projections, the changes in warm extremes are consistent with the variation of average summer temperature, while cold extremes warm faster especially in regions that occur the snow retreats (Moore et al, 2019). The rise of the intensity of precipitation and the reduction of interval time between extreme events are also highlighted in the future climatic simulation.

The percentage of change in recharge and precipitation are shown in Figure 12 and Figure 13 prospectively. According to future projection, the changes of both recharge and precipitation in 2080 is larger than the changes in 2050 (Burgess and Allen, 2016). In Figure 12, the projected recharge changes the most in summer compared to winter, the recharge will increase by 11% in summer and 4% in winter of 2050, and the recharge will increase by 16% in summer and 8% in winter of 2080. According to projection (Figure 13), precipitation of 2050 and 2080 will increase in spring and decrease significantly in summer. The projection of 2050 shows the precipitation is going to increase by 10% whereas decrease by 7.5% in winter, and the projection of 2080 indicate there will be 10% increase of precipitation in summer and 8% decrease in winter.

The calculated water balance based on the projection of recharge and precipitation is shown in Figure 14. The amount of precipitation, runoff, and recharge will decrease slightly, while the amount of actual evapotranspiration is going to increase dramatically, which indicate the stress of available freshwater will become intense in 2080 compared to 2050.

Figure 12.

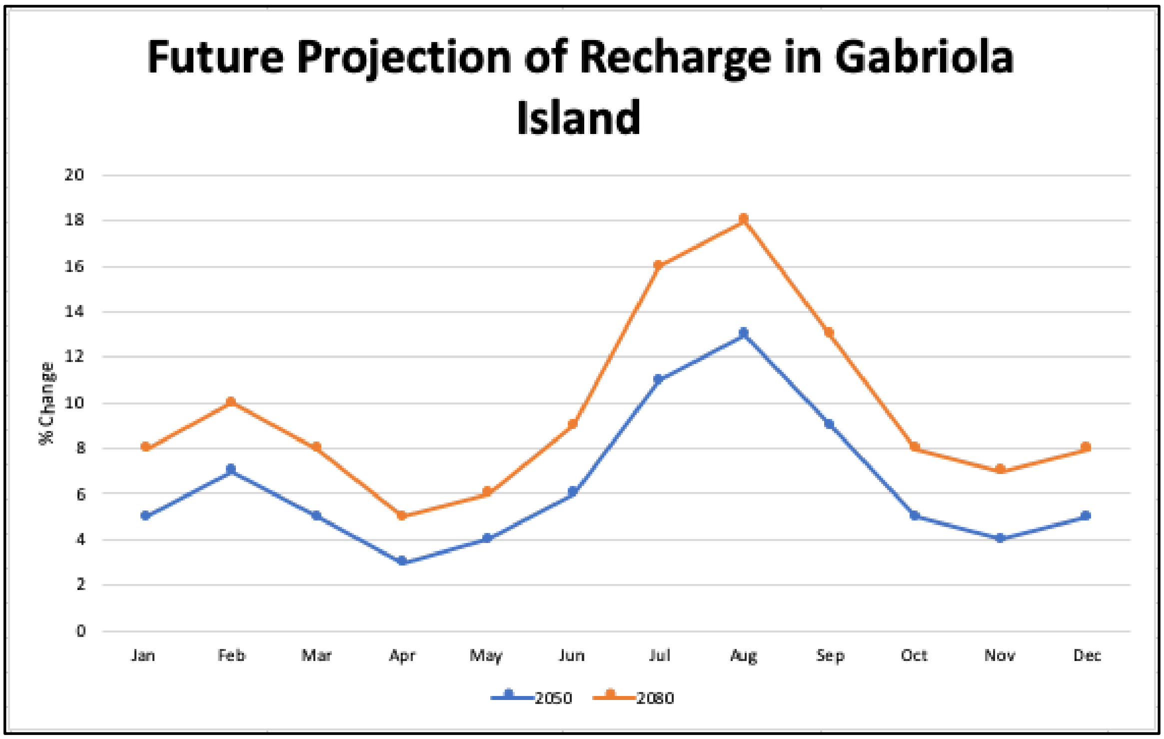

Figure 12 shows the projection of percentage variation of recharge for 2050 and 2080 prospectively (Retrieved from Burgess and Allen, 2016).

Figure 13.

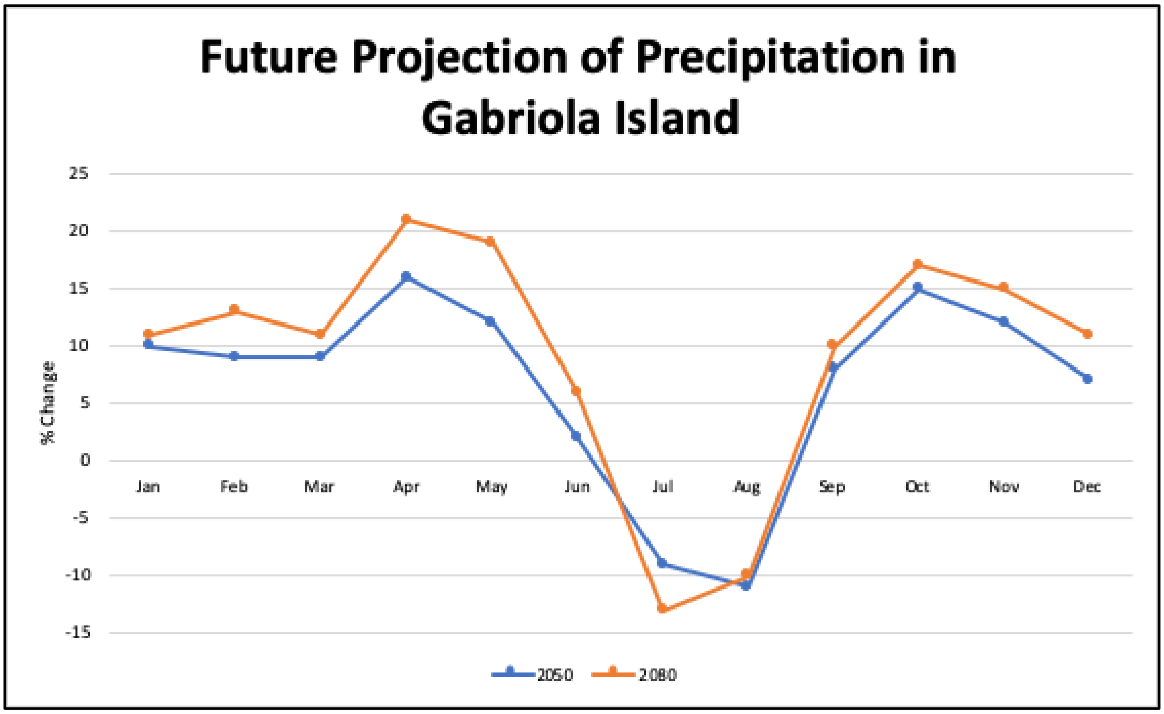

Figure 13 shows the projection of percentage variation of precipitation for 2050 and 2080 prospectively (Retrieved from Burgess and Allen, 2016)

Figure 14.

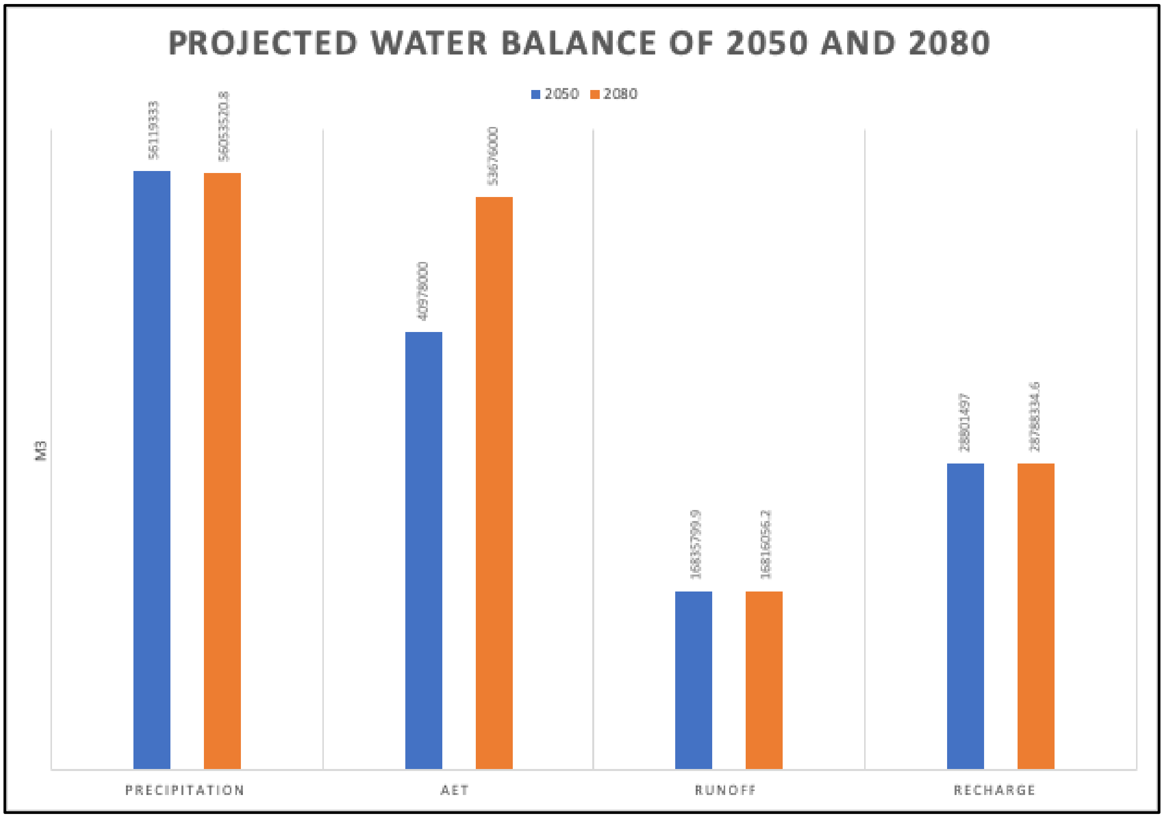

Figure 14 shows the calculated water balance based on future projection of 2050 and 2080.

4. The Estimation of Salt Water Intrusion on Gabriola Island

Seawater intrusion associated with groundwater overdraft and lowering of groundwater levels has occurred in many of the coastal aquifers and is one of the most common water quality issues. Under natural conditions, the seaward moving of freshwater prevents seawater from encroaching coastal aquifers. An interface between freshwater and seawater is maintained with denser seawater underlying freshwater. When groundwater is pumped from coastal aquifers, low water levels can cause seawater to be drawn toward the freshwater zones of the aquifer. Therefore, the intruding seawater decreases the freshwater storage in the groundwater system. The saltwater intrusion may also occur during pumping overload, which causing lower hydraulic heads near the wells that draws seawater upwards. The saltwater intrusion has occurred on Gabriola Island in a number of cases near the shoreline. The salt water intrusion risk is estimated based on the water level map of Gabriola island (SRK, 2013) and the location of domestic wells (Figure 1). As seen in Figure 15, there is a higher risk of saltwater intrusion in the southeastern part of the island than the northern part. According to the topography of the Gabriola island, the risk of seawater intrusion in the central area is lower than near the shores.

Figure 15. Salt Water Intrusion Risk Distribution

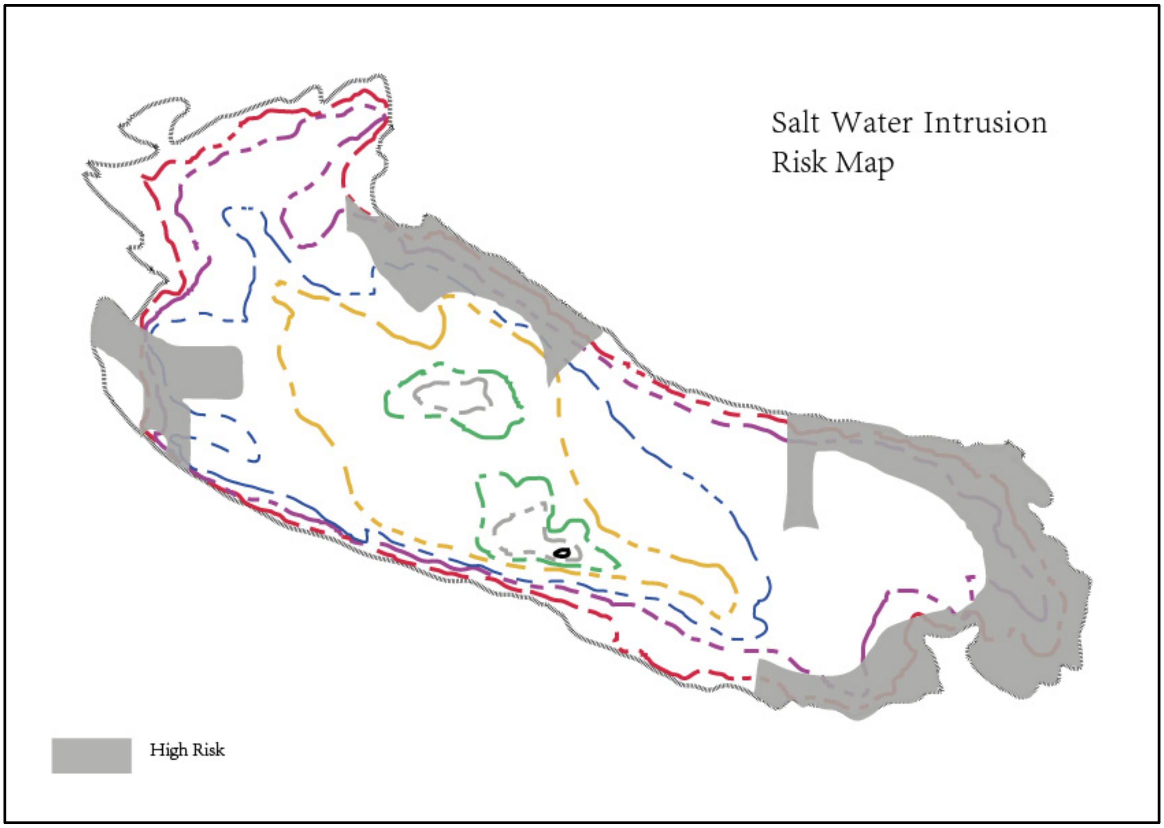

Figure 15 shows the distribution of salt water intrusion level

4.2 Water Conservation Method

There are several methods that can be adapted to reduce the water demand and supply stress. Conservation efforts to reduce and outdoor water use, roof water harvesting, updating infrastructure, improving distribution systems and artificially recharging the aquifer are all effective options to be considered. Also, seawater desalination is an option. Desalination secures water resources and is not influenced by precipitation but its energy intensive and disposing of the eliminated salt is of major concern (Elimelech and Phillip, 2011). From agricultural perspective, increasing soil holding capacity is another efficient measure to reduce the amount water extracted for irrigation purposes through adding organic matters.

5. Limitations

Although the current status and future status of water balance on Gabriola Island are estimated based on the conceptual model, there are several limitations of this project. Initially, the estimation of groundwater consumptions is not actual water use volumes but are based on assumptions and the data available. The uncertainty exists when estimates are presented. There is also inadequate information on groundwater level because of lacking field investigation. Finally, the conceptual water balance model has not run for a sensitive test that means the results could contain some bias.

6. Summary and Conclusions

Estimation of water balance is an important tool to assess the current status and trends in water resource availability in the future. The water demand of Gabriola Island varies for agricultural, commercial, and residential sectors, and the farm and residential water demand accounts for the majority of groundwater consumption. The groundwater is under stress during the dry season from April to September that will be more intense with changing climate on Gabriola island. In addition, as water demand increase with increasing people living on the island in summer, the chance of seawater intrusion will also increase. Therefore, beware of data gap and update the conceptual water balance model is important in improving understanding of the local hydrological system. Water balance calculation is providing a quantitative evaluation of water resources. It will eventually strengthen water management decision-making by improving scenarios and strategies.

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