Groundwater Elevation and Chemistry at Camosun Bog, British Columbia, and Implications for Bog Restoration

by

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Abstract

A bog is a type of wetland with a high water table, acidic soil and is nutrient poor. Camosun Bog is the oldest bog in the Lower Mainland of British Columbia, and remained undisturbed until development of the surrounding residential neighborhood caused changes to its groundwater conditions, threatening its current persistence. The goal of this study is to provide an updated examination of Camosun Bog's groundwater conditions and to discuss relevant bog restoration measures. Groundwater elevation and chemistry (pH, conductivity, nitrogen and phosphorus) were monitored for several months in 2019. Results indicate that current groundwater elevations are lower in Camosun Bog than they were thirty years ago, especially in the north and northeast regions. Locations in the north and center parts of the open bog experienced groundwater nitrogen enrichment and higher pH, indicating that raising the water table should be the main goal of restoration for Camosun Bog.

Keywords: Camosun Bog; bog; groundwater elevation; groundwater chemistry; restoration

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Introduction

To provide context for this research project, background on the ecology of bog ecosystems is presented first. Site-specific details of Camosun Bog (the study area of this report) and the rationale for the goals and objectives of this project is then discussed.

Bog Ecology

Bog Formation

A wetland is defined as: "land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment" (National Wetlands Working Group 1988). In general, wetlands can be divided into two groups based on the presence of peat (incompletely decomposed organic matter from plant debris); the two groups are organic wetland (also known as peatlands) and mineral wetlands (Warner and Rubec 1997). Organic wetlands contain more than 40 cm of peat on top of which organic soils can develop, whereas mineral wetlands have little or no peat (Warner and Rubec 1997). A bog is a type of organic wetland/peatland and is one of the five classes of wetlands in the Canadian Wetland Classification System (Zoltai and Vitt 1995; Warner and Rubec 1997).

The development and persistence of wetlands mainly depends on four factors: climate (temperature, precipitation, wind), hydrology (internal and external drainage patterns), geomorphology (landform, soil parent material) and biology (flora and fauna). Hydrologically, wetland development is affected by the depth of the water table relative to the ground surface and the chemistry of surface water. Wetland development is not a static process; wetlands can transition from one type to another depending on changes in the factors that drive their development (Warner and Rubec 1997).

Peatlands, such as bogs, develop when the ecosystem's net primary productivity and production of biomass exceeds organic matter decomposition over a time scale of thousands of years (Weider and Vitt 2006). Most peatlands in the northern hemisphere developed in boreal areas that were once completely under glacial ice 10,000 to 25,000 years ago (Weider and Vitt 2006). Bog development usually occurs in cool temperate areas (45-46 º latitude) with high precipitation (precipitation greater than evaporation during the growing season, summer precipitation deficit <100-150 mm) (Proctor 1995; Warner and Rubec 1997).

A bog is created from the establishment of peat-forming *Sphagnum* mosses along the edges of a shallow lake. Infilling of the lake basin with plant debris (terrestrialization) and outward accumulation of organic matter at the shorelines (paludification) then occurs (Klinger 1996) (Figure 1). This process of bog formation impedes the drainage of the lake, leading to water-logged soil conditions (Quinty and Rochefort 2003; Weider and Vitt 2006). Restricted water flow allows hydrophytes (plants which grow in or on water) and *Sphagnum* mosses to establish and form a ground layer (Zoltai and Vitt 1995). Plant nutrients are sequestered in their non-available forms by this ground layer, which decreases the nutrient availability required to produce vascular plants (Bayley et al 1987). Soil conditions also become increasingly acidic due to the production of humic acid during decomposition of plant debris and from the production of uronic acid from *Sphagnum* mosses (Hemond 1980). The combination of water-saturated, acidic soils and low nutrients reduce decomposition rates in the ecosystem (as not many decomposers can survive in such conditions); this promotes the net accumulation of organic matter as peat (Zoltai and Vitt 1995).

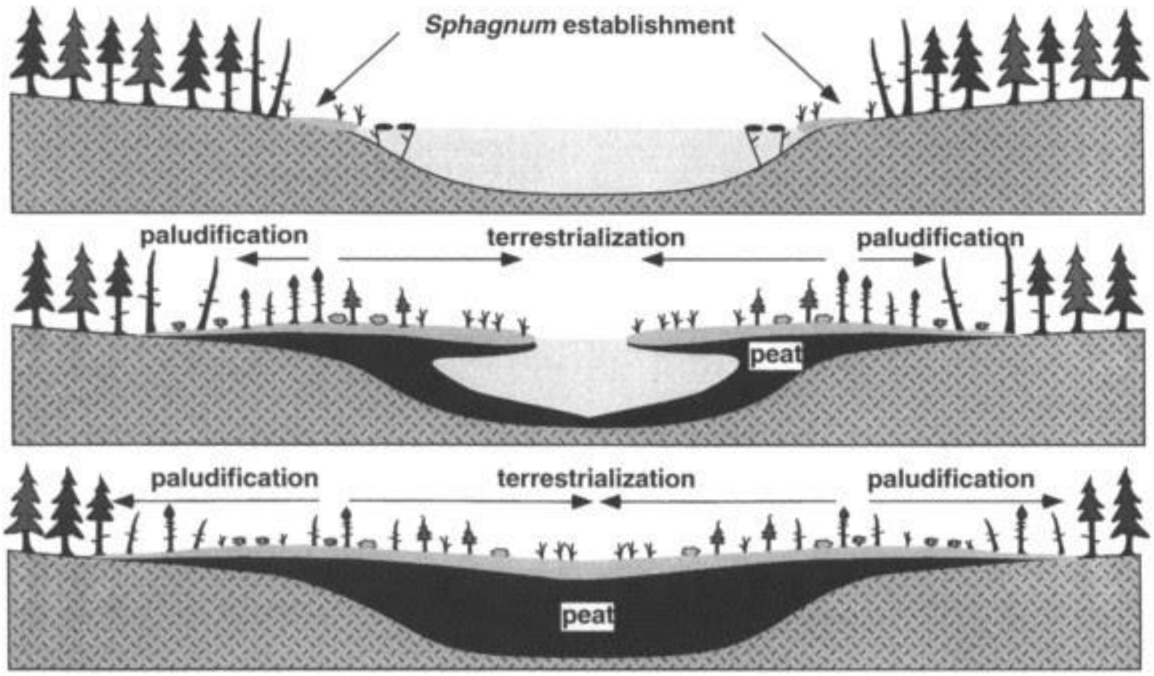


Figure 1 **Stages of bog formation: establishment of Sphagnum mosses along the edges of a shallow lake and the infilling of the lake basin with peat through terrestrialization and paludification. Figure from Klinger (1996).**

As peat accumulates in the lake basin, the surface of the peat eventually becomes level with or slightly higher (usually <50 cm) than the surrounding terrain (Wetzel 2001; Quinty and Rochefort 2003). The water table within the peat layer becomes slightly lower than the bog surface due to peat accumulation, plant growth at the peat surface, and the water storage ability of established mosses hindering drainage (Heinselman 1963; Wetzel 2001). As bog succession continues, this perched water table in the peat becomes isolated from the water table of the local terrain, and the bog is unaffected by runoff or groundwater from the surrounding mineral soil (Warner and Rubec 1997; Wetzel 2001). In most situations, direct precipitation (i.e., rain, fog, or snow) becomes the primary source of water for bogs (ie. they are ombrotrophic) (Warner and Rubec 1997). Surrounding the central peat mat of a bog are lagg zones, which are areas of shallow surface water and slower organic matter accumulation where remaining flowing groundwater has been diverted (Wetzel 2001). As succession proceeds from lake to bog, the origin of nutrients in the ecosystem also shifts from mineral soil in the lake basin to minimal concentrations found in precipitation and particulate fallout; this limits the amount of nutrients available for plant growth (Wetzel 2001). In the absence of major environmental disturbances, bogs are climax communities which can persist for thousands of years (Klinger 1996).

Bog Hydrology

Bog persistence depends on low seasonal water level fluctuation and low water flow through the wetland (Zoltai and Vit 1995; Weider and Vitt 2006). As bogs are ombrotrophic, and since precipitation is usually mildly acidic and contains minimal amounts of dissolved minerals, bog water is nutrient-poor and has a low pH (Warner and Rubec 1997). Water is stored in the peat of a bog if water input (mainly precipitation) exceeds water output (mainly summer evaporation) (Quinty and Rochefort 2003).

The two soil layers of peat (the acrotelm and catotelm) play a major role in the hydrological system of bogs (Quinty and Rochefort 2003). The acrotelm is the surface peat layer (usually between 30-50 cm in thickness) that contains the roots of the plants living on the peat surface, the living parts of mosses, and partially decomposed plant matter (Warner and Rubec 1997; Quinty and Rochefort 2003). The acrotelm helps maintain water close to the ground surface by capillary water flow among peat fibres, providing suitable wet conditions for *Sphagnum* moss growth (Quinty and Rochefort 2003). The peat structure is relatively loose in the acrotelm, making this the layer where most lateral groundwater movement occurs (Warner and Rubec 1997; Quinty and Rochefort 2003). When the water table is low, aerobic soil conditions are present in acrotelm, which can allow for plant decomposition to occur (Quinty and Rochefort 2003).

The lower limit of the bog water table defines the boundary between the acrotelm and the catotelm (Warner and Rubec 1997). The catotelm is the deeper peat layer (about 30 cm to an average of 3-5 m thick) underneath the acrotelm (Warner and Rubec 1997). Any peat and woody remains of shrubs not fully decomposed in the acrotelm eventually becomes water-saturated and incorporated into the catotelm layer (Warner and Rubec 1997). The catotelm is below the water table and is anaerobic, severely limiting decomposition rates in this layer (Warner and Rubec 1997) and allows methane to be generated. In addition, the peat in the catotelm is compacted, making groundwater movement very slow (Quinty and Rochefort 2003).

Bog Vegetation

Overall, bog plants are adapted to low nutrient availability and acidic soil conditions, and typically grow slowly (Wetzel 2001). Bogs can be treed or treeless, but the plant community is dominated by *Sphagnum* mosses and ericaceous shrubs (shrubs that need infertile or acidic soils) (Warner and Rubec 1997). In North America, black spruce (*Piecea mariana*), shore pine (*Pinus subsp. contorta*) and western red cedar (*Thuja plicata*) are common in the tree layer. Labrador tea (*Ledum groenlandicum)* and shrubs from the genus Kalmia (e.g. bog laurel, *Kalmia polifolia*) are often found in the understorey (Weider and Vitt 2006). *Sphagnum* mosses are key drivers in the development and persistence of bog ecosystems. Their dead litter forms peat deposits, and their presence helps sustain wet, nutrient poor, and acidic conditions. This is due to *Sphagnum* mosses' ability to retain water and nutrients and release organic acids (Quinty and Rochefort 2003; Weider and Vitt 2006).

Nitrogen is typically the limiting nutrient in undisturbed bog ecosystems (Wetzel 2001), whereas phosphorus becomes the limiting nutrient in nutrient-enriched ecosystems (Weider and Vitt 2006). The plant nutrients found in bogs are the dissolved inorganic forms of nitrogen (nitrate, ammonium) and phosphorus (orthophosphate) (Weider and Vitt 2006). The vegetation community in bogs is considered oligotrophic (lacking in nutrients), with the trophic state of plants mainly controlled by nutrients that enter the ecosystem through precipitation (Warner and Rubec 1997). In general, the plant biodiversity in bogs are unique due to the establishment of specific species adapted to acidic, nutrient-poor growing conditions that are not usually found in other ecosystems (Quinty and Rochefort 2003).

Function of Bogs and Impacts of Climate Change

Bogs have many important ecosystem functions, including regulating water flow by storing excess water during high precipitation events. They also serve as paleo-archives of past environmental conditions by preserving plant seeds and pollen in their peat layers (Clymo 1998, Quinty and Rochefort 2003). Bogs can also have recreational, aesthetics and educational value if they are accessible to human communities.

In the context of climate change, an important function of bogs is their ability to act as a carbon sink by storing large amounts of organic carbon in peat (Makila and Saarnisto 2008). Although peatlands only constitute about 3% of Earth's land area (Clymo 1998), they store about one-third of the world's carbon (Gorham 1991). However, changes in climate and human activity have made peatlands such as bogs vulnerable to drying. This can lead to subsequent increases in decomposition, carbon release to the atmosphere, and susceptibility to peat fires (Teretsky et al. 2014). Bogs are sensitive to warming, which can lead to loss of organic carbon in the peat (Ise et al. 2008), and emissions of carbon dioxide and methane gas trapped in soil carbon (Billet et al 2010). Higher air temperature and evaporation from bog ecosystems that is not offset by increased precipitation can lead to changes in acrotelm peat chemistry and lowering of the groundwater table. This can result in decreased diversity of bog vegetation patterns, slowing or stopping of peat accumulation, and the drying and potential death of *Sphagnum* moss carpets (Schouten et al 1992). Due to their high ecological value and sensitivity to environmental conditions, sustainable management and restoration of bogs is important to maintain their persistence in the future (Harenda et al 2017).

Background of Camosun Bog

Location

Camosun Bog (49º 15'N, 123º15'W) is located on the Point Grey Peninsula of Vancouver, British Columbia, on the northeastern corner of Pacific Spirit Regional Park (Figure 2). The outer boundaries of Camosun Bog are not precise as much bog vegetation has been displaced over the past hundred years, but Pearson (1983) assumed that Camosun Bog was located in areas where *Sphagnum* moss was observed (Figure 3). However, as this assessment was conducted nearly forty years ago, the delineation is likely not currently accurate and may require updating.

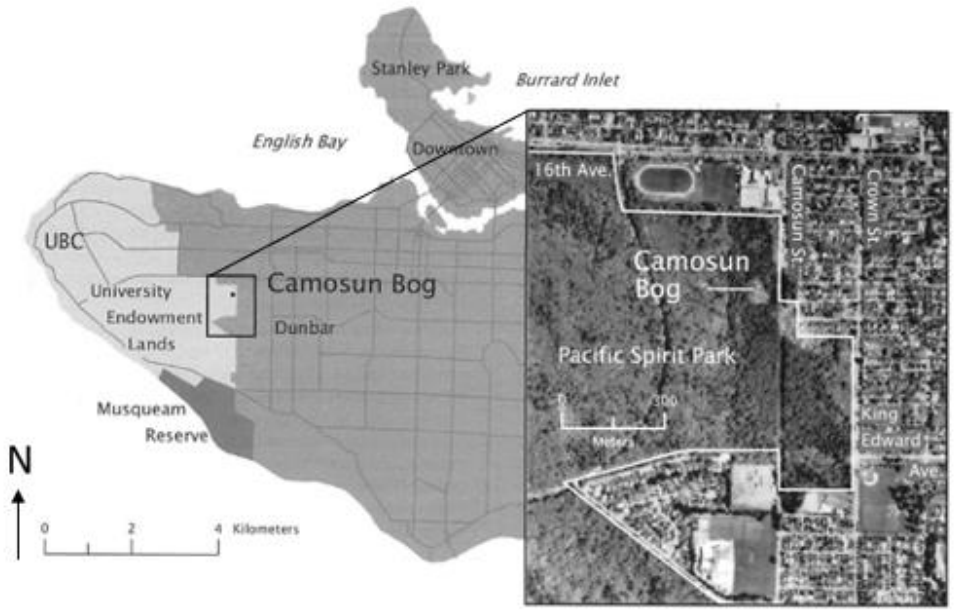


Figure 2 **Location of Camosun Bog within the context of Vancouver, BC. Source: modified from Hermansen and Wynn (2005).**

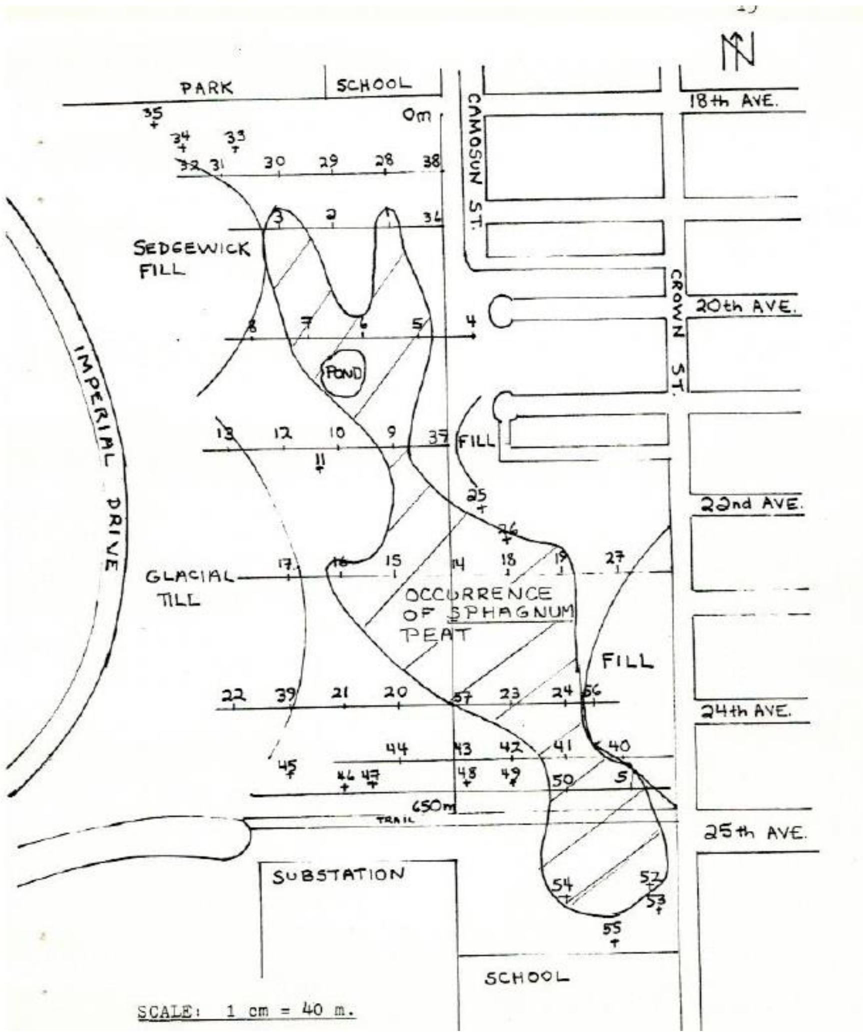


Figure 3 **Extent of Camosun Bog, as defined by the occurrence of Sphagnum peat. Source: Pearson (1983).**

Geologic History

Camosun Bog is the oldest bog in the Lower Mainland of British Columbia (Watmough and Pearson 1990) and is one of the northernmost locations of peat deposits on the west coast (Kiss 1961). Based on pollen analysis, Camosun Bog developed from a post-glacial lake after the retreat of the Vashon glacier 12,500 years ago (Mathewes 1973), and its first peat deposits are between four to six thousand years old (Kiss 1961). *Sphagnum* moss communities have existed in the central area of Camosun Bog for over a thousand years, indicating that the bog ecosystem is the climax community for this area (Pearson 1983).

Climate

Camosun Bog is located in the Coastal Western Hemlock Biogeoclimatic Zone, which is characterized by cool summers and mild, wet winters (BC Ministry of Forests 1999). Climate data from 1981 to 2010 at the Vancouver International Airport Weather Station indicate that the wettest month in this area is November (average monthly rainfall of 185.8mm) and the driest month is July (average monthly rainfall of 35.6mm) (Meteorological Service of Canada 2019).

Topography and Drainage

Camosun Bog lies in a shallow depression that is oriented northwest to southeast (Pearson 1983) (Fig 3). The ground surface of Camosun Bog is relatively flat, with gradual slopes towards the north and west, and a steep slope to the east. Prior to human disturbance, the drainage of Camosun Bog flowed to the southeast (Pearson 1985), potentially once reaching the Fraser River via Camosun Creek (Lesack and Proctor 2011).

Stressors and Impacts

Camosun Bog was relatively undisturbed until the 20th century, when development of the Point Grey neighborhood caused ecological changes to the bog; this resulted in only a small remnant open bog area by the 1980s (Figure 4) (Pearson 1985). A fire in 1919 led to the establishment of shore pine and western hemlock trees (Pearson 1985). Since then, change from a bog ecosystem towards a forest community dominated by western hemlock has occurred over the last 50-100 years (Pearson 1985).

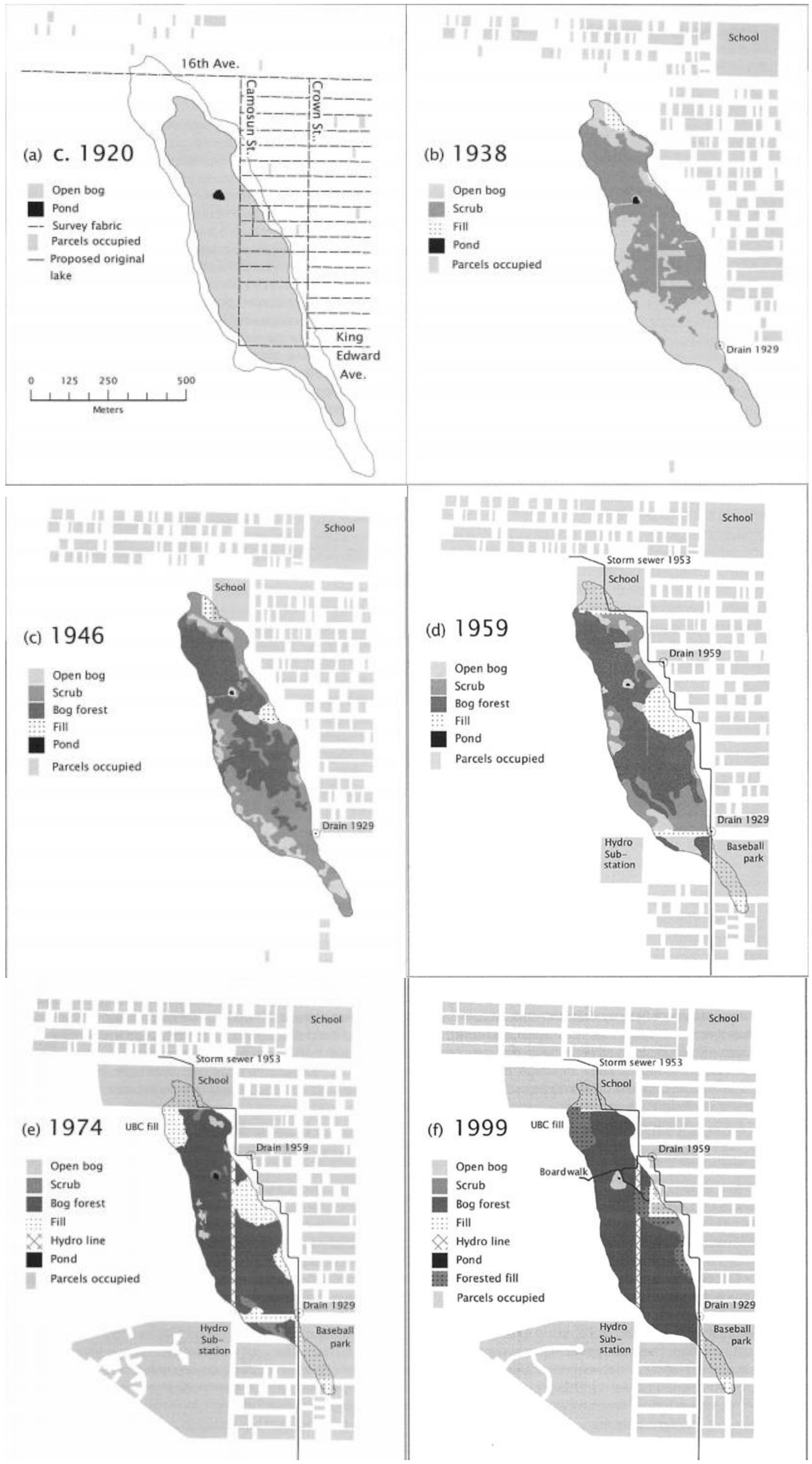


Figure 4 **Transformation of Camosun Bog over time, from 1920 to 1999. Source: modified from Hermansen and Wynn (2005).**

Currently, a significant stressor to Camosun Bog's persistence is declining water table levels, which is the result of several factors driven by urbanization. The current drainage regime has been altered from its historic patterns. This is due to a reduction in the precipitation catchment area feeding the bog, and the installation of ditches, catch basins, and sewers in 1929 and 1959 along the bog's eastern perimeter to manage stormwater runoff into the surrounding residential neighborhood (Marowitch 1982, Jull 1983, Pearson 1985, Piteau Associates 1989). Before urban development, the bog drained to the southeast. Currently, it is believed the northern area of the bog drains northeast into a deposit of highly permeable inorganic fill around the city sewer pipe located at the southern end of Camosun Street. The remaining southern two-thirds of the bog continues draining southeast (Piteau Associates 1989) (Figure 5). Groundwater monitoring records since the 1980s show declines in water table levels during late spring and summer months (Jull 1983). From 2008 to 2016, there was a decline in both summer (annual low) and winter (annual high) water levels, which also coincided with lower than average monthly precipitation patterns (Dakin 2017). Summer evapotranspiration now exceeds precipitation, which has likely contributed to the decline of the water table (Piteau Associates 1991).

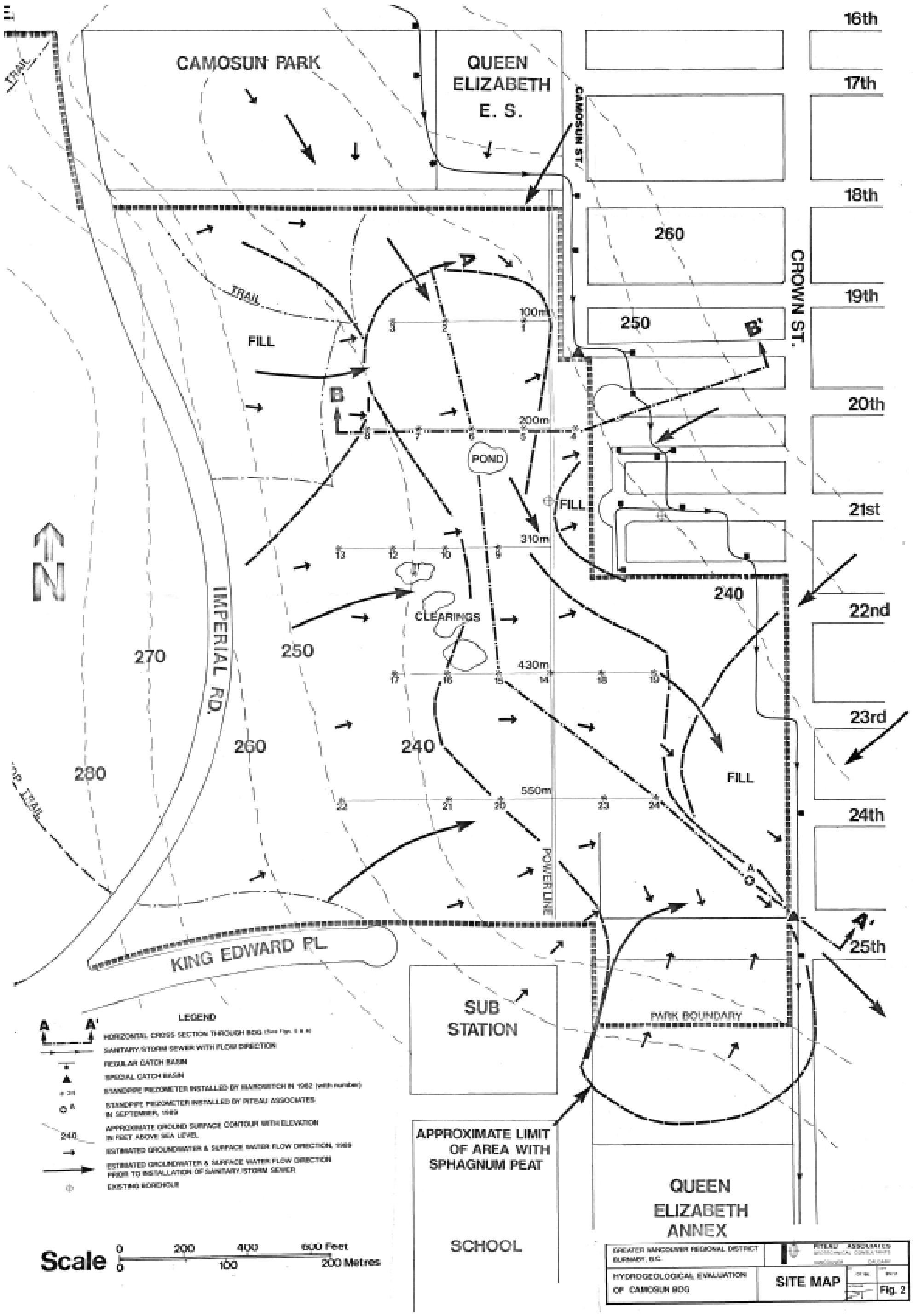


Figure 5 Hydrogeological map of Camosun Bog, indicating direction of groundwater flow and location of inorganic fill placement. Large black arrows indicate direction of groundwater flow prior to storm sewer installation, small black arrows indication direction of groundwater flow in 1989. Source: Piteau Associates (1989).

A declining water table has negative impacts on bog vegetation, which will accelerate the encroachment of western hemlock trees that are found along the perimeter of Camosun Bog (Jull 1983). However, this a concern as western hemlock trees are not considered to be bog vegetation. Hemlock establishment and growth in response to lower water table levels will lead to canopy interception and evapotranspiration, which promotes further groundwater level reduction and accelerates dominance by hemlock (Jull 1983). Without sufficient water to maintain a high water table, Camosun Bog will transition to an upland forest (Klinger 1996).

An additional stressor to the ecosystem at Camosun Bog is altered bog water quality. The ecology of bog ecosystems is in part controlled by their groundwater chemistry (Bourbonniere 2009). There is limited water chemistry data from Camosun Bog, but past reports indicated that there is nutrient enrichment from alterations in drainage (Marowitch 1982, Jull 1983, Pearson 1985). Nutrient enrichment in turn can promote the establishment of non-bog plant species (Berendse et al 2001).

Project Rationale and Goal

Protection and restoration initiatives began at Camosun Bog in the 1980s. This included the formation of the Camosun Bog Sub-committee in 1981 to study the deterioration of the bog, the inclusion of Camosun Bog as part of Pacific Spirit Regional Park in 1989, the helicopter removal of 150 hemlock trees from the core area of Camosun Bog in 1991, and the establishment of the Camosun Bog Restoration Group in 1995. Several hydrogeological assessments have been conducted at Camosun Bog in the past to investigate its groundwater conditions (e.g. Marowitch 1982, Jull 1983, Pearson 1983, Piteau Associates 1989). However, between 2005 and 2016 there was little monitoring of groundwater at Camosun Bog. In 2018, Metro Vancouver Regional Parks established several new groundwater monitoring locations in and around Camosun Bog in preparation for the proposed construction of a groundwater dam on the bog’s northeast corner to increase groundwater retention.

The goal of this project is to provide an updated study of groundwater conditions at Camosun Bog in partnership with the Pacific Spirit Park Society. Specifically, this project used newly installed groundwater monitoring stations to assess groundwater elevation and water chemistry from 2018-2019 in order to address the following objectives:

Objective 1.

Identify areas in Camosun Bog that experience the highest degree of drying in terms of summer (annual low) groundwater elevation.

Objective 2.

Identify potential areas of nutrient enrichment or mineral leaching in Camosun Bog, in terms of nitrogen and phosphorus groundwater concentration, pH, and conductivity.

Objective 3.

Recommend bog restoration measures for Camosun Bog that will mitigate negative impacts associated with drying (Objective 1) and nutrient enrichment (Objective 2).

Methods

Study Area

The specific study area for this project at Camosun Bog is approximately 17.5-ha in size and is bounded by West 19th Avenue to the north, West King Edward Avenue to the south, Crown Street to the east, and Camosun Trail to the west (Figure 6). The study area includes the remaining open bog area of Camosun Bog (as encircled by the boardwalk in Figure 6), as well as the surrounding bog forest.

Figure 6 **Map of project study area delineated in red, with the remaining open bog area circled in purple. Labelled sampling locations are shown as coloured dots: yellow dots (groundwater elevation and chemistry monitoring) and red dots (groundwater elevation monitoring only). Map modified from GoogleMaps (2019).**

Sampling Design

Groundwater elevation measurements were recorded from all 31 piezometers and groundwater monitoring wells found intact within the study area (Figure 7). Piezometers and monitoring wells are perforated tubes placed vertically in soil that are used to measure the water table depth below the ground surface (Or et al 2005). Monitoring wells have perforations along the length of the pipe below ground, whereas piezometers have perforations only at the bottom of the pipe. Their lengths extend to a depth lower than the water table, protrudes from the soil surface and is open to the atmosphere (although is usually capped) (Or et al 2005). Perforations in the tubes allow for the entry of groundwater, which rises to a height equal to the surrounding water table; the elevation of this water table is usually measured relative to the ground surface with a groundwater level meter (Or et al 2005) (Figure 7). A groundwater level meter consists of a measuring tape with a bell sounder that rings when in contact with water.

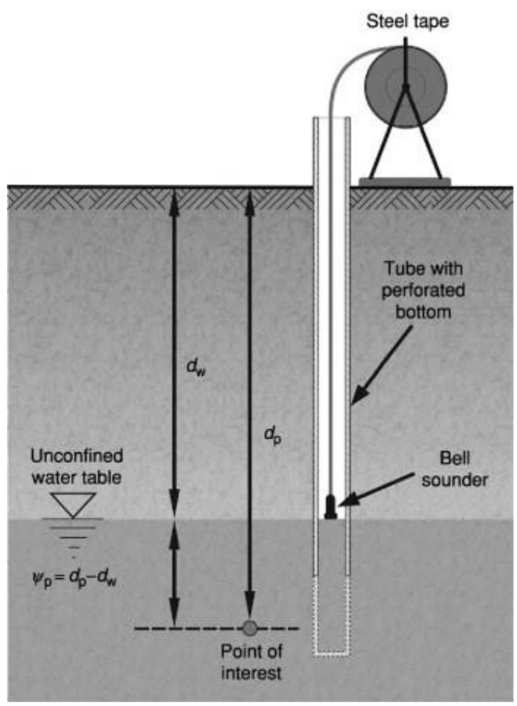


Figure 7 **Image of a standpipe piezometer, with the water table depth measured by a water level meter. Source: Or et al (2005).**

Piezometers and monitoring wells were originally installed in and around Camosun Bog in 1981 (Marowitch 1981), 1990 (Piteau Associates 1991), 1996, 1999 and 2018 (Dakin 2017). Location names beginning in P are piezometers, while the remaining locations are monitoring wells (Figure 6). A number of piezometers and wells had been not monitored and maintained since 2005, therefore several have been lost, vandalized or buried. I used all intact piezometers and wells found within the study area. For simplicity, both monitoring wells and piezometers will be referred to as “piezometers” in the data analysis.

Any piezometers and wells found in an unusable condition prior to sampling were repaired by removing mud or plant litter that had fallen into the tube, extending the piezometer/well to a greater height (i.e., if the tube was found broken and/or protruded only several centimeters from the ground surface), or by replacing missing or broken lids.

For groundwater chemistry measurements, sampling occurred at 8 of the 31 piezometers/well locations (Figure 6). The groundwater chemistry sampling locations were concentrated in the northern part of the study site as this is where the remaining open bog area was located, and where all current restoration projects done by the Pacific Spirit Park Society and Metro Vancouver Regional Parks occur. The 8 locations were chosen because they are used by the Pacific Spirit Park Society’s volunteer water chemistry program that was established in 2018 in order to continue their water chemistry dataset. In addition, they were selected to achieve a relatively even distribution of sampling locations around the open bog area (2 locations north of the boardwalk, 2 locations east of the boardwalk, 2 locations south of the boardwalk, and 2 locations within the core bog that is encircled by the boardwalk).

Data Collection

Groundwater Elevation Data Collection

In four monitoring wells (S1, S2, S3 S4), automated HOBO Onset Freshwater Water Level Data Loggers installed in each well recorded groundwater elevation. The loggers were first installed in February 2018 and have recorded groundwater elevation on an hourly basis since their installation. For this project, I used automated logger data from February 2018 to February 2020.

Groundwater elevation in the remaining 27 piezometers/wells was manually measured with a Heron Water Level Meter from May 2019 to December 2019/January 2020 on a weekly basis. For piezometers/wells that required maintenance to be suitable for monitoring, groundwater depth data was measured starting on the day the piezometer/well was fixed. May 2019 was the earliest sampling date in this project, and some of the 27 piezometers/well that needed repair had sampling that started later. Appendix A, Table 5 lists the range of dates for which sampling occurred at each of these 27 locations.

The Pacific Spirit Park Society also measured groundwater elevation manually in 13 of the 31 locations in the study area from January 2018 to April 2019. The piezometers/wells that the Pacific Spirit Park Society measured groundwater elevation from are: P9-2, P12-2, N7, S5, S7, S8, S9, S10, S11, B1, B9, YP, CTS. For this project, both the groundwater elevation data collected from the Pacific Spirit Park Society in 2018/2019 and the data I collected during May 2019 to January 2020 will be used for analysis.

In the field, groundwater elevation was measured relative to the top of the piezometer tube with the water level meter. To determine groundwater depth below the ground surface, the height of each piezometer/well above the ground surface was recorded, and this value was then subtracted from the initial depth measured by the water level meter. However, during times of high precipitation, more water is stored in the peat of bogs, causing the bog surface to rise (Howie and Hebda 2018). During drier months, the bog surface lowers because of the decreased available groundwater (Howie and Hebda 2018). This bog surface oscillation can affect the calculated depth of groundwater, so to account for this change in piezometer/well height over the sampling time, the height of each tube above the ground surface was recorded once near the beginning of sampling (June) and once near the end of sampling (December). The bog surface did not change by more than 2 cm at all sampling locations, therefore the average height of the piezometer/well from June and December was used in calculating the groundwater depth of the ground surface.

Groundwater Chemistry Data Collection

From April 2019 to January 2020, groundwater chemistry was measured once a month at the 8 piezometers/wells identified in Figure 6. Prior to each sampling, groundwater in each piezometer/well was purged with a pump and the water allowed to recharge in the piezometer/well for approximately 1-2 hours before the groundwater was sampled. Groundwater was purged prior to each sampling to replace the stagnant water (which is exposed to, and could potentially have reacted with, the air in the tube) with recharged water that newly entered from the surrounding soils. The groundwater was tested for pH, water temperature, and conductivity with an Oakton PCTS50 Multimeter. In August and September 2019, recharge rates were very low and thus water samples were gathered about 24 hours after purging.

From May to December 2019 groundwater samples were collected at 7 of the 8 piezometers/wells to be sent for lab analysis for groundwater nutrient concentrations of nitrogen and phosphorus. These samples were collected at the same time as the measurements for the other groundwater chemistry parameters. Only 7 of the 8 piezometers were sampled every month of the project timeline due to budget costs of the lab analysis; Piezometer C1 was not regularly sampled for nutrient concentrations (only sampled for nutrients in May and June 2019), but was sampled every month for all other groundwater chemistry parameters of pH, water temperature, and conductivity.

The plant nutrients found in bogs are the dissolved inorganic forms of nitrogen (nitrate, ammonium) and phosphorus (orthophosphate) (Weider and Vitt 2006). Dissolved orthophosphate was selected as the form of phosphorus to be analyzed at 7 sampling locations. Nitrate was initially selected to be the form of nitrogen to be analyzed at all 7 sampling locations in May 2019. One groundwater sample from Piezometer P9-1 was also sent for lab analysis for total ammonia in May 2019. In June

2019, samples from all 7 sampling locations were sent for analysis for both nitrate and total ammonia. Due to low nitrate concentrations (below lab detection levels of 0.005 mg/L as N) across all sampling locations in May and June and comparatively higher concentrations of total ammonia found at the sampling locations, total ammonia was then chosen to be the form of nitrogen to be monitored from July 2019 to December 2019 instead.

Vegetation Survey

A vegetation survey was conducted on October 13, 2019 at each of the 8 groundwater chemistry sampling locations (Piezometers P12-1, C2, P9-1, B2, P7, S11, S9, C1). The timing of the vegetation survey was not ideal as it was late within the typical growing season for most plants. However, the intent of the survey was to broadly categorize the immediate surrounding vegetation of each piezometer as either bog vegetation or non-bog vegetation based on the presence of *Sphagnum* mosses, which is present year-round. Vegetation was surveyed within an approximately 3.2 x 3.2 m plot centered around each piezometer/well. Each plot was divided into 4 square quadrats of 2.5 m^2 oriented towards the north, south, east and west, where each plant species within the quadrats was identified and assessed for percent cover.

Data Analysis

Groundwater Elevation Analysis

Across the study area, piezometers/wells were grouped into clusters of 1-4 for groundwater elevation analysis to examine groundwater trends in the different spatial regions of Camosun Bog (Figure 8). The regions are: North Bog (4 piezometers: P12-1, P12-2, S10, S7), Northwest Bog (3 piezometers: S5, N7, C2), East Bog (4 piezometers: C1, YP, S11, CTS), South Bog (4 piezometers: B1, B2, P9-1, P9-2), Southwest Bog (3 piezometers: B9, S8, S9), North Forest (P7, P6-1, P6-2), Central Forest (5 piezometers: N15, N18, P5, N23, P3), South Drain (1 piezometer: P15). Weather data of mean monthly temperature and total monthly precipitation from 2018 to 2020 was obtained from the Vancouver International Airport Weather Station. To examine if annual low and high groundwater elevation trends were significantly different between regions in the bog from 2018 to 2019, Loess smooth trendlines were created for each bog region and fitted with 95% confidence bands using R software. Pairwise comparisons of the smoothed trendlines were made between the North Bog, Northwest Bog, East bog, South Bog, and Southwest Bog to determine which area near the open bog area at Camosun Bog experienced the lowest groundwater during the summer months.

To examine spatial patterns in groundwater elevation, a contour plot of groundwater elevation was created in R to show the annual low of 2019, chosen as the day with the lowest mean groundwater elevation for which all sampling locations were sampled (August 31, 2019). Another contour plot of groundwater elevation was created to show the annual high of 2019 (the day with the highest mean groundwater elevation for which all sampling locations were sampled: December 14, 2019).

Finally, historical groundwater elevation from 1990 to 2016 from Brown (2017) and EcoLeaders (1990) was compared to the current 2018-2019 groundwater elevations to examine if there have been changes to groundwater elevation over time. Groundwater measurements were collected from five piezometers from 1990 to 2016 by Brown (2016). The yearly lowest and highest groundwater elevations at each of these piezometers from the year of the earliest available data were compared to the current data from 2019. Data from EcoLeaders (1990) was used to create a contour plot of annual low groundwater elevation sampled at Camosun Bog on August 28, 1990. This contour plot was compared with the contour plot of groundwater elevation from August 31, 2019 to show differences in groundwater elevation between the two time periods.

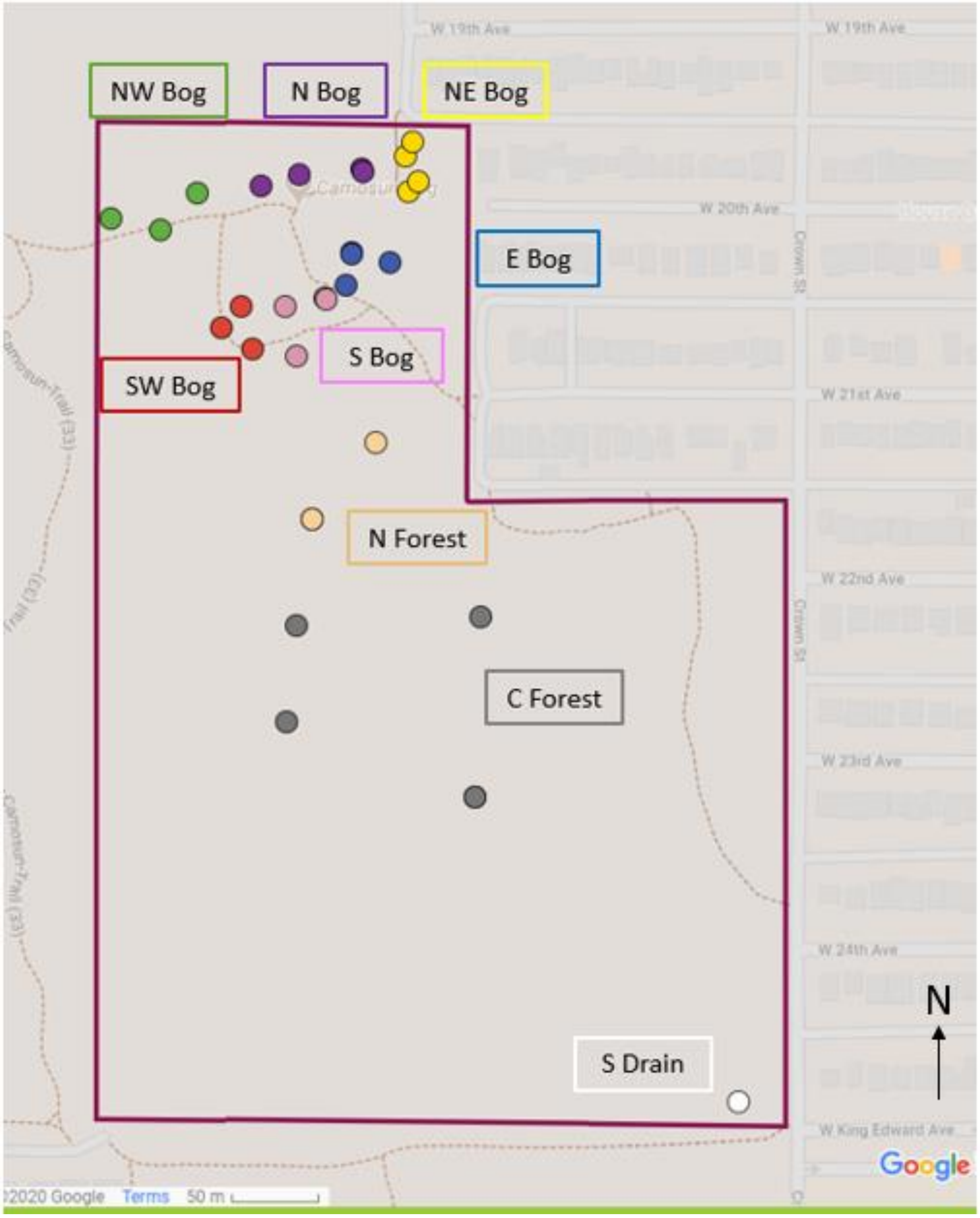


Figure 8 **Map of piezometers in the study area, colour-coded to the region in which they lie (yellow: Northeast Bog, dark purple: North Bog, green: Northwest Bog, Blue: East Bog, light purple: South Bog, red: Southwest Bog, beige: North Forest, grey: Central Forest, white: South Drain). Source: modified from Google Maps (2020).**

Groundwater Chemistry Analysis

To examine trends in the groundwater chemistry variables, time series graphs were visually analyzed for each variable. A Kendall's Tau correlation was done to determine if there was a significant correlation between any of the measured variables at each sampling location. To determine if groundwater chemistry variables were different between sampling locations, a Kruskall-Wallis test and post-hoc Dunn test were used. For all statistical analyses where total ammonia or dissolved orthophosphate were below detection limits in the laboratory analysis I used a value of (detection limit x ½) as recommended by Farnham (2002).

Vegetation Survey Analysis

The percent cover of each vegetation species within each of the eight 3.2 x 3.2 m plots was calculated. The vegetation surrounding each of the eight piezometers (of which the plots were centered around) was broadly classified as either bog or non-bog vegetation. A plot was classified as bog if there was presence of *Sphagnum* moss within the plot, non-bog classification was used if there was no presence of *Sphagnum* moss and there was presence of non-bog vegetation (e.g. western hemlock, salmonberry, ferns).

Results

Groundwater Elevation Results

2018-2019 Groundwater Elevation Results

In general, mean groundwater elevation in 2018 and 2019 showed similar seasonal trends across all bog regions (Figure 9A) and forest regions (Figure 10A), with groundwater elevation reaching annual lows in late summer, and reaching annual highs in winter. Groundwater recharge occurs from September to early January, groundwater depletion occurs from late April to late August, and a static phase in groundwater elevation occurs from January to April. Annual low groundwater elevations in both bog and forest regions coincide with times of the year with higher monthly mean temperature and lower monthly total precipitation (Figure 9B, Figure 10B).

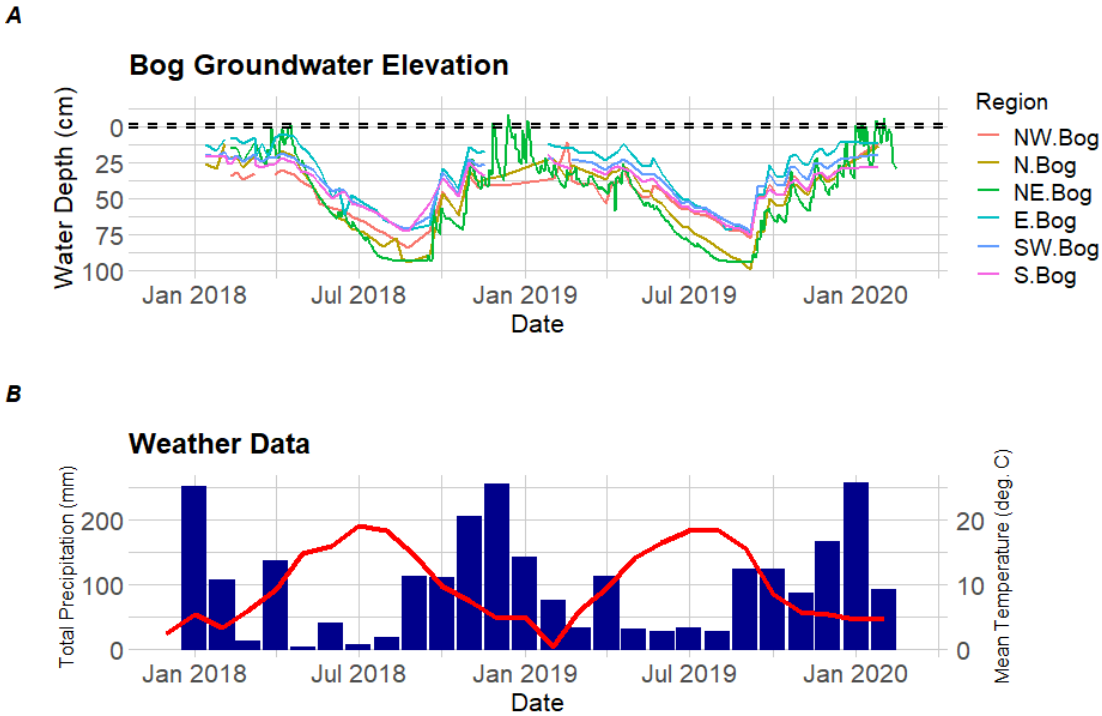


Figure 9 (A) Mean groundwater elevation in bog regions within the study area from January 2018 to February 2020 (see Figure 6 for locations of piezometers/wells within each bog region). Dashed line indicates elevation of the ground surface. Groundwater elevation was sampled every 1-7 days at 1-4 piezometers/wells for each region. (B) Monthly total precipitation (mm) (blue bars) and monthly mean temperature (°C) (red line) from Vancouver International Airport Weather Station from January 2018 to February 2020.

A

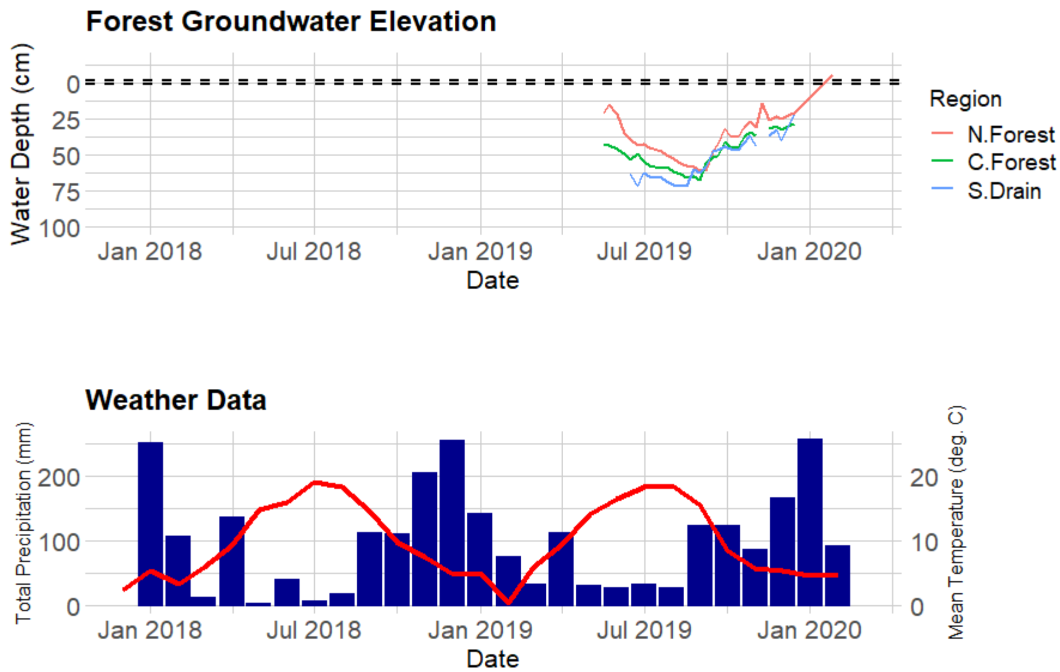


Figure 10 **(A) Mean groundwater elevation in forest regions within the study area from May 2019 to January 2020 (see Figure 6 for lovations of piezometers/wells within each forest region). Dashed line indicates the elevation of the ground surface. Groundwater elevation was sampled every 7 days at 1-4 piezometers/wells for each region. (B) Monthly total precipitation (mm) (blue bars) and monthly mean temperature (°C) (red line) from Vancouver International Airport Weather Station from January 2018 to February 2020.**

Among all six bog regions in 2018 and 2019, the North East Bog region reached its annual low groundwater elevation earliest in the summer (Table 1). Both the North East Bog and North Bog region had the lowest values for annual groundwater lows, with groundwater reaching 93.4 cm and 93.9 cm below the ground surface in 2018, and 93.9 cm and 98.9 cm in 2019 for the North East and North Bog region respectively. The North East Bog region also had the highest annual groundwater elevation in 2018 and 2019 compared to all other regions, with -7.7 cm and -3.8 cm in 2018 and 2019, respectively. Negative groundwater elevation values indicated that groundwater was above the ground surface. The North East Bog region also reached its annual high groundwater elevation earlier (December or early January) in the winter for both 2018 and 2019 compared to the other bog regions, which reached their annual high in late January or

February. In both 2018 and 2019, summer groundwater elevation was the highest in the Southwest Bog region compared to other bog regions.

For the period in which groundwater elevation was measured in 2019 in the forest regions (N. Forest, C, Forest, S. Drain), the South Drain region reached a lower annual low groundwater elevation (72 cm below the ground surface) compared to the other two regions. The South Drain region also reached its annual low elevation earlier in the summer (August 10) compared to the other two regions.

Table 1 Lowest and highest groundwater elevation (cm below ground surface) in 2018 and 2019 and the date at which it occurs for each region within the study area.

Region	2018				2019			
	Low (cm)	Date (MM-DD)	High (cm)	Date (MM-DD)	Low (cm)	Date (MM-DD)	High (cm)	Date (MM-DD)
NW.Bog	84.1	08-25	30.1	04-27	77.8	09-07	11.5	02-16
N. Bog	93.9	08-25	12.0	02-03	98.9	09-07	22.8	02-02
NE. Bog	93.4	08-13	-7.7	12-13	93.9	08-13	-3.8	01-04
E. Bog	72.1	08-25	5.5	04-07	73.5	09-07	10.7	12-14
SW. Bog	70.7	08-25	17.7	02-23	72.4	09-07	21.6	02-02
S. Bog	72.7	08-25	20.5	02-03	75.1	09-07	19.5	01-26
N. Forest	NA	NA	NA	NA	61.2	09-07	-3.3	02-16
C. Forest	NA	NA	NA	NA	67.3	08-31	28.4	12-14
S. Drain	NA	NA	NA	NA	72.0	08-10	22.0	12-14

In pairwise comparisons between seasonal groundwater elevation trendlines for the different bog regions, the North and Northeast Bog regions showed similar trends in groundwater elevation over time, reaching similar annual groundwater low and high values in 2018 and 2019 (Figure 11A). The Northeast Bog region showed significantly lower groundwater elevation in the summer months of 2018 and 2019 compared to the Northwest Bog (Figure 11B), East Bog (Figure 11C), Southwest Bog (Figure 11D), and South Bog regions (Figure 11E). Given that the North and Northeast Bog groundwater trends were very similar, it can be assumed that the groundwater elevation in the North Bog region was also lower than other bog regions. The East Bog region showed similar summer groundwater elevation to the Southwest Bog (Figure 11F), South Bog (Figure 11G), and Northwest Bog (Figure 11H) regions. The Southwest Bog and South Bog regions showed similar groundwater elevation trends across all seasons in 2018 and 2019 (Figure 11I), while the Southwest Bog and Northwest Bog showed similar summer groundwater elevations (Figure 11J).

Contour plots of the spatial distribution of groundwater elevation at Camosun Bog in 2019 during annual low conditions (the maximum extent of groundwater depletion) in August indicated that the northeast corner of the study area experienced the lowest groundwater (about 100 cm below the ground surface) (Figure 12, top). The center of the study area south of West 21st Avenue showed the highest groundwater elevation at this time (about 50-60 cm below the ground surface).

During the 2019 annual high conditions (the maximum extent of groundwater recharge) in December, groundwater elevation was higher in all parts of the study site compared to August (Figure 12, bottom). Sampled groundwater elevation in December ranged from -3 cm to 50 cm below the ground surface, compared the 53 cm to 111 cm in August. There were two areas south of West 21st Avenue with the lowest groundwater elevation in December, and a region slightly to the northeast of these two areas that had the highest groundwater elevation.

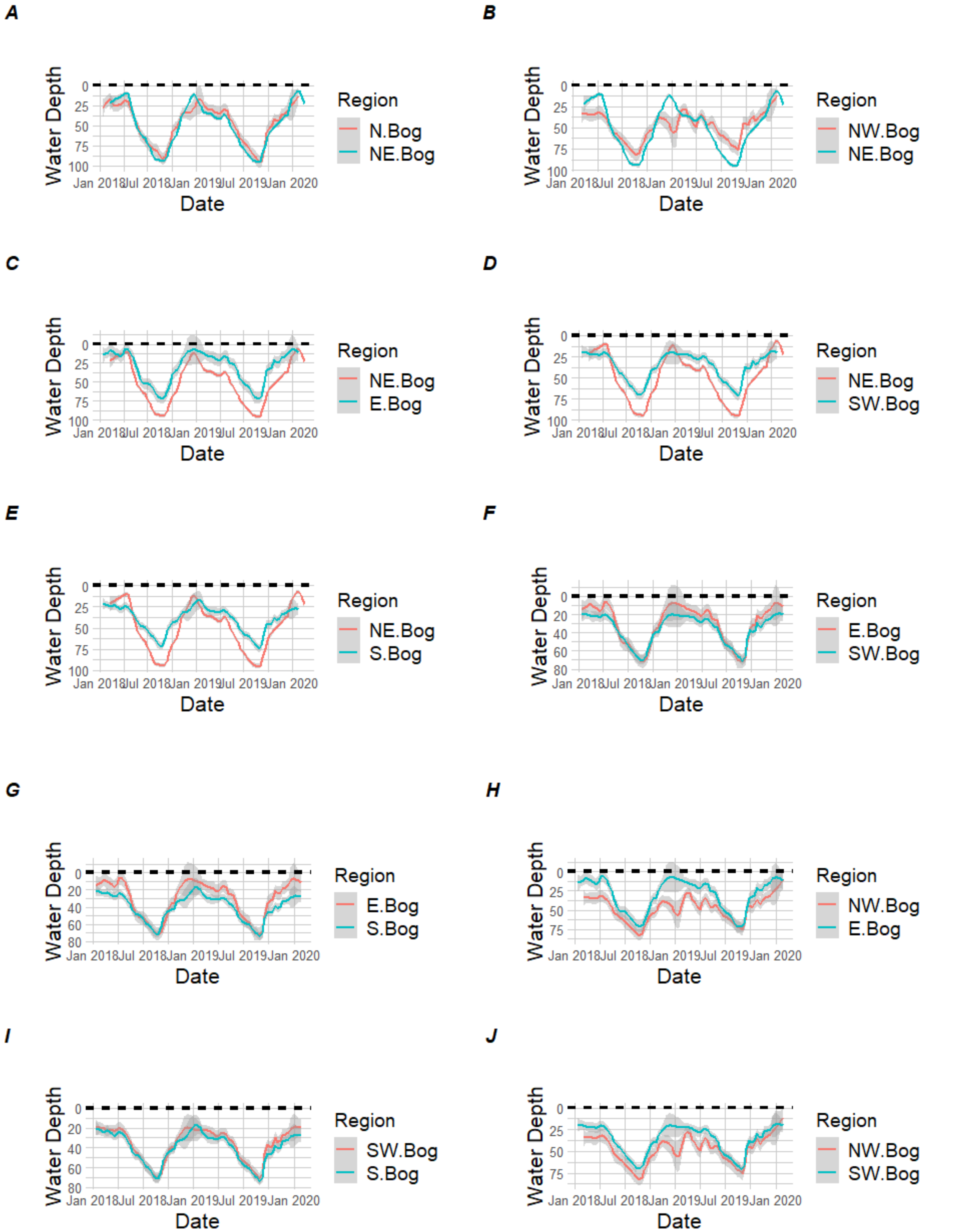


Figure 11 **Water table depth (cm below ground surface) compared between select bog regions within the study area from January 13, 2018 to Jan 26, 2020. Data displayed as smoothed loess trend lines for each region, with 95% confidence bands.**

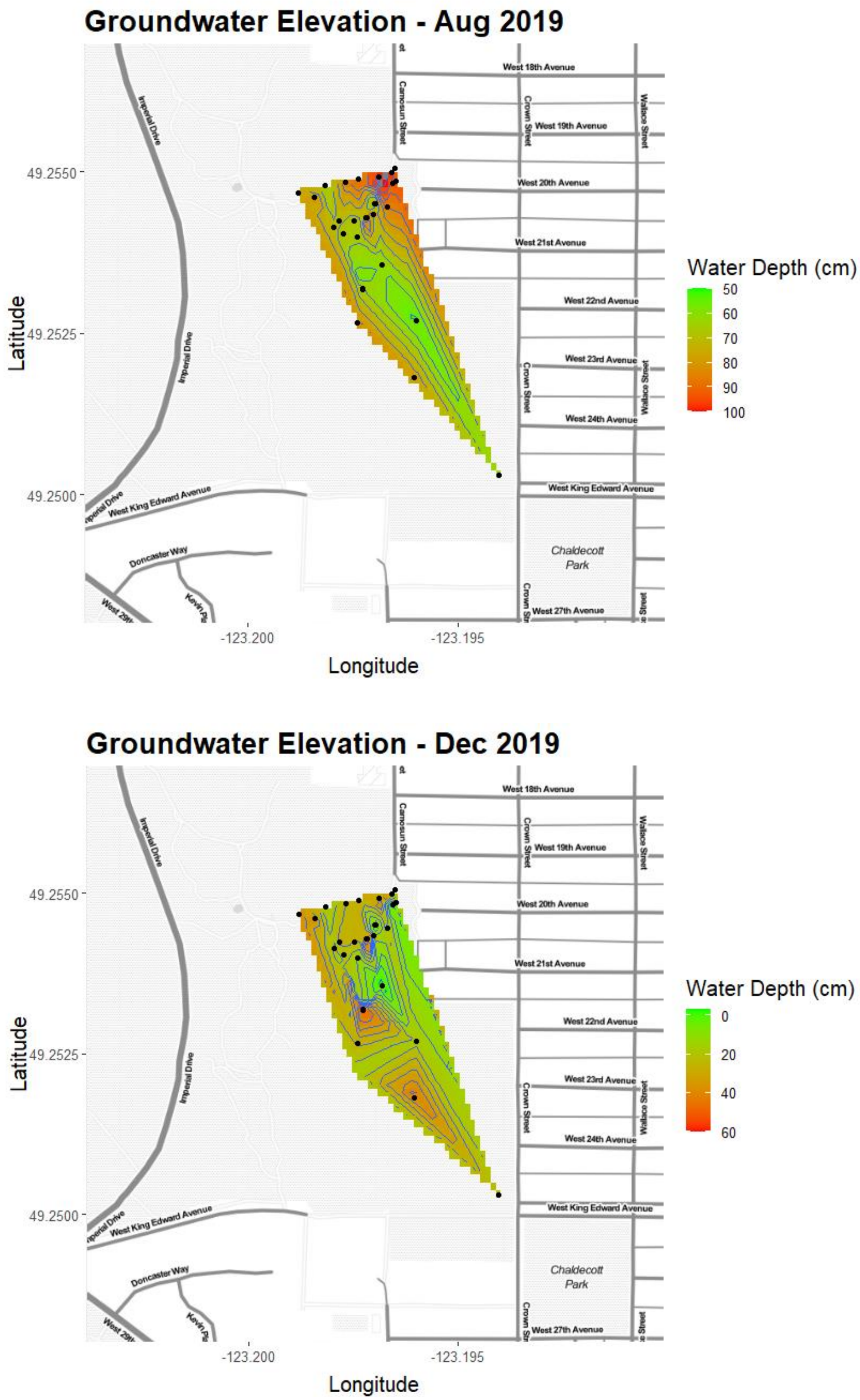


Figure 12 **Contour plots of groundwater elevation at Camosun Bog in 2019, with annual low elevation in August (top) and annual high elevation in December (bottom). Groundwater elevation was interpolated from n=31 piezometers/wells.**

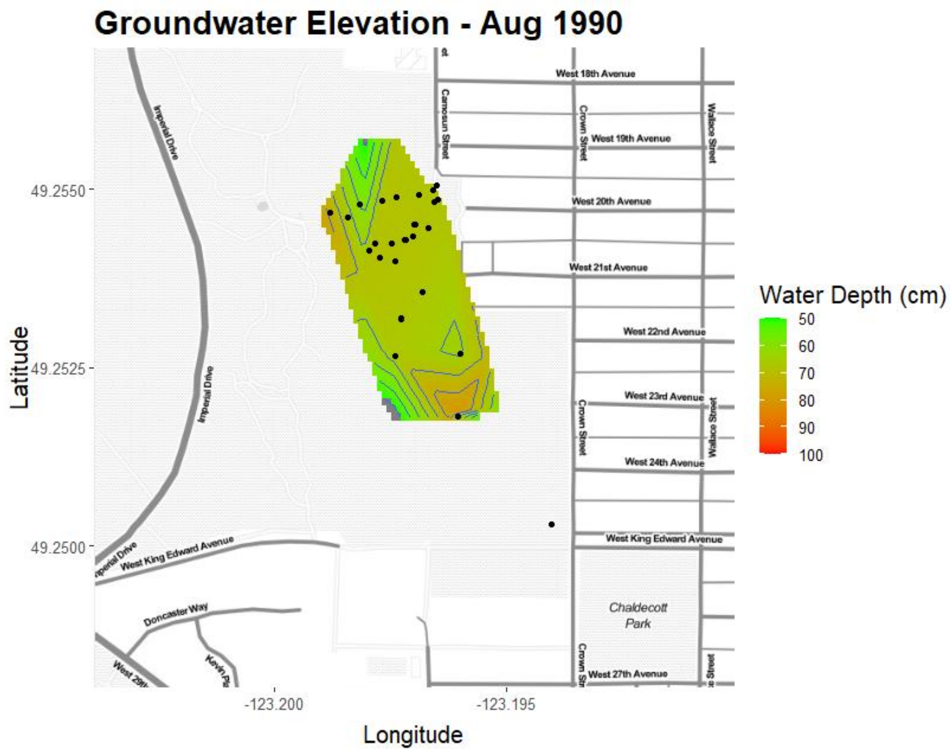
Historical Groundwater Elevation Comparison

For previous years (1990-2016), the annual high groundwater elevation was at or above the ground surface, whereas in 2019, the highest groundwater was below the ground surface (Table 2). The lowest yearly groundwater elevation in 2019 also reached greater depths than it did in all locations except at Piezometer YP.

Table 2 Comparison of lowest and highest groundwater elevation (cm below the ground surface) at 5 piezometers between 2019 and the year of the earliest groundwater collection at each location. Historic data from Brown (2017).

	Past Data			Current Data		
Piezometer	**Year of Earliest Data**	**Lowest ground-water depth (cm)**	**Highest ground-water depth (cm)**	**Year of Current Data**	**Lowest ground-water depth (cm)**	**Highest ground-water depth (cm)**
P12-2	1990	85	-4	2019	99.5	21.9
P9-2	1990	52	-1	2019	71.6	19.5
B9	1998	53	0	2019	73.1	25.7
CTS	2008	43	-10	2019	73.9	16.5
YP	2016	73	-2	2019	58.8	2.1

Contour plots of groundwater elevation in August show that groundwater elevation was higher across sampling locations in 1990 compared to 2019 (Figure 13). In 2019, the northeast region had the lowest groundwater elevation compared to other regions of the study area; however, this region did not show similar low groundwater elevation values in 1990. Compared to 2019, groundwater elevations in August were less variable across sites and had higher groundwater elevations.



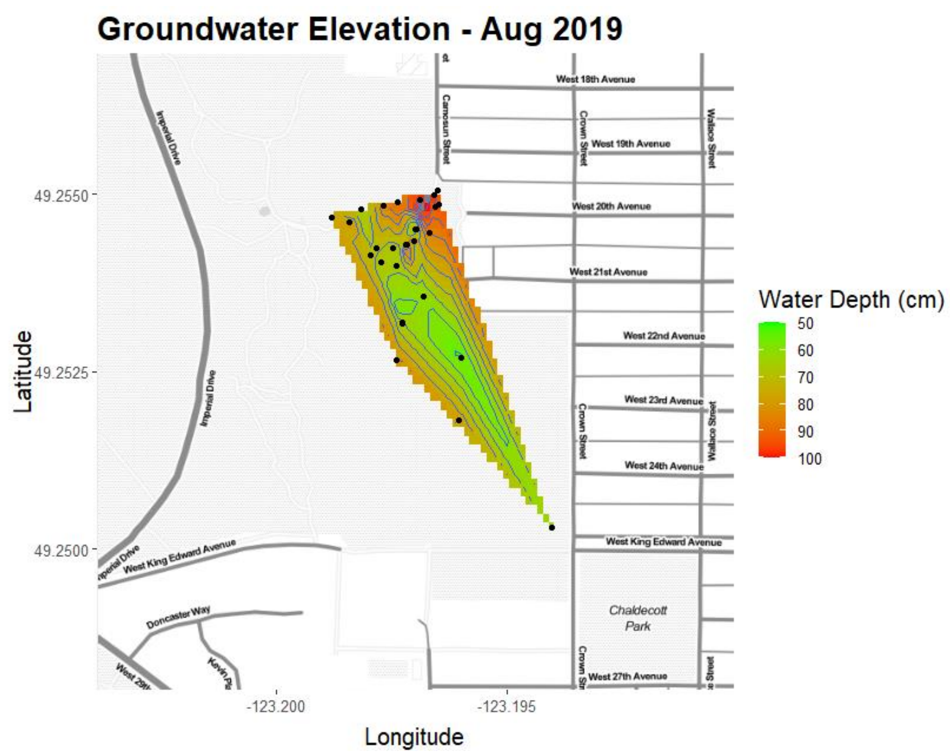


Figure 13 **Contour plots of annual low groundwater elevation at Camosun Bog in August 1990 (top) and August 2019 (bottom). Groundwater elevation was interpolated with n=24 piezometers/wells in 1990 and n=31 in 2019.**

Groundwater Chemistry Results

Groundwater temperature showed a seasonal trend across all sampling locations, with cooler temperatures in spring, fall and winter, and hotter temperatures in the summer (Figure 14A). Mean groundwater temperature across all locations ranged from 9.5 ºC to 11.2 ºC in spring (May June), from 11.0 ºC to 13.0 ºC in summer (June, July, August), from 11.1 ºC to 11.8 ºC in fall (September, October), and from 6.9 ºC to 9.1 ºC in winter (December, January). Other groundwater chemistry variables did not show a significant seasonal trend (Figure 14B-E). Results from the Kendall's Tau Correlation did not show significant correlation among the different water chemistry variables except between groundwater temperature and total ammonia concentration at Piezometer B2 ($r = 0.810$, $p = 0.027$), conductivity and pH at Piezometer C1 ($r = -0.733$, $p = 0.016$), and between pH and ammonia at Piezometer S11 ($r = 9.05$, $p = 0.005$).

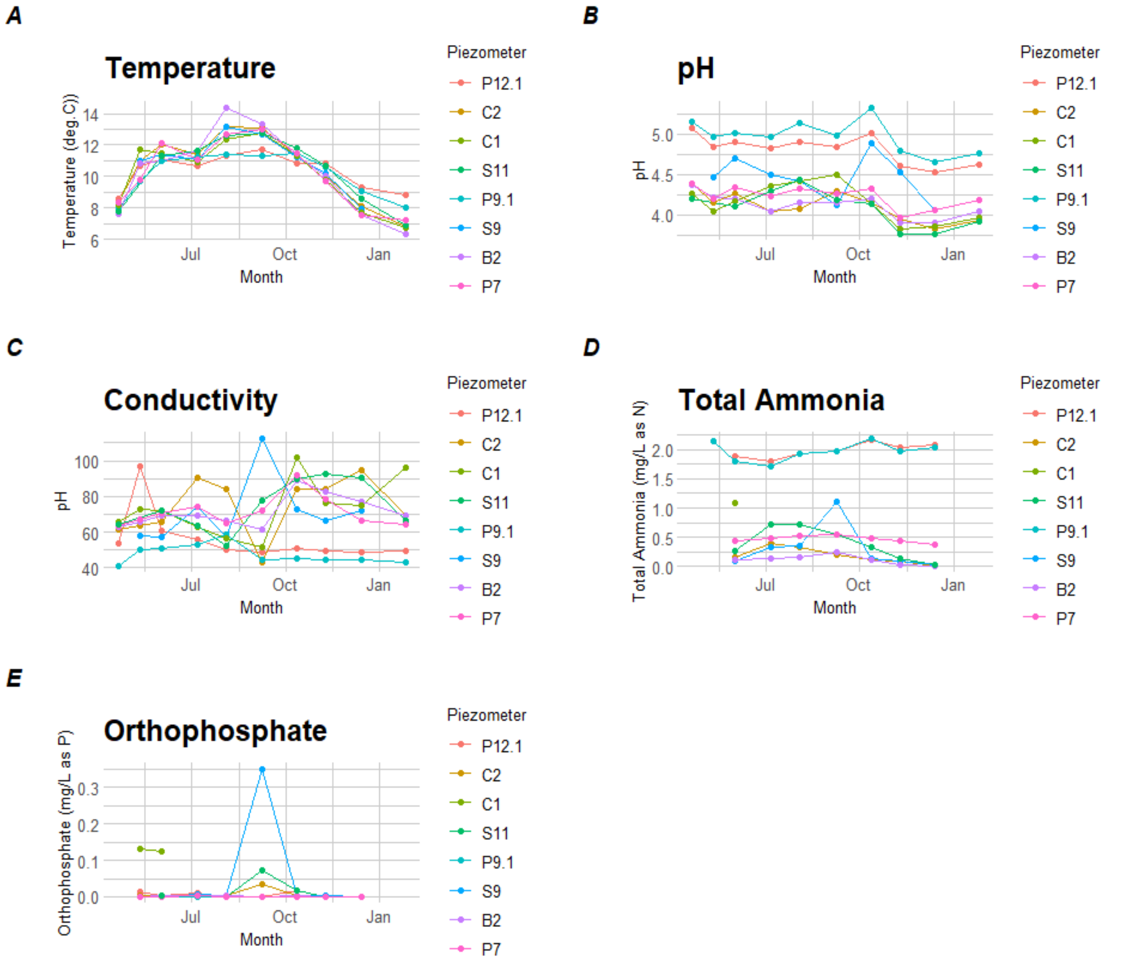


Figure 14 (A) Groundwater temperature (ºC), (B) pH, (C) conductivity (µS/cm), (D) total ammonia concentration (mg/L as N) and (E) dissolved orthophosphate concentration (mg/L as P) at different piezometer locations. Samples taken from April 2019 to January 2020.

Table 3 summarizes the range of values for each groundwater chemistry variable at different piezometer locations over the sampling period. Statistically significant comparisons and corresponding p-values from the Kruskal-Wallis and post-hoc Dunn test are shown in Appendix B: Table 6 for pH, Table 7 for conductivity, Table 8 for total ammonia, and Table 9 for dissolved orthophosphate. Groundwater temperature was not significantly different between piezometer locations.

Table 3 **Ranges of groundwater chemistry variables at different piezometer locations at Camosun Bog sampled monthly (n=1 to 10) from April 2019 to January 2020. See Figure 2.1 for sampling locations. Statistically significant comparisons denoted by non-overlapping lettered superscripts, p-values are found in Appendix B.**

Piezometer	Temperature (deg. C)	pH	Conductivity (uS/cm)	Total Ammonia (mg/L as N)	Dissolved Orthophosphate (mg/L)
P12-1	8.6-11.7	4.53-5.07^{bc}	48.8-96.9^{ab}	1.81-2.16^{b}	<0.001-0.0158^{ab}
C2	6.8-13.2	3.82-4.39^{a}	43.3-94.6^{a}	0.017-0.395^{a}	<0.001-0.0342^{a}
C1	6.7-12.8	3.82-4.50^{a}	51.3-101.7^{a}	1.09^{ab}	0.124-0.131^{a}
S11	6.9-12.8	3.76-4.44^{a}	52.1-92.9^{a}	0.029-0.726^{ab}	<0.001-0.071^{ab}
P9-1	7.9-11.5	4.66-5.33^{c}	41.3-58.7^{b}	1.72-2.19^{b}	<0.001^{b}
S9	7.9-13.2	4.06-4.89^{abc}	57.3-112.4^{a}	0.025-1.10^{a}	<0.001-0.348^{ab}
B2	6.3-14.4	3.91-4.37^{a}	61.4-89.0^{a}	0.014-0.243^{a}	<0.001-0.004^{ab}
P7	7.2-13.0	3.97-4.39^{ab}	63.8-91.6^{a}	0.38-0.546^{ab}	<0.001-0.0019^{ab}

Significant differences between pairs of piezometers/wells in chemical parameters included: pH at Piezometer P9-1 (mean pH of 5.0) was significantly higher than at Piezometer B2 (mean pH of 4.1), Piezometer C1 (mean pH of 4.2), Piezometer C2 (mean pH of 4.1), Piezometer S11 (mean pH of 4.1), and Piezometer P7 (mean pH of 4.2) over the course of the sampling period. pH at Piezometer P12-1 (mean pH of 4.8) was also significantly higher than at Piezometer B2, C1, C2, and S11. Conductivity measurements in Piezometer P9-1 (mean of 47.69 µS/cm) was significantly lower from that in Piezometer B2 (mean of 71.39 µS/cm), Piezometer C1 (mean of 73.19 µS/cm), Piezometer C2 (mean of 74.19 µS/cm), Piezometer P7 (mean of 71.39 µS/cm), Piezometer S9 (mean of 71.49 µS/cm), and Piezometer S11 (mean of 74.39 µS/cm).

Total ammonia concentration was significantly greater at Piezometers P9-1 and P12-1 (mean total ammonia concentration of 1.98 mg/L for both locations) compared to Piezometer B2 (mean of 0.11 mg/L), Piezometer C2 (mean of 0.19 mg/L) and Piezometer S9 (mean of 0.30mg/L). Total ammonia concentration at Piezometer C1 and Piezometer CTS was sampled only once in June 2019, with total ammonia concentrations at 1.09 mg/L and 0.97 mg/L, respectively.

Dissolved orthophosphate concentrations were significantly lower at Piezometer P9-1 (mean of <0.001 mg/L as P) compared to Piezometer C1 (mean of 0.128 mg/L) and Piezometer C2 (mean of 0.007 mg/L). The dissolved orthophosphate concentration at Piezometer P9-1 was measured to be below the lab detection limit of <0.001 mg/L for all sampling dates.

Vegetation Survey Results

Piezometers C1, P9-1, and S9 were located in areas with bog vegetation, whereas piezometers P7, S11, B2, C2, and P12-1 were located in areas with non-bog vegetation (considered to be part of the bog forest) (Table 4).

Table 4 Results of the vegetation survey conducted at eight groundwater chemistry sampling locations. Survey conducted on Oct 13, 2019, plot size = 10m².

Piezometer	Percent Cover (%)	Species (common name)	Species (scientific name)	Bog or Non-bog Region
P7	13	western hemlock	*Tsuga heterophylla*	Non-bog
	1	waved silkmoss	*Plagiothecium undulatum*	
	40	woody debris	NA	
	0.5	bog laurel	*Kalmia polifolia*	
S11	30	salal	*Gaultheria shallon*	Non-bog
	3	spreading wood fern	*Dryopteris expansa*	
	1	salmonberry	*Rubus spectabilis*	
	1	red huckleberry	*Vaccinium parvifolium*	
C1	1	labrador tea	*Rhododendron groenlandicum*	Bog
	1	gray birch	*Betula populifolia*	
	2	bog laurel	*Kalmia polifolia*	
	0.5	rose spirea/hardhack	*Spiraea douglasii*	
	8	haircap moss	*Polytrichum spp.*	
	3	sphagnum moss	*Sphagnum spp.*	
	14	salal	*Gaultheria shallon*	
	2	salmonberry	*Rubus spectabilis*	
P9-1	64	labrador tea	*Rhododendron groenlandicum*	Bog
	48	sphagnum moss	*Sphagnum spp.*	
	19	haircap moss	*Polytrichum spp.*	
	3	salal	*Gaultheria shallon*	
	6	bog laurel	*Kalmia polifolia*	
	3	bog cranberry	*Vaccinium oxycoccos*	

Piezometer	Percent Cover (%)	Species (common name)	Species (scientific name)	Bog or Non-bog Vegetation
B2	3	western hemlock	*Tsuga heterophylla*	Non-bog
	3	salal	*Gaultheria shallon*	
	5	waved silkmoss	*Plagiothecium undulatum*	
	5	red huckleberry	*Vaccinium parvifolium*	
	0.5	spreading wood fern	*Dryopteris expansa*	
	0.5	salal	*Gaultheria shallon*	
	0.5	salmonberry	*Rubus spectabilis*	
S9	4	stairstep moss	*Hylocomium splendens*	Bog
	20	sphagnum moss	*Sphagnum spp.*	
	17	broom moss	*Dicranum scoparium*	
	7	red huckleberry	*Vaccinium parvifolium*	
	1	gilled mushroom	*Agaricales*	
	2	red-stemmed feather moss	*Pleurozium schreberi*	
	2	waved silkmoss	*Plagiothecium undulatum*	
	4	western hemlock	*Tsuga heterophylla*	
C2	3	stairstep moss	*Hylocomium splendens*	Non-bog
	6	oregon beaked moss	*Kindbergia oregana*	
	6	waved silkmoss	*Plagiothecium undulatum*	
	3	spreading wood fern	*Dryopteris expansa*	
	8	woody debris	NA	
	0.5	salal	*Gaultheria shallon*	
	1	red huckleberry	*Vaccinium parvifolium*	
	1	western sword fern	*Polystichum munitum*	
P12-1	36	salal	*Gaultheria shallon*	Non-bog
	1	spreading wood fern	*Dryopteris expansa*	
	0.5	gilled mushroom	*Agaricales*	
	1	oregon beaked moss	*Kindbergia oregana*	
	3	salal	*Gaultheria shallon*	
	2	western hemlock	*Tsuga heterophylla*	

Discussion

Major Findings

My results from 2018 and 2019 indicate that the north and northeast regions of Camosun Bog were drier than other regions (Objective 1). These two regions were also the areas of Camosun Bog closest to the city storm drain at the southern end of Camosun Street and 19th Avenue, and to permeable inorganic fill that was deposited in the area prior to residential development (Pearson 1985). As groundwater is assumed to flow from higher elevations to lower elevations (Dodds and Whiles 2010), my results from 2018-2019 indicate that groundwater from the open bog area at Camosun Bog was flowing out towards the north and northeast direction, potentially into the inorganic fill. These results are consistent with the drainage pattern outlined in previous hydrogeological assessments of Camosun Bog (Jull 1983, Piteau Associates 1989, Dakin 2017).

Current groundwater conditions were drier in 2019 in comparison to historical groundwater elevation data from the 1980s (Marowitch 1982, Jull 1983), and from the monitoring that occurred from 1990 to 2016 (Brown 2017). In piezometers that have historical monitoring records, yearly maximum groundwater elevation was at or above the ground surface. However, maximum groundwater elevation from 2019 did not reach the ground surface, remaining about 20 cm below the ground surface (Table 2). Past assessments have showed a 30-100 cm decline in water table levels at different locations in Camosun Bog in the summer months (Piteau Associates 1989); the results from this project indicate that there is currently a 56-98 cm decline in the water table in the core bog region during the summer months, and a decline of 38-58 cm in the bog forest region in the southern part of the study area (Table 1). Although the maximum value of groundwater depletion has not increased in 2019, the minimum value has, indicating that some areas of Camosun Bog are experiencing more drying during the summer than they have previously.

My groundwater chemistry results show that the groundwater in Piezometer P12-1 and Piezometer P9-1 is experiencing nitrogen nutrient enrichment as indicated by higher total ammonia concentrations (Figure 13) (Objective 2). In undisturbed bog ecosystems, nitrogen is usually the limiting nutrient (Wetzel 2001). However, the results from this project show that dissolved orthophosphate concentrations (the main form of phosphorus in bog ecosystems) is relatively much lower compared the total ammonia concentrations at these two locations. This indicates that phosphorus is the limiting nutrient at those locations instead. The range of ammonia concentrations in bogs in the Northern Hemisphere is 0.01-2.3 mg/L as ammonium (Bourbonniere 2009); however the ammonia concentrations measured at these two locations in Camosun Bog ranged from 1.72-2.19 mg/L as N (or 2.38-3.03 mg/L as ammonium after conversion). This indicates that the nitrogen concentrations present in these two locations are near or exceed the maximum concentrations typical of bog ecosystems.

In addition, both locations of Piezometer P12-1 and P9-1 had pH values of 4.53-5.33, which is higher than other pH values at other sampling locations. Bog water acidity is usually between 4.0-4.8 pH (Gorham and Janssens 1992); this indicates that the pH of groundwater at P12-1 and P9-1 is at times higher than typical values of bog ecosystems.

Although piezometer P12-1 and P9-1 show similarities in their ammonia concentration and pH, the vegetation that surrounds Piezometer P12-1 and P9-1 are not the same. P12-1 is surrounded by forest vegetation that is typical of drier, nutrient rich sites (e.g. hemlock and salal), while P9-1 is surrounded by characteristic bog vegetation (*Sphagnnum* moss, Labrador tea) (Table 4). This suggests that the combination of higher ammonia and pH has persisted at Piezometer P12-1 over a period of time sufficient for non-bog vegetation to establish. P12-1 is also located in the region I classified as North Bog in the groundwater elevation analysis; this area experienced lower groundwater levels compared to P9-1 (that is located in the region I classified as South Bog) (Figure 8).

Given the location of P9-1 in the centre of the bog is surrounded by bog vegetation, and the lack of high ammonia concentrations and pH in the locations sampled around it, it is unclear if there are other factors that contribute to the groundwater conditions at this location. Potential explanations may be that there is an underlying drainage pattern not yet detected that brings in non-precipitation-supplied groundwater from the surrounding residential neighborhood from the east. Additional nitrogen may be supplied from the atmosphere through nitrogen fixation due to the presence of symbiotic microorganisms (diazotrophs) that are found in peat and mosses (van den Elzen et al. 2018). P9-1 could also be in the early phase of becoming enriched in nitrogen, and the vegetation on the ground surface has not yet reflected that change. If this is the case, this may indicate that without significant intervention, bog vegetation at P9-1 may change over time to match that of the non-bog vegetation found at P12-1.

An increase in nitrogen concentration at Camosun Bog has been attributed to the lowering of the water table and an increase in pH, which causes soil aeration and promotes microbial activity and decomposition that release nutrients once stored within the peat soils (Marowitch 1982). Decomposition of peat can also lead to reduction in the water storing capacity of the peat, further promoting groundwater declines and also causing emission of stored carbon dioxide (Quinty and Rochefort 2003). Declines in water table levels from greater aeration of the acrotelm peat layer allow non-bog vascular plants to establish and potentially replace bog vegetation (Milecka et al 2016). Vascular plants also inhibit a bog's ability to accumulate peat by aerating the soil with their roots (Weider and Vitt 2006). Past studies have indicated that groundwater depth is a primary control on the distribution of bog plant species at Camosun Bog (Marowitch 1982) and on the encroachment of the surrounding western hemlock forest (Jull 1983). Should lower water table conditions and higher pH conditions remain, there may be a positive feedback in which soil aeration is promoted, allowing the establishment of nutrient rich plants that further lower the groundwater elevation.

Restoration Measures

To address the third objective of this project, some restoration measures will be discussed that could mitigate the impact of the current groundwater conditions found at Camosun Bog.

Water is the primary factor in determining the occurrence and growth of bog ecosystems (Keddy 2010). This indicates that the main goal of restoration at Camosun Bog is to promote an increase in the groundwater elevation, especially during the summer months when precipitation is low and evaporation is high from an increase in air temperatures. Rewetting techniques are often the most common method of restoration for bogs, as raising the water table close to the ground surface can promote the development of bog plants adapted to wet conditions (Tuittila et al 2000).

Metro Vancouver Regional Parks is currently in the process of constructing a groundwater dam in the northeast corner of Camosun Bog with the intention to inhibit the groundwater flow out of the bog area. Construction began briefly in June 2019 before continuing in October and November 2019. The groundwater dam was not yet complete at the time my study was published. The design of the dam involves overlapping sheets of corrugated plastic hammered into the upper peat layer (Figure 15), with the final dimensions of the dam intended to be 60 m long and 1.2 m deep. The goal of the dam is to reduce the depletion of groundwater in the summer months and retain more water within the bog boundaries. However, given that groundwater elevation dropped to about 1 m below the ground surface in the summer of 2019, the proposed 1.2 m depth of the plastic groundwater dam may need to be extended to better prevent groundwater flow beneath the structure. Most groundwater flow occurs in the acrotelm (Warner and Rubec 1997; Quinty and Rochefort 2003); Camosun Bog the acrotelm depth is about 1.5 m (Dakin 2017). Considering this, the constructed dam may need to be extended to the depth of the acrotelm to restrict the majority of groundwater flow. In addition, alternate materials for the groundwater dam can include wooden planks or metal panels (Landry and Rochefort 2012). A study by Armstrong et al. (2009) indicated that wooden planks were more effective at rewetting peatlands compared to corrugated plastic. Other suitable materials such as non-oxidizing metal sheets, although expensive, are the most durable for dam construction and do not degrade over time (Landry and Rochefort 2012).

An increase in groundwater levels does not always lead to restoration success as it may take years for significant differences in groundwater elevation to be observed (Harenda et al. 2017). Piteau Associates (1991) also noted that limiting drainage may not be sufficient to raise summer groundwater elevations if evaporation and evapotranspiration from vascular non-bog plants continue to exceed precipitation. This indicates that long term monitoring of the effects of the groundwater dam at Camosun Bog is needed to determine its success and if modifications to its design are required.

Figure 15 Photo of groundwater dam construction at the northeast corner of Camosun Bog in June 2019. Shown are sheets of corrugated plastic hammered into the upper peat layer.

Another suitable restoration measure may entail spreading of *Sphagnum* mosses by transplanting them onto prepared sites of peat that lack establishment of bog vegetation (Quinty and Rochefort 2003). This has previously been done by members of the Camosun Bog Restoration Group and could be continued in parts of Camosun Bog with bare peat. In accordance to restoration recommendations set out in the Peatland Restoration Guide, site preparation involves the removal of any crusts formed because of dried peat on the ground surface of the transplant site. Suitable *Spahgnum* mosses (especially of the species *Sphagnum fuscum* and *Sphagnum rubellum)* should be collected and shredded. The size of the collection area should be in a 1:10 ratio to the size of the transplant area. The moss plant fragments should be spread in a thin, continuous layer onto the transplant site. This is restoration method should ideally conducted be in the early spring or fall to avoid the negative impacts of frost formation on moss survival in the winter (Quinty and Rochefort 2003).

Straw mulch spreading is also considered to be an effective restoration method for success in peatland restoration. It aids in protecting newly transplanted mosses and bare peat soil from higher air temperatures and promotes the rewetting of restoration sites (Quinty and Rochefort 2003). The straw is intended to maintain cooler daytime air temperatures and higher humidity for the plant fragments that it covers. Straw is usually spread immediately after the transplant of bog plants because they dry quickly when exposed to air (Quinty and Rochefort 2003). Fresh straw is preferred to straw that has been left outdoors for long periods of time for this restoration method. In addition, caution should be taken to use only certified “Weed-Free” straw to avoid introducing invasive plant species onto the site (Northwest Invasive Plant Council 2012).

Removal of non-bog vegetation is also recommended as the plant litter from this vegetation can introduce more nutrients to the ecosystem during their decomposition, and affect the chemistry of the peat soil it grows on (Weider and Vitt 2006). I observed skunk cabbage in the open bog area of Camosun Bog during the field data collection of this project, but this plant is usually typical of more nutrient rich marsh habitats (Hebda 2014) and should be removed. Past clearing of areas with non-bog vegetation to achieve bare peat surface has led to the successful establishment of *Sphagnum* mosses at Camosun Bog after three years (Brown et al. n.d.). This involved the removal and lowering of peat soil by 5 to 15 cm to effectively raise the groundwater elevation relative the ground surface (Brown et al. n.d.). However, peat only accumulates a depth of 0.5 to 1 mm per year and can release carbon gas once aerated (Quinty and Rochefort 2003). Further removal of peat to raise the groundwater elevation closer to the surface is not recommended as it is not scientifically supportable. Instead, the focus of restoration should be on retaining existing groundwater within Camosun Bog during the summer depletion months.

Overall Conclusion

Overall, the results from this project indicate that current groundwater conditions at Camosun Bog are drier compared to the past (1990-2016), particularly in the northeast region of the bog. Groundwater nitrogen enrichment and high pH is present at two locations near the remaining open bog area, which is atypical of a natural bog ecosystem. These current conditions indicate that the persistence of Camosun Bog is threatened as encroachment of non-bog vegetation and depletion of wet soil conditions will continue to replace bog vegetation uniquely adapted to wet, acidic, and nutrient poor conditions. A restoration project is underway at Camosun Bog with manual placement of a shallow plastic groundwater dam. However, the long-term effects on the structure changing the groundwater conditions is currently uncertain. Given that groundwater elevation dropped to about 1 m below the ground surface in the summer of 2019, the proposed 1.2 m depth of the plastic groundwater dam may need to be replaced with a deeper non-oxidizing metal sheet-pile groundwater dam to better prevent groundwater flow beneath the structure. Further groundwater elevation and chemistry monitoring will be needed to determine restoration success at Camosun Bog.

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Appendix A. Sampling Dates

Table 5 Groundwater elevation sampling dates in 2019 at piezometer/well locations in Camosun Bog with no automated water level loggers.

Sampling Location ID	Sampling Start Date	Sampling End Date
P3	May 8, 2019	December 14, 2019
P5	September 7, 2019	December 14, 2019
P6-1	June 9, 2019	December 14, 2019
P6-2	May 18, 2019	December 14, 2019
P7	May 23, 2019	January 26, 2020
P9-1	May 23, 2019	January 26, 2020
P9-2	May 18, 2019	December 14, 2019
P12-1	May 23, 2019	January 26, 2020
P12-2	May 23, 2019	January 26, 2020
P15	June 16, 2019	December 14, 2019
N7	May 18, 2019	December 14, 2019
N15	May 18, 2019	December 14, 2019
N18	June 23, 2019	December 14, 2019
N23	June 23, 2019	December 14, 2019
S5	May 18, 2019	December 14, 2019
S7	May 18, 2019	December 14, 2019
S8	May 18, 2019	December 14, 2019
S9	May 18, 2019	January 26, 2020
S10	May 18, 2019	December 14, 2019
S11	May 18, 2019	January 26, 2020
B1	May 18, 2019	December 14, 2019
B2	May 23, 2019	January 26, 2020
B9	May 18, 2019	December 14, 2019
C1	May 23, 2019	December 14, 2019
C2	May 23, 2019	January 26, 2020
YP	May 23, 2019	December 14, 2019
CTS	May 18, 2019	December 14, 2019

Appendix B. Groundwater Quality Statistical Outputs

Table 6 **Water chemistry statistical analysis for pH – Dunn Test (post hoc test, p-values adjusted with the Bonferroni method) for pH by Piezometer, with α = 0.05, significant p-values (p<0.05) marked with ** .**

Comparison	Adjusted p-value
B2 - C1	1.000
B2 - C2	1.000
C1 - C2	1.000
B2 - P12.1	0.001**
C1 - P12.1	0.005**
C2 - P12.1	0.001**
B2 - P7	1.000
C1 - P7	1.000
C2 - P7	1.000
P12.1 - P7	0.070
B2 - P9.1	0.0002**
C1 - P9.1	0.0007**
C2 - P9.1	0.0001**
P12.1 - P9.1	1.000
P7 - P9.1	0.013**
B2 - S11	1.000
C1 - S11	1.000
C2 - S11	1.000
P12.1 - S11	0.002**
P7 - S11	1.000
P9.1 - S11	0.0002**
B2 - S9	0.850
C1 - S9	1.000
C2 - S9	0.736
P12.1 - S9	1.000
P7 - S9	1.000
P9.1 - S9	0.979
S11 - S9	0.795

Table 7 Water chemistry statistical analysis for Conductivity – Dunn Test (post hoc test, p-values adjusted with the Bonferroni method) for Conductivity by Piezometer, with α = 0.05, significant p-values (p<0.05) marked with ** .

Comparison	Adjusted p-value
B2 - C1	1.000
B2 - C2	1.000
C1 - C2	1.000
B2 - P12.1	0.282
C1 - P12.1	0.175
C2 - P12.1	0.137
B2 - P7	1.000
C1 - P7	1.000
C2 - P7	1.000
P12.1 - P7	0.181
B2 - P9.1	0.007**
C1 - P9.1	0.004**
C2 - P9.1	0.003**
P12.1 - P9.1	1.000
P7 - P9.1	0.004**
B2 - S11	1.000
C1 - S11	1.000
C2 - S11	1.000
P12.1 - S11	0.136
P7 - S11	1.000
P9.1 - S11	0.003**
B2 - S9	1.000
C1 - S9	1.000
C2 - S9	1.000
P12.1 - S9	0.728
P7 - S9	1.000
P9.1 - S9	0.031**
S11 - S9	1.000

Table 8 Water chemistry statistical analysis for Total Ammonia – Dunn Test (post hoc test, p-values adjusted with the Bonferroni method) for Total Ammonia by Piezometer, with α = 0.05, significant p-values (p<0.05) marked with ** .

Comparison	Adjusted p-value
B2 - C1	1.000
B2 - C2	1.000
C1 - C2	1.000
B2 - P12.1	0.001**
C1 - P12.1	1.000
C2 - P12.1	0.005**
B2 - P7	0.756
C1 - P7	1.000
C2 - P7	1.000
P12.1 - P7	1.000
B2 - P9.1	0.0003**
C1 - P9.1	1.000
C2 - P9.1	0.003**
P12.1 - P9.1	1.000
P7 - P9.1	0.985
B2 - S11	1.000
C1 - S11	1.000
C2 - S11	1.000
P12.1 - S11	0.166
P7 - S11	1.000
P9.1 - S11	0.119
B2 - S9	1.000
C1 - S9	1.000
C2 - S9	1.000
P12.1 - S9	0.011**
P7 - S9	1.000
P9.1 - S9	0.006**
S11 - S9	1.000

Table 9 **Water chemistry statistical analysis for Dissolved Orthophosphate – Dunn Test (post hoc test, p-values adjusted with the Bonferroni method) for Orthophosphate by Piezometer, with α = 0.05, significant p-values (p<0.05) marked with ** .**

Comparison	Adjusted p-value
B2 - C1	1.000
B2 - C2	1.000
C1 - C2	1.000
B2 - P12.1	1.000
C1 - P12.1	1.000
C2 - P12.1	1.000
B2 - P7	1.000
C1 - P7	0.079
C2 - P7	0.149
P12.1 - P7	1.000
B2 - P9.1	0.567
C1 - P9.1	0.020**
C2 - P9.1	0.018**
P12.1 - P9.1	0.683
P7 - P9.1	1.000
B2 - S11	1.000
C1 - S11	1.000
C2 - S11	1.000
P12.1 - S11	1.000
P7 - S11	0.429
P9.1 - S11	0.068
B2 - S9	1.000
C1 - S9	0.540
C2 - S9	1.000
P12.1 - S9	1.000
P7 - S9	1.000
P9.1 - S9	1.000
S11 - S9	1.000