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Research Article

Potential Influence of Climate Change on the Acid-Sensitivity of High-Elevation Lakes in the Georgia Basin, British Columbia

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Global climate models predict increased temperature and precipitation in the Georgia Basin, British Colmbia; however, little is known about the impacts on high-elevation regions. In the current study, fifty-four high-elevation lakes (754–2005 m a.s.l.) were studied to investigate the potential influence of climate change on surface water acid-sensitivity. Redundancy analysis indicated that the concentration of nitrate, dissolved organic carbon, and associated metals was significantly influenced by climate parameters. Furthermore, these components differed significantly between biogeoclimatic zones. Modelled soil base cation weathering for a subset of the study lakes ($n = 11$) was predicted to increase by 9% per 1°C increase in temperature. Changes in temperature and precipitation may potentially decrease the pH of surface waters owing to changes in anthropogenic deposition and organic acid production. In contrast, increased soil base cation weathering may increase the critical load (of acidity) of high-elevation lakes. Ultimately, the determining factor will be whether enhanced base cation weathering is sufficient to buffer changes in natural and anthropogenic acidity. Mountain and high-elevation regions are considered early warning systems to climate change; as such, future monitoring is imperative to assess the potential ramifications of climate change on the hydrochemistry and acid-sensitivity of these surface waters.

1. Introduction

It is widely accepted that changes in climate may significantly alter the biological, physical, and chemical systems of mountainous regions [1–3]. Their potentially dramatic response has been attributed to the pronounced rise in temperature (1.5–2.0°C during 1980 to 1995) in high-elevation regions compared with the global average (0.5°C; [4]) and to the influence of changes in glacier, ice, and snow cover [5]. Accordingly, mountain and high-elevation regions are considered as early warning systems, providing valuable insight into the potential hydrological and ecological responses owing to climate [1].

A range of potential impacts on the hydrogeochemistry of high-elevation and alpine aquatic ecosystems have been reported. It has been suggested that altered hydrological flushing rates and residence times, and increased inputs of nutrients and other solutes may cause the acidification of surface waters [6, 7]. Soil mineral weathering rates [8] and the amount and duration of snowpack are also expected to vary [9]. Experimental climate change treatments in regions of the Rocky Mountains, USA, have shown that changes in snow pack cover significantly influence the mineralization rate of both nitrogen (N) and carbon [10]. These changes in nutrient hydrogeochemistry have been associated with altered plant community competition, species dominance, and their geographical range [11].

The Georgia Basin, located in southwestern British Columbia, Canada, is dominated by four mountain ranges. Few studies have focused on the high-elevation lakes and catchments that scatter this region. One recent study [12], however, indicated that these lakes ($n = 72$) are sensitive to acidification and that 18% currently receive sulphur (S) deposition in excess of their critical load of acidification (CL(A)). The study also suggested that precipitation and the cover of glacier and ice significantly influenced the pH and acid neutralizing capacity (ANC) of these lakes. Temperature and precipitation are predicted to increase in the Georgia Basin [13, 14]; it is uncertain how the hydrogeochemistry of these catchments will respond.

Although it is difficult to predict the impacts of climate change on the hydrogeochemistry of high-elevation and alpine ecosystems, an attempt to understand the potential implications of changes in temperature and precipitation may aid in the protection (or rehabilitation) of these systems. The objective of this study, therefore, was to evaluate which chemical components of these ecosystems are significantly influenced by temperature and precipitation and how climate change may influence the acid-sensitivity of these high-elevation catchments. Potential changes in lake chemistry, according to biogeoclimatic zone, were assessed based on a recent survey of high-elevation lakes [12]. In addition, weathering rates under increased temperature were estimated for a subset of catchments using the PROFILE model [15].

2. Methods

2.1. Study Area. The Georgia Basin encompasses 48 000 km^2 and is surrounded by four mountain ranges: the Olympic Mountains, Vancouver Island Ranges, the Coast Ranges, and the Cascades. The area receives high levels of precipitation especially along the coastal regions as a result of orographic precipitation. Modelled precipitation amounts (Parameter Elevation Regressions on Independent Slopes Model (PRISM) [16]) range from 400 to almost 5000 mm yr^{-1} for the 30-year climate normals (1961–1990). The basin encompasses seven biogeoclimatic zones (regions characterized as having specific climate, soil, and vegetation communities): Coast Douglas Fir (CDF), Coastal Western Hemlock (CWH), Mountain Hemlock (MH), Interior Douglas Fir, Engelmann Spruce-subalpine Fir, and Coastal and Interior Mountain-heather Alpine (AT) zones ([17]; Figure 1). Air temperature within these zones varies greatly, with mean annual temperatures (MAT) ranging from 10.5°C in the low elevation CDF zone to −4.0°C in the high altitude AT zone [17].

During October 2008, 72 lakes were sampled within the Georgia Basin and 54 were classified as high-elevation (>750 m) lakes (Figure 1). The lakes were chosen based on lithology, the majority of the lake catchments being dominated by the rock types of granodiorite and quartz diorite, both characterized by low buffering capacity and low mineral weathering rates. The elevation of the study lakes ranged between 754 and 2005 m a.s.l. with 72% of the lakes ≥ 1000 m a.s.l. The lakes were characterised by low conductivity (median = 6.0 μS cm^{-1} at 25°C) and low base cation and nutrient concentrations (Table 1), typical of the dilute nature of high-elevation lakes. Twenty percent of the study lakes had pH < 6 and 24% had ANC (estimated as the difference between the sum of base cations and the sum of acid anions in μeq L^{-1}) below 20.0 μeq L^{-1} (Table 1). The lakes were classified as sensitive to acidic atmospheric deposition [12] and for many of the same reasons are considered to be sensitive to climate change.

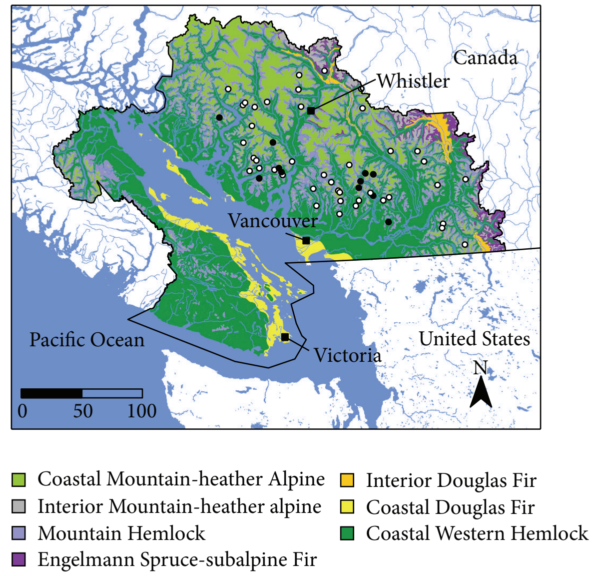


Figure 1: Location of the Georgia Basin, British Columbia, Canada (delineated by bold black line). The study lakes (n = 54) are denoted by circles while major cities are denoted by filled squares. Filled circles are indicative of sites where both water and soil samples were collected (n = 11). The major biogeoclimatic zones within the Georgia Basin are also shown.

2.2. Field Sampling and Laboratory Analysis

2.2.1. Water Sampling. Water samples were collected centre-lake from a float-equipped Bell 206 helicopter in October 2008. Positions were logged using a Garmin 76S global positioning unit. Surface water conductivity, pH, and temperature were measured *in situ* using a Yellow Springs Instrument Model 6600 sonde. Near-surface water samples were collected in precleaned plastic bottles and kept cool during shipment to laboratories (within approximately 24 hours). Water samples were analyzed for pH, major anions and cations, dissolved organic carbon (DOC), and metals. A summary of methods used for all water chemistry analysis and quality assurance/quality control procedures is given by Strang et al. [12].

2.2.2. Soil Sampling. Soil samples were collected at two depths (0–15 cm and 15–30 cm) from a subset of the lake sites (n = 11) between 2006 and 2008 using a soil auger; at each lake catchment three distal plots were established and composite soil samples were collected by auger from four points by depth. Soil bulk density and volumetric moisture content were measured by soil core following de Vos et al. [21]. Soil samples were air-dried, sieved to <2 mm, and analysed for particle size (sand, silt, and clay) using a Horiba Partica LA-950; soil surface area was calculated from particle size following Warfvinge and Sverdrup [15]. Soil organic matter content was estimated as loss on ignition (LOI), which was determined by igniting samples in a muffle furnace at 450°C for 8 hours. Quantitative mineralogy was determined for site composited soil samples (n = 11, composite of plot and

Table 1: Selected chemical characteristics of study lakes ($n = 54$) in the Georgia Basin, British Columbia, sampled during October 2008 (P25 refers to the 25th percentile while P75 refers to the 75th percentile; ANC = acid neutralizing capacity and DOC = dissolved organic carbon).

Variable	Mean	Min.	P25	Median	P75	Max
Conductivity (μS cm^{-1} at 25°C)	6.50	2.00	4.00	6.00	8.00	18.0
ANC (μeq L^{-1})	47.7	10.6	20.9	41.5	72.0	159
NO_3^- (μeq L^{-1})	1.82	0.01	0.29	0.87	2.44	8.64
SO_4^{2-} (μeq L^{-1})	8.86	0.44	5.21	7.91	10.2	42.5
Ca^{2+} (μeq L^{-1})	39.5	8.08	19.7	35.2	55.9	119
Na^+ (μeq L^{-1})	13.7	4.92	9.98	13.5	17.1	27.4
Mg^{2+} (μeq L^{-1})	6.64	1.32	3.21	5.06	9.22	29.8
K^+ (μeq L^{-1})	3.15	1.07	1.69	2.36	3.56	14.0
DOC (mg L^{-1})	1.15	0.00	0.46	0.74	1.54	7.22
pH	6.34	5.44	6.12	6.22	6.70	7.12
Al (μg L^{-1})	59.9	8.00	20.7	35.8	77.0	337
Pb (μg L^{-1})	0.05	0.00	0.02	0.03	0.06	0.66

depth samples) by X-ray powder diffraction using a Siemens (Bruker) D5000 Bragg-Brentano diffractometer under the Rietveld method [22]. The percentage of plagioclase (determined by X-ray diffraction) consisting of albite and anorthite was set at 65% and 35%, respectively, based on previous studies in the Georgia Basin [23]. Weathering rate for each study site ($n = 1$) was calculated using the PROFILE (version 5.1) steady-state soil chemistry model, which is driven by soil mineralogy, bulk density, mineral surface area, and moisture content [15]. PROFILE has been widely used in Europe and North America to estimate weathering rates [24–26]. Model application and data inputs followed Aherne et al. [27] and Mongeon et al. [28].

2.3. Catchment Data. Catchment boundaries for the study sites were delineated from a digital elevation model (DEM: 1 : 20 000, BC Ministry of Environment) using a geographic information system (GIS). Land cover data for each catchment were delineated from the 1 : 250 000 Baseline Thematic Mapping (version 2, BC Ministry of Environment), which was compiled from Landsat 7 imagery. Catchment lithology was obtained from the digital geology map of BC (1 : 250 000, BC Ministry of Energy, Mines and Petroleum Resources). Long-term mean annual precipitation (MAP) and MAT data were estimated by PRISM at a 4 km by 4 km grid resolution [16]. The biogeoclimatic zone of each study site was assigned using a digital map of biogeoclimatic zones for the region (1 : 20 000; BC Forest Service Forest Science Program). Future climate forecasts (i.e., temperature and precipitation) were taken from the CGCM2 model developed by the Canadian Centre for Climate Modelling and Analysis [19] under the Intergovernmental Panel on Climate Change (IPCC) A2 scenario (continued population and temperature rise, increasing atmospheric CO_2 concentrations [20]). Climate forecasts were downscaled (400 m by 400 m resolution) to each study lake using the ClimateBC model and obtained from Wang et al. [18]. Annual average total (wet and dry) anthropogenic S and N deposition for the period 2005-2006 was obtained from the Community Multiscale Air Quality (CMAQ [29]) model at a 4 km by 4 km grid resolution.

2.4. Data Management and Statistical Analysis. Lake chemical variables with observations < detection limit (DL) and deemed pertinent to the objective of the study (i.e., nitrate (NO_3^-) and DOC) were assigned random values between 0 and the analytical DL for the variable, following standard data imputation techniques.

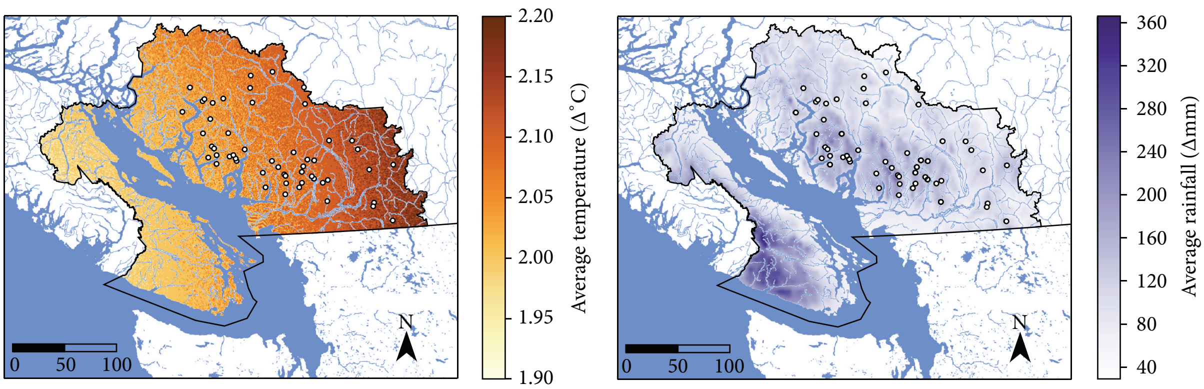
All statistical analyses were conducted using STATISTICA 7.0 and XLStat software; alpha values were set at 0.05. Redundancy analysis (RDA) was used to evaluate which lake chemical variables were significantly influenced by temperature and precipitation. Redundancy analysis is a multivariate technique similar to principal component analysis but explains the variance of the dependent variables by a linear combination of predictor variables [30], and it has been widely used in hydrogeochemical studies (e.g., [31–33]). Variables that were not normally distributed were log-transformed to ensure normality; however, parameters that remained non-normal (primarily land cover and geology characteristics) were retained in the analysis due to the robustness of the RDA statistic and the importance of these parameters to lake water chemistry. Differences in lake chemistry between biogeoclimatic zones were evaluated to explore how the hydrogeochemistry of high-elevation aquatic ecosystems might respond to climate change, as these zones are characterized by different temperature and precipitation regimes ([17]; Table 2). The nonparametric Kruskal-Wallis test was used to determine which chemical variables differed significantly between biogeoclimatic zones; only variables found to be significantly different were reported in detail.

3. Results and Discussion

3.1. Climate Change in the Georgia Basin. The CGCM2 model predicted that both air temperature and precipitation will increase in the Georgia Basin under the IPCC A2 scenario; the average increase in mean temperature from present day at the study catchments was 1.1, 2.1, and 3.4°C for the years 2020, 2050 (Figure 2, [18]) and 2080, respectively. Increases in precipitation were predicted at 82, 143, and 239 mm (2.4, 4.2, and 7.0%) for 2020, 2050 (Figure 2, [18]) and 2080,

Table 2: Elevation, climate, vegetation, and soil characteristics of the Coastal Western Hemlock (CWH), Mountain Hemlock (MH), and Mountain-heather Alpine (AT) biogeoclimatic zones in the Georgia Basin, British Columbia [17]. (MAT = mean annual temperature, MAP = mean annual precipitation, and MMT = mean monthly temperature).

Biogeoclimatic zone	Elevation (m)	Climate	Dominant vegetation communities	Soil regime
CWH	900–1050	MAT = 8°C MAP = 1000–4400 mm MMT >10°C for 4–6 months	Western hemlock (*Tsuga heterophylla*), amabilis fir (*Abies amabilis*), yellow cedar (*Callitropsis nootkatensis*)	Humoferric podzols, ferrohumic podzols
MH	900–1800	MAT = 0–5°C MAP = 1700–5000 mm MMT <0°C for 1–5 months and >10°C for 1–3 months	Mountain hemlock (*Tsuga mertensiana*), amabilis fir (*Abies amabilis*), yellow cedar (*Callitropsis nootkatensis*)	Podzols, folisols
AT	>1650	MAT = −4–0°C MAP = 700–3000 mm MMT <0°C for 7–11 months	Primarily treeless	Orthic Regosols, Humic Regosols



(a) (b)

Figure 2: Predicted average temperature (a) and precipitation (b) delta increase for the Georgia Basin, British Columbia, between present day and 2050 [18]. Predictions based on model outputs from the CGCM2 model [19] under the IPCC A2 scenario [20]. The study lakes (n = 54) are depicted as white open circles.

respectively. Although general circulation models provide valuable insight into future climate scenarios, precision in estimating temperature and precipitation is limited owing to the complex topography of mountainous regions [1]. Furthermore, most meteorological stations in the Georgia Basin are located close to sea level; therefore estimates may be biased towards lower elevation regions [34]. The CGCM2 projections, however, were in good agreement with those released by the IPCC in their Fourth Assessment Report [35].

3.2. Climate Change and Its Influence on Lake Water Chemistry. Changes in temperature and precipitation regimes in the Georgia Basin will undoubtedly influence the chemical composition of high-elevation lakes and the biogeochemical processes governing solute input and output within catchments. Therefore it is important to evaluate which chemical components of freshwater ecosystems are heavily influenced by temperature and precipitation. Redundancy analysis indicated that several chemical variables were significantly influenced by temperature and precipitation; two axes accounted for over 86% of the variance in the water chemistry data (Figure 3). The first axis (accounting for >62% of the variance) was dominated by climate related variables (i.e., air temperature (0.828) and precipitation (0.422)). Modelled sulphur deposition was also heavily weighted on the first axis (0.718) accounting for anthropogenic influences (Figure 3); however, because of its strong relationship with precipitation and air temperature it was classified as a climate parameter. Deposition is highly influenced by precipitation [36, 37], with greater deposition found in areas with large amounts of precipitation owing to elevated "wash-out" or the "seeder-feeder" effect in mountainous regions [6, 38, 39]. Similarly, higher temperatures influence the conversion of SO_2 to SO_4^{2-}, thereby increasing the concentration in wet deposition [36]. The second axis, accounting for approximately 24% of the variance, represented differences in land cover (e.g., forested area (0.469) and alpine area (−0.484)).

Lake chemical parameters that were primarily related to climate characteristics were NO_3^- (0.995), DOC (0.882), potassium (K^+: −0.637), pH (−0.967), antimony (Sb: 0.731), cobalt (Co: 0.854), copper (Cu: 0.442), and lead (Pb: 1.188; Figure 3). Parameters that were primarily related to land

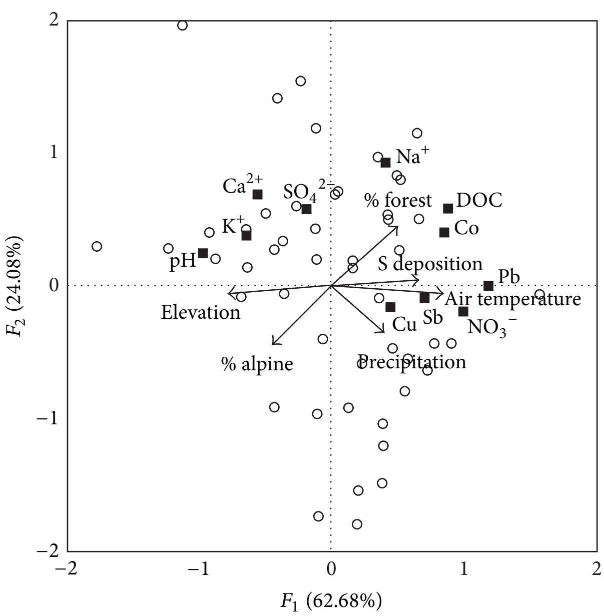


Figure 3: Redundancy analysis biplot for water chemical parameters in study lakes in the Georgia Basin, British Columbia. Black solid lines represent the explanatory variables (elevation, precipitation, air temperature, S deposition = sulphur deposition, % alpine = % alpine land cover, and % forest = % forested land cover) and black solid squares represent the water chemistry variables. (Note: several water chemistry variables were grouped together in the biplot to improve visual presentation: Cu = copper, NO_3^- = nitrate, Sb = antimony, Pb = lead, Co = cobalt, surface water temperature, DOC = dissolved organic carbon, aluminum, manganese, Na^+ = sodium, silicon, Ca^{2+} = calcium, conductivity, magnesium, acid-neutralizing capacity, strontium, SO_4^{2-} = sulphate, vanadium, barium, alkalinity, pH = pH, field pH, K^+ = potassium, phosphorus, and uranium.) Open circles represent the study lakes.

Table 3: Mean values of the chemical characteristics of study lakes in each of the AT (n = 18), CWH (n = 16), and MH (n = 20) biogeoclimatic zones. Chemical parameters that differ significantly are indicated by bold lettering. Where differences lie is indicated by superscripts "a," "b," and "c" (e.g., elevation: the AT zone is significantly different than both the CWH and the MH zone; the CWH zone is significantly different than the MH zone).

Variable	Biogeoclimatic zone		
	CWH	MH	AT
ANC (μeq L^{-1})	40.9	54.2	46.3
NO_3^- (μeq L^{-1})	3.77^a	1.23^b	0.68^b
SO_4^{2-} (μeq L^{-1})	7.88	9.01	9.87
Ca^{2+} (μeq L^{-1})	34.8	43.6	38.9
DOC (mg L^{-1})	2.00^b	1.17^b	0.39^a
Mg^{2+} (μeq L^{-1})	6.12	7.34	6.31
K^+ (μeq L^{-1})	2.31	3.44	3.57
Na^+ (μeq L^{-1})	15.9^b	15.0^b	10.2^a
pH	6.07^a	6.45^b	6.46^b
Si (μg L^{-1})	827^b	813^b	560^a
Al (μg L^{-1})	110^b	53.4^b	21.8^a
Sb (μg L^{-1})	0.03	0.02	0.02
Co (μg L^{-1})	0.04^a	0.02^b	0.01^b
Cu (μg L^{-1})	0.27^a	0.18^b	0.20
Mn (μg L^{-1})	2.57^b	1.62	1.10^a
Pb (μg L^{-1})	0.11^b	0.04^b	0.02^a
Mean annual air temperature (°C)	6.36^b	4.37^c	2.87^a
Elevation (m)	887^b	1242^c	1514^a
Nitrogen deposition (kg ha^{-1} yr^{-1})	10.4^b	8.48	5.80^a
Sulphur deposition (kg ha^{-1} yr^{-1})	5.38^a	3.61^b	2.72^b
Precipitation (mm yr^{-1})	3617	3488	3218
% Forested	56.4^b	39.3^b	0.72^a
% Ice and glacier	0.35^b	0.69^b	6.87^a
% Alpine	23.1^b	35.4^b	73.8^a

cover characteristics were sulphate (SO_4^{2-}: 0.588), calcium (Ca^{2+}: 0.690), and sodium (Na^+: 0.935; Figure 3). It is important to note, however, that the two land cover types (alpine and forested), although treated separately from climate parameters, are significantly influenced by differences in temperature and precipitation. In general, low temperature (higher elevation) catchments are dominated by alpine land cover whereas catchments with higher temperatures have a greater proportion of forested land cover.

Biogeoclimatic zones within mountains are characterized by different vegetation, MAT, MAP, and soil properties ([17]; Table 2); climate change is predicted to alter the range and size of these zones [40–42] and influence the chemistry of high-elevation lakes. The 54 study catchments were located across three biogeoclimatic zones: MH, CWH, and AT (Figure 1). Many of the chemical parameters that were strongly influenced by temperature and precipitation were also found to be significantly different between these three zones. The Kruskal-Wallis test indicated that NO_3^-, DOC, pH, Co, Cu, and Pb lake concentrations were significantly different between zones (Table 3).

The relationship between DOC and temperature has been reported in many studies [43, 44]; DOC decreased significantly from the CWH biogeoclimatic zone (2.00 mg L^{-1}) through the MH zone (1.17 mg L^{-1}) with its lowest concentrations found in the AT zone (0.39 mg L^{-1}; $H_{2,54} = 27.53$, $P < 0.05$; Table 3). Along with temperature, the RDA analysis indicated that DOC concentrations were significantly weighted on the amount of forested land cover within the lake catchment (0.589; Figure 3). Most of the DOC in lakes is derived from surrounding soils or wetlands [45]. Accordingly, lakes draining catchments primarily dominated by thin soils or bare rocks typically have low DOC concentrations [46, 47]. The percent of forested land cover between the biogeoclimatic zones differed significantly and decreased from the CWH zone (56.4%) through the MH zone (39.3%) with lowest values located in the AT zone (0.72%; $H_{2,54}$ = 36.24, $P < 0.05$; Table 3).

Lakes in the AT biogeoclimatic zone will potentially have the most significant change in DOC concentrations as a result of climate change. Krannitz and Kesting [41] predicted that tree lines will migrate upwards into the AT zone under future climatic conditions; some researchers have suggested that a 1°C increase in temperature will result in a 150–200 m elevational increase in forested land [48]. This encroachment into the AT zone may result in elevated DOC concentrations as a result of increased nutrient cycling [9], terrestrial productivity, and leaf litter production [49, 50]. Increased DOC in surface waters could lead to shifts in biological species composition [51] due to changes in nutrient and light regimes [46]. Changes in the DOC concentrations of the CWH and MH biogeoclimatic zones may also be observed under increased warming due to projected increased terrestrial productivity in the MH zone [52] and decreased wetland area in the CWH zone [53].

Climate change induced fluctuations in DOC can alter metal concentrations in surface waters as many metals are transported to surface waters through complexation processes with DOC [46]. In particular, metals such as manganese (Mn), aluminium (Al), Pb, Cu, and Co are highly associated with DOC [54, 55]. Metal concentrations in the surface waters of high-elevation lakes in the Georgia Basin are quite low ([12]; Table 1); nonetheless, metals in the 54 study lakes follow the same pattern of DOC. Lakes located in the AT biogeoclimatic zone had lower levels of metals compared with the MH and CWH zones (Table 3). Specifically, significant differences ($P < 0.05$) in Al ($H_{2,54} = 23.39$), Co ($H_{2,54} = 21.32$), Cu ($H_{2,54} = 6.92$), Mn ($H_{2,54} = 11.71$), and Pb ($H_{2,54} = 18.49$) were observed. Under higher precipitation and temperature regimes, the toxicity of metals to aquatic organisms could be enhanced [56]. The AT biogeoclimatic zone may also experience increased DOC and metal concentrations owing to the significantly higher proportion of ice and glacier cover within the AT zone (6.87%), compared to the CWH (0.35%) and MH (0.69%) zones ($H_{2,54} = 16.91$, $P < 0.05$; Table 3). Increased runoff from the melting of alpine glaciers [7] has been reported in high-elevation lakes in the European Alps [57] and increased runoff may further dilute lakes. Recent estimates suggest that, with increased temperature, glaciers in BC may disappear within the next 100 years [58].

Surface water NO_3^- concentrations were heavily weighted on the first axis of the RDA (Figure 3), indicative of the strong influence climatic parameters have on the cycling of N in the Georgia Basin. Nitrate concentrations were found to be significantly different between the three biogeoclimatic zones with the CWH zone having significantly greater concentrations than the MH and AT zones (3.77 μeq L^{-1}, 1.23 μeq L^{-1}, and 0.68 μeq L^{-1}, resp.; $H_{2,54} = 17.19$, $P < 0.05$; Table 3). The influence of increased temperature and precipitation on N dynamics is difficult to determine as many climatic, biological, and physical processes govern the cycling of N in ecosystems and the expected time scale of such changes has yet to be determined [59]. In the current study, statistical analysis of NO_3^- suggests that temperature and precipitation play an integral role in the N dynamics of high-elevation catchments.

Park et al. [60] in their study of watersheds in Northeast Asia found that NO_3^- concentrations in stream waters were the greatest during periods of high rainfall. They attributed this finding to the increased wet deposition of N resulting from increased wash-out in precipitation, also supported by Williams et al. [6, 61] in their study of high-elevation catchments in the Colorado Front Range, USA. Although not significant, in the Georgia Basin, precipitation differed between the three biogeoclimatic zones with the CWH zone having greater MAP than the MH and AT zones (3617 mm yr^{-1}, 3488 mm yr^{-1}, and 3218 mm yr^{-1}, resp.; Table 3). Modelled N deposition, however, did vary significantly with the CWH zone receiving significantly greater deposition (10.4 kg ha^{-1} yr^{-1}) than the MH (8.48 kg ha^{-1} yr^{-1}) and AT (5.80 kg ha^{-1} yr^{-1}) zones ($H_{2,54} = 9.57$, $P < 0.05$; Table 3). Changes in precipitation volume, seasonality, and N oxides (NO_x) emissions under future conditions may potentially lead to increased N deposition and elevated NO_3^- concentrations in high-elevation lakes in the Georgia Basin. However, in a recent report by Metro Vancouver [62], NO_x emissions are projected to decrease until 2020 but are then predicted to remain stable (at approximately 45 kilotonnes yr^{-1}) due primarily to increased marine traffic in southwest British Columbia.

Higher temperatures may intensify NO_3^- leaching from catchment soils owing to increased rates of N mineralization by soil microbes [37, 63]. Increased nitrification rates have been observed in the Catskill Mountains of New York under increased temperature resulting in greater leaching of NO_3^- into surface waters [63]. Several studies have suggested that increased NO_3^- transport has resulted in episodic and chronic acidification of acid-sensitive surface waters [37, 64]. In the Georgia Basin, surface waters in the AT biogeoclimatic zone may be most influenced by increased temperature induced NO_3^- leaching because of its present low temperatures and low NO_3^- concentrations compared to the CWH and MH zones.

In contrast, enhanced N assimilation by terrestrial plant life may limit NO_3^- entering aquatic systems through soil leaching and runoff [47, 59, 65]. Nitrogen is a limiting nutrient for terrestrial systems and if future projections of increased terrestrial productivity occur in the AT and MH biogeoclimatic zones [41, 52], NO_3^- export to surface waters may be alleviated by the increased demand by alpine and subalpine vegetation. However, when the demand for N is reached or exceeded, NO_3^- concentrations in surface waters are hypothesised to increase [61, 66].

Accurately predicting the response of N and DOC to climate change is arguably more difficult than other chemical constituents in surface waters because of the extremely complex interactions with biological, physical, and climate related systems. It is therefore important that increased monitoring and research be carried out in high-elevation and alpine environments.

3.3. Climate Change and Its Influence on Soil Base Cation Weathering Rates. Weathering rates in alpine and high-elevation catchments are typically very low because of their thin soils, low temperatures, highly resistant bedrock, and small catchment to lake ratios [67–70]. Water residence times in alpine and high-elevation soils also tend to be quite low, decreasing the contact time between water and weatherable

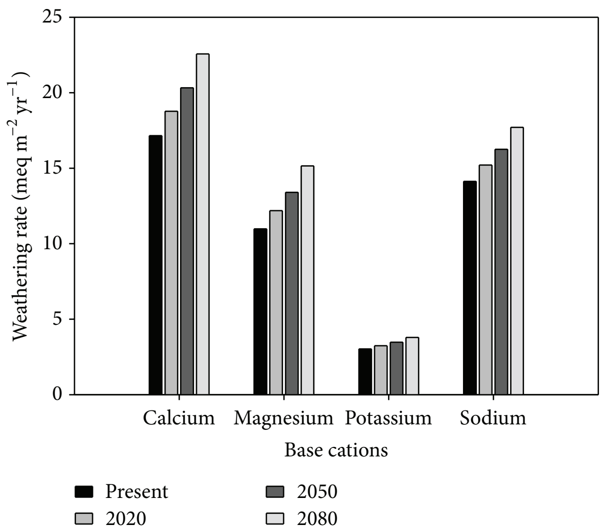


Figure 4: Average PROFILE weathering rates for calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+}) for soil study sites ($n = 11$) under present day and future climate change conditions in the Georgia Basin, British Columbia. Future weathering rates were based on temperature increases of 1.1°C, 2.1°C, and 3.4°C for the years 2020, 2050, and 2080, respectively.

minerals [68]. Studies in the Swiss Alps have shown decreased weathering rates with increasing altitude [68]. Similarly, a study by Mongeon et al. [28] at 19 sites in the Georgia Basin suggested that weathering rates were the lowest at the highest elevations, owing to their shallow soils and low quantities of easily weatherable minerals. Similarly, in the present study, lake concentrations of Na^{+} and silicon (Si; typically associated with weathering rates) were significantly different between the three biogeoclimatic zones. The high-elevation AT biogeoclimatic zone had significantly lower Na^{+} and Si concentrations than the MH and CWH zones ($H_{2,54} = 12.51$, $P < 0.05$ and $H_{2,54} = 10.01$, $P < 0.05$, resp.; Table 3), indicative of lower weathering rates. As a result, mountain lakes are typically very dilute and sensitive to climate change [71].

Increased soil base cation weathering rates with higher temperature have been widely reported [15, 59, 72, 73]. In the current study, PROFILE was used to estimate future weathering rates for the 11 high-elevation study catchments in the Georgia Basin (9 located in the MH biogeoclimatic zone and 2 located in the CWH biogeoclimatic zone) under predicted average temperature increases of 1.1°C, 2.1°C, and 3.4°C for 2020, 2050, and 2080. In all three simulations, estimated weathering rates increased from present day conditions, with total base cation flux estimated to increase by 9.1% in 2020, 18% in 2050, and 30.7% in 2080 (Figure 4). The approximately 9% increase per 1°C in temperature is consistent with previous studies [73, 74]. The importance of temperature on mineral weathering rates has been debated; while laboratory studies show a strong dependence on temperature, field studies are often obscured by other environmental factors that covary with temperature [75]. Nonetheless, several studies have reported field-based temperature dependence on natural weathering [73, 76]. In the current study, Ca^{2+} was the dominant weathered element, followed by Mg^{2+}, Na^{+}, and K^{+} (Figure 4). This may be the result of the high concentrations of calcic-plagioclase in the catchments (average of 13.2%) which is considered extremely unstable and, as such, is easily weathered [77].

Mineral weathering ultimately depends on soil mineralogy, and chemical kinetics dictate that the dissolution rate of minerals per unit surface area is temperature dependent [78]. Moreover, the active mineral surface area is influenced by soil moisture and acidity [79]. In the current study, other climate-related controls on weathering rates, such as soil moisture [73, 78], could potentially offset increases due to temperature; however, soil moisture (on an annual basis) is not expected to change much under A2 climate change in the Georgia Basin given the increase in precipitation (Figure 2). Higher temperatures will not only accelerate the dissolution of minerals from bedrock and soils [23, 59] but will also promote the production of organic acids that can further influence base cation weathering rates [80]. Predicted decreases in glacier, ice, and snow cover will expose greater proportions of soil and bedrock to climatic parameters and freeze-thaw cycles [81, 82]. Recently exposed bedrock is considered to be extremely reactive and thus extremely sensitive to chemical weathering [8].

In the Central Alps, Rogora et al. [59] have suggested that the recent increase in solute concentrations of high-elevation lakes can be attributed to the increased transport of weathered minerals associated with higher temperatures, lower snow cover, and enhanced weathering rates. Greater export of base cations from catchments to lakes will alter the chemical composition of surface waters such as ANC [83] and may modify the acid-sensitivity of surface waters.

3.4. Climate Change and Its Influence on the Acid-Sensitivity of High-Elevation Lakes. Determining how climate change will affect the acidity and acid-sensitivity of high-elevation lakes is difficult as other factors aside from climate parameters (i.e., land cover, lithology) play an integral role. A recent study on the acidity of high-elevation lakes in the Georgia Basin ($n = 72$) indicated that 20% of the study lakes had pH levels less than 6 [12]. In the present study, results from the RDA analysis indicated that pH was primarily attributed to climatic parameters (−0.967; Figure 2). As such, differences in surface water pH between the biogeoclimatic zones were observed with the CWH zone having significantly lower pH levels (6.07) than the MH (6.45) and AT (6.46) biogeoclimatic zones ($H_{2,54} = 9.14$, $P = 0.01$; Table 3).

The pH of high-elevation lakes has been reported to decrease with increasing elevation [68]. The increase in pH with elevation in the Georgia Basin has been attributed to the lower levels of atmospheric (S and N) deposition at higher elevations as well as the decreased production of acidic organic anions [12]. Modelled N and S deposition were greater in the lower elevation CWH zone and decreased significantly through the higher elevation MH and AT zones ($H_{2,54} = 9.57$, $P < 0.05$ and $H_{2,54} = 17.25$, $P < 0.05$, resp.; Table 3) in concert with DOC concentrations. As such, natural acidification resulting from increased terrestrial productivity and organic acid production [37] may play an important role, especially in the MH and AT zones. Furthermore, with increased warming, surface waters located in the AT zone may experience episodic acidification resulting from NO_3^- inputs from melting glaciers and runoff from catchment soils [3, 37].

It has been suggested that surface water pH and ANC in the Georgia Basin are significantly influenced by the amount of ice and glacier cover in the surrounding catchment with greater pH and ANC occurring in glacier dominated catchments [12]. Glacial melt waters have been shown to be high in base cation concentrations [84]. Increasing temperatures will alter the natural dynamics of glacier accumulation and recession [85] potentially altering the pH, ANC, and CL(A) of these surface waters through the increased transport of base rich glacial melt waters. Another result of retreating glaciers and decreasing snowpack is the greater proportion of the lake catchments becoming exposed and, consequently, influenced by weathering processes [59, 81, 82]. Higher temperatures and precipitation leading to increased weathering have been directly linked to the increased transport of base cations and other solutes from catchments to surface waters [59, 72, 86]. Weathering rates in the Georgia Basin were predicted to increase under future climate conditions and such increases may alter the CL(A) of high-elevation lakes in this region.

The critical load of acidity was developed to characterize the sensitivity of surface waters to acidification from atmospheric deposition. It is defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" [87]. In the Georgia Basin, approximately 18% of the lakes surveyed ($n = 72$) received S deposition in excess of their CL(A) [12]. Critical loads are influenced by climate change and previous studies have suggested that increased temperature and precipitation lead to increased CL(A) [88]. Accordingly, the number of lakes currently exceeding their CL(A) in the Georgia Basin may decrease; the determining factor will be whether enhanced weathering of base cations from the catchment soils and bedrock are sufficient to buffer changes in natural acidity and anthropogenic inputs from atmospheric S and N deposition.

4. Conclusions

It is difficult to predict how the hydrochemistry of surface waters will be influenced by climate change. Temperature and precipitation are expected to increase based on the CGCM2 model under the IPCC A2 scenario. These increases may potentially result in significant changes in the chemical composition of surface waters in high-elevation regions of the Georgia Basin.

Biogeoclimatic zones are characterized by a specific range of temperature and precipitation regimes; based on the current chemical composition of lakes in each of these zones, changes in DOC (associated trace metals) and NO_3^- will most likely be observed, resulting from increased terrestrial productivity and greater runoff originating from melting glacier and snow cover. Such changes could alter the pH of surface waters through the natural acidification process associated with organic acid production and by episodic acidification. Base cation weathering rates were predicted to increase under future climate. The greater flux of these elements into surface waters may influence the acid-sensitivity of high-elevation lakes in the Georgia Basin. The ratio between increased transport of base cations into surface waters, deposition levels, and increased acidifying components from organic anion production will ultimately determine whether lakes will continue to be susceptible to acidification.

Future monitoring is essential in assessing the sensitivity of high-elevation lakes to climate change both in the Georgia Basin and in mountainous regions worldwide. Increased monitoring efforts are imperative in developing accurate estimates of temperature and precipitation changes in these complex topographical regions and the potential ramifications of climate change on the acid-sensitivity of high-elevation surface waters.

Conflict of Interests

The authors declare that no competing interests exist.

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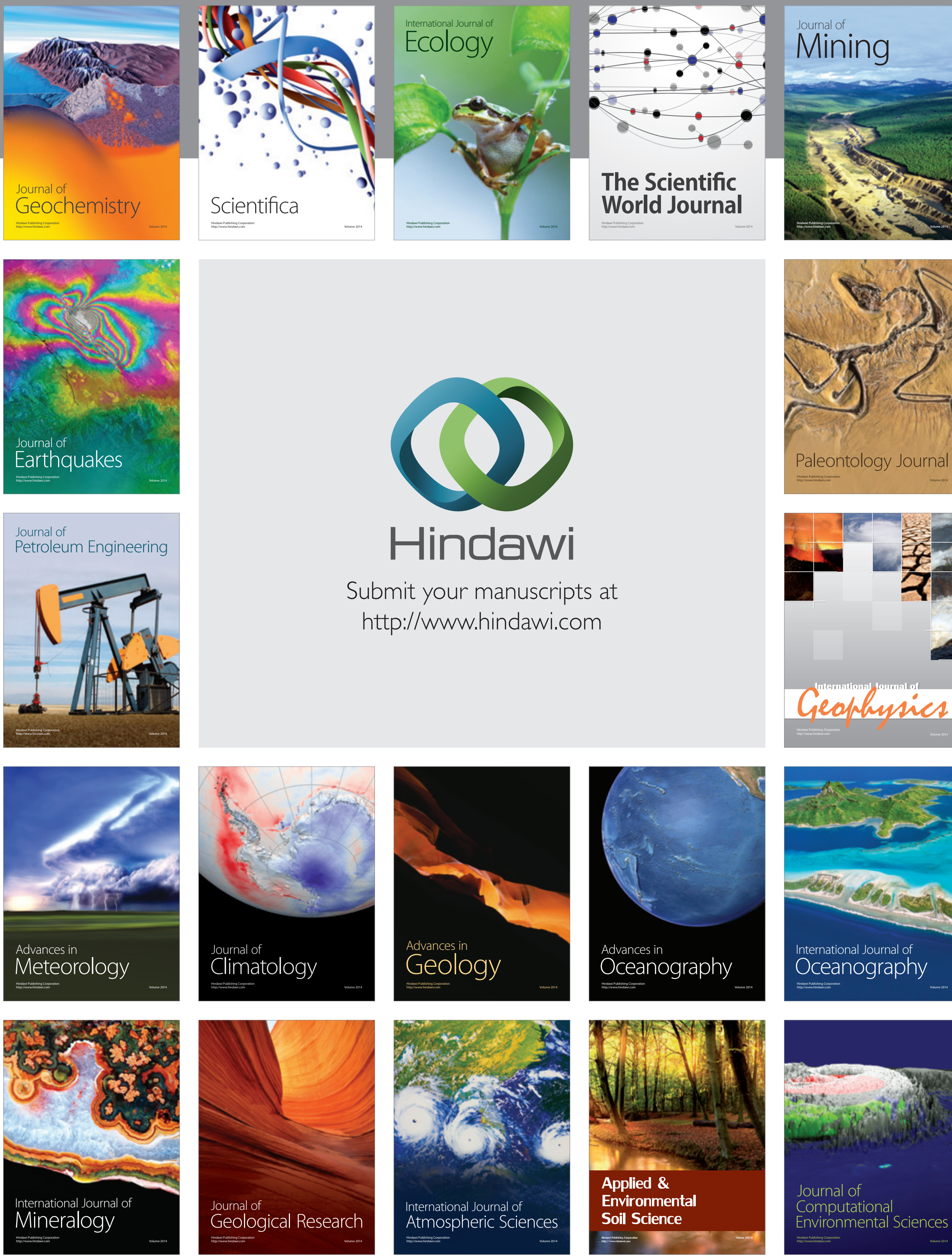
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