Spatiotemporal nutrient loading to Cultus Lake: Context for eutrophication and implications for integrated watershed-lake management

by

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Abstract

Cultus Lake, British Columbia experiences significant anthropogenic nutrient loadings and eutrophication. If continued unabated, these stresses threaten the persistence of two resident species at risk (coastrange sculpin and Cultus Lake sockeye salmon) and the many ecosystem services provided by the lake. We constructed water and nutrient budgets for the Cultus Lake watershed to identify major sources of nitrogen and phosphorus loadings to the lake. A steady-state water quality model calibrated against current nutrient loadings and limnological data was then used to explore water quality changes in response to various scenarios of nutrient loading to the lake. Atmospheric deposition was a major source of both nitrogen and phosphorous, agriculture was a large source of nitrogen, and septic leaching and migratory gull guano were major phosphorous sources to Cultus Lake. Future loading scenarios suggest that Cultus Lake may become mesotrophic in response to unmitigated increases in projected nutrient loadings from gull guano, septic leaching, agricultural intensification, and atmospheric deposition, highlighting the need to abate phosphorus loading to the lake. Although mitigating phosphorous sources such as gull guano and septic leaching will slow the eutrophication of Cultus Lake, a reduction in atmospheric phosphorus deposition from the regional airshed will be necessary to halt or reverse eutrophication and protect the ecosystem services and species at risk habitat provided by the lake.

Keywords: Cultus Lake; Coastrange sculpin (Cultus population); eutrophication; integrated watershed management; nutrient budget; sockeye salmon (Cultus population)

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1. Introduction

Lakes and watersheds in proximity to urban centres may experience intensive recreational, residential, and commercial use with commensurate impacts on water quality and aquatic resources (e.g., eutrophication, habitat degradation, overexploitation; Carpenter et al. 1998, Smith et al. 1999). Watershed-scale integrated management requires cooperation among residents, businesses, land developers, local and regional governments, and other watershed stakeholders to develop long-term management plans for land and aquatic resources at the watershed scale that reflect all community interests (Saravanan et al. 2009, Ghadouani and Coggins 2011). Given the cultural and socioeconomic importance of many lake-derived ecosystem services (e.g., fisheries, recreation, drinking water, irrigation), conserving lake water quality and ecosystem integrity is crucial to sustainable future use (Wilson and Carpenter 1999, Baron et al. 2002). In particular, eutrophication combined with the cumulative effects of other stressors (e.g., overexploitation, invasive species, pollution, habitat destruction), and a changing climate can threaten lake ecosystems and their associated ecosystem services, making broad-scale integrated management essential to sound watershed planning (Schindler 2001, Moss 2012).

Cultus Lake, British Columbia, Canada is situated near the major urban centre of Vancouver and is currently experiencing eutrophication and associated water quality degradation (Shortreed 2007). The lake is adjacent to intensive agricultural activities, transportation corridors, and industries in the Lower Mainland and in Whatcom County, USA. Cultus Lake is a prized recreational and residential area of significant socioeconomic importance to the region, and it also hosts two endemic species at risk: the threatened coastrange sculpin (*Cottus aleuticus,* also known as the Cultus Lake pygmy sculpin; COSEWIC 2010) and endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka;* COSEWIC 2003). Water quality is known to be a contributory factor to the risk of extinction for Cultus Lake sockeye salmon and the coastrange sculpin, with eutrophication having the potential to disrupt physical, biological, and chemical aspects of their freshwater habitat (Schubert et al. 2002, COSEWIC 2010, 2003, Chiang et al. in press). Hypolimnetic oxygen depletion during stratification has doubled in Cultus Lake since the 1920's and 1930's (Shortreed 2007), likely resulting from the deepwater aerobic decomposition of increasing organic matter loading to the profundal zone of the lake. In addition, increased algal turbidity and decreased water clarity associated with eutrophication may reduce the contributions of metalimnetic production to the lake food web, forcing cold water fish in Cultus Lake to forage for zooplankton in epilimnetic waters where temperatures during summer are deleterious to their growth and survival (Brett 1971, Schubert et al. 2002, Chiang et al. in press).

Eutrophication will also likely negatively impact many of the ecosystem services derived from Cultus Lake (cultural, recreational, and aesthetic), affecting tourism and impairing local economies. Algal productivity increases and the proliferation of cyanobacteria can result in decreased water clarity and unsightly mats of algae that reduce aesthetic and tourism values and may be toxic to humans and animals (Aylward et al. 2005, O'Neil et al. 2012). Eutrophication-enhanced growth of littoral macrophytes, including the invasive Eurasian watermilfoil (*Myriophyllum spicatum*), may also decrease recreational values and are a nuisance for recreational boaters (Dodds et al. 2009), while altered food webs driven by changing algal composition can impair recreational fisheries (Mossop and Bradford 2004, Aylward et al. 2005). The Cultus Lake watershed has over 1,000 permanent residents and 2 to 3 million visitors each year (FVRD 2011, Delcan 2012), and preserving these ecosystem services through sound integrated watershed management is critical for sustainable future use and enjoyment of the lake.

The population in the Lower Mainland of British Columbia is expected to grow substantially in the next 25 years (increasing by 47%; BC Stats 2013, FVRD 2004), and visitation to Cultus Lake will likely increase proportionally (Delcan, 2012), highlighting the need for timely and effective watershed nutrient management. Here we present a watershed-scale nitrogen and phosphorous source and loading analysis as a first step towards informing nutrient mitigation in the Cultus Lake watershed. We developed a seasonally- and annually-resolved nutrient loading model for Cultus Lake and undertook scenario-based lake modeling to examine the potential effects of future watershed and airshed changes and targeted mitigation strategies on lake water quality. Our study informs an integrated watershed management approach to nutrient management and development planning within the watershed, and provides insight into the nutrient dynamics of similar multi-use watersheds near urban areas in the Pacific Northwest.

2. Study Site

The Cultus Lake watershed (69 km^2) is located in the Lower Mainland of southwestern British Columbia (BC), Canada, 10 km south of the city of Chilliwack along the Canada-USA border (Figure 2-1). The single-basin lake (surface area 6.3 km^2) has a mean depth of 31 m and a maximum recorded depth of 44 m (Shortreed 2007). The lake basin is steep-sided with a limited littoral area (12% of the total area), 70% of which is colonized by invasive Eurasian watermilfoil (*Myriophyllum spicatum L.*; COSEWIC 2003). The watershed is located in the coastal western hemlock biogeoclimatic zone characterised by a temperate maritime climate with mild winters and warm dry summers (Meidinger and Pojar 1991). Daily average temperatures in Chilliwack range from 18.8 C in August to 3.3 C in December and January, while total annual precipitation averages 1,580 mm and generally falls between the months of October and April (Environment Canada 2013a).

Cultus Lake is located in a valley bounded by the Vedder Mountain ridge to the west, the International Ridge to the east, and the Columbia Valley to the south (Figure 2-2). There are 11 major tributaries in the Cultus Lake watershed, the catchments of which drain ~60% of the total watershed area, with the remainder being drained by un-channelized runoff (Table 2-1). The two ridges and the Columbia Valley have very different geologic and hydrologic properties. The bedrock of Vedder Mountain is primarily metasedimentary sandstone, conglomerate and shale while International Ridge is primarily slatey argillite (Holding and Allen 2012). Both are overlain by shallow glacial gravel tills and rapidly drained sandy organic soils (Holding and Allen 2012, MapPlace 2014). The surficial geology in the Columbia Valley is characterized by glaciofluvial sand and gravel outwash sediments (part of the Sumas Drift deposit) that are greater than 120 m deep (Zubel 2000, Holding and Allen 2012). The unconfined Columbia Valley aquifer is formed by these deep outwash sediments and extends from a topographic groundwater divide near the Canada-USA border to the Cultus Lake shoreline (Zubel 2000). The valley features a raised terrace of outwash deposits that abruptly drops

500 m south of Cultus Lake. The terrace is bisected by a deep gorge (ca. 50 m) cut through the sediments by Frosst Creek as it flows from International Ridge on the south-east side across the valley to the lake.

Stream drainage areas in the Cultus Lake watershed were grouped into 5 subwatersheds based on similar geomorphologies, land uses, and stream characteristics (Appendix A). The Vedder Mountain subwatershed encompasses 3 main tributaries (Ascaphus, Fin, and Reservoir creeks) and several ungauged areas that drain Vedder Mountain on the northwest lakeshore. The subwatershed was logged through the 1930s, and secondary forest dominated by broadleaf species including bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*) cover over 50% of the subwatershed area (Government of Canada 2009). The International Ridge subwatershed (Windfall, Clear, Teapot, and Watt creeks) is primarily coniferous forest, with 80% of the total area categorized as open or dense coniferous cover dominated by western redcedar (*Thuja plicata*) and Douglas-fir (*Pseudotsuga mensiesii*; Government of Canada 2009). Most of the subwatershed lies within Cultus Lake Provincial Park, with campgrounds and day use areas along the shoreline and hiking and other recreation trails extending into the ridge's upper slopes.

The largest subwatershed, the Columbia Valley, encompasses the southern extents of both ridges and the valley bottom. Two creeks that drain into the lake are located within the subwatershed: Frosst Creek, which is the largest inflowing tributary to Cultus Lake, and Spring Creek, emerging directly from the Columbia Valley aquifer near the lake. The eastern and western slopes bounding the Columbia Valley are predominantly forested, while agriculture and other developments (20% of the total area) occur along the central valley floor (Government of Canada 2009). The community of Lindell Beach and numerous small residential and tourism developments are located along the southern shore of Cultus Lake.

Two subwatersheds, Smith Falls and the Sweltzer Creek outflow, are located in the northern portion of the Cultus Lake watershed. A single tributary, Smith Falls Creek, drains the Smith Falls subwatershed on the northern border of International Ridge. A portion of the catchment lies within the densely forested Cultus Lake Provincial Park, while a more north-eastern portion is sparsely covered and contains meadows and wetlands that disrupt the flow of Smith Falls Creek. The Sweltzer Creek subwatershed encompasses the small community of Cultus Lake (population ~1,000) and the outlet of the lake, Sweltzer Creek, flows northward along a shallow gradient into the Chilliwack River. Due to the northward sloping groundwater gradient, most un-channelized flows from this subwatershed likely flow towards the Chilliwack River and do not contribute significant runoff to Cultus Lake (Holding and Allen 2012).

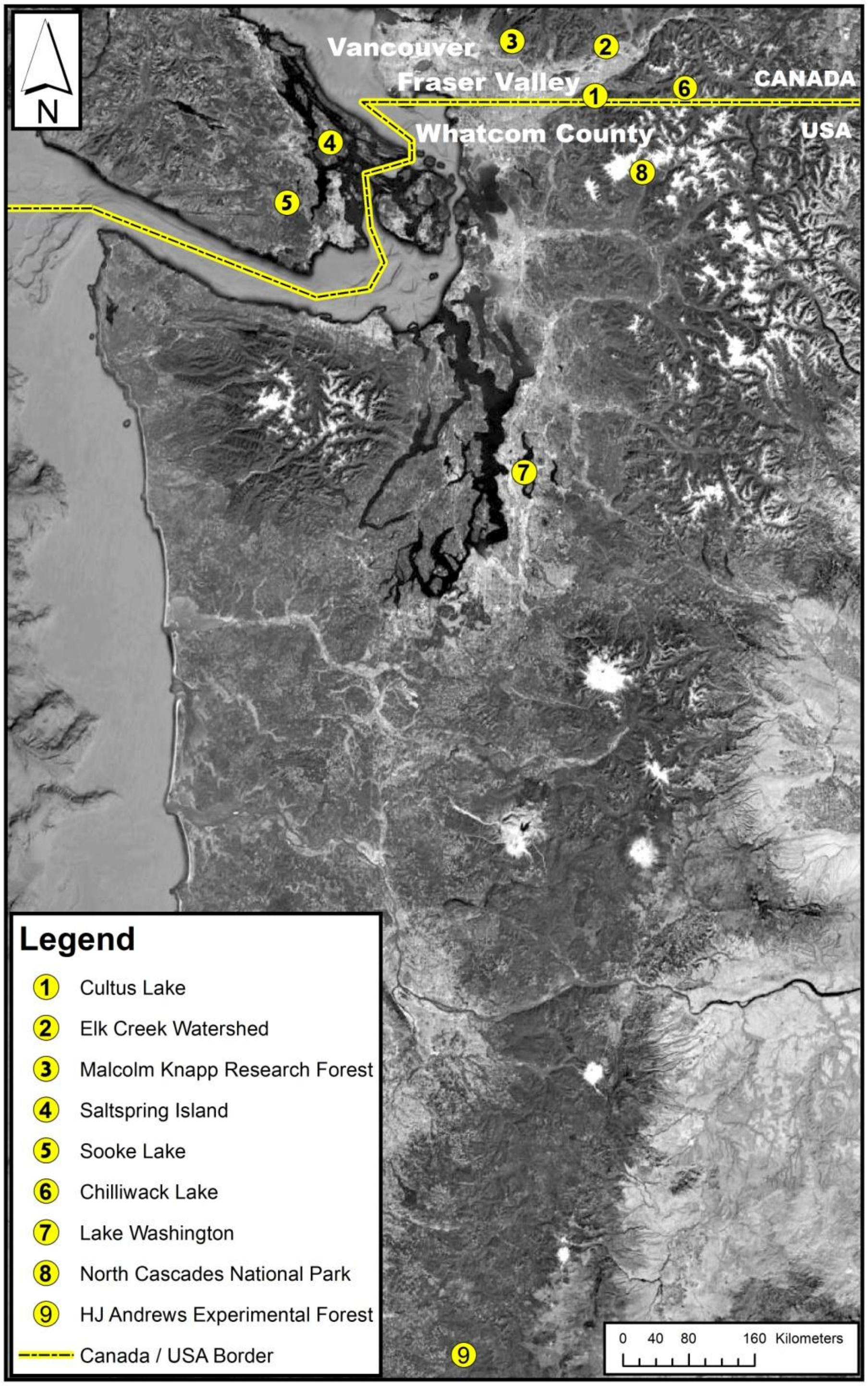

Figure 2-1 Regional map of the Pacific Northwest including locations of relevant watersheds and lakes with available water quality monitoring data.

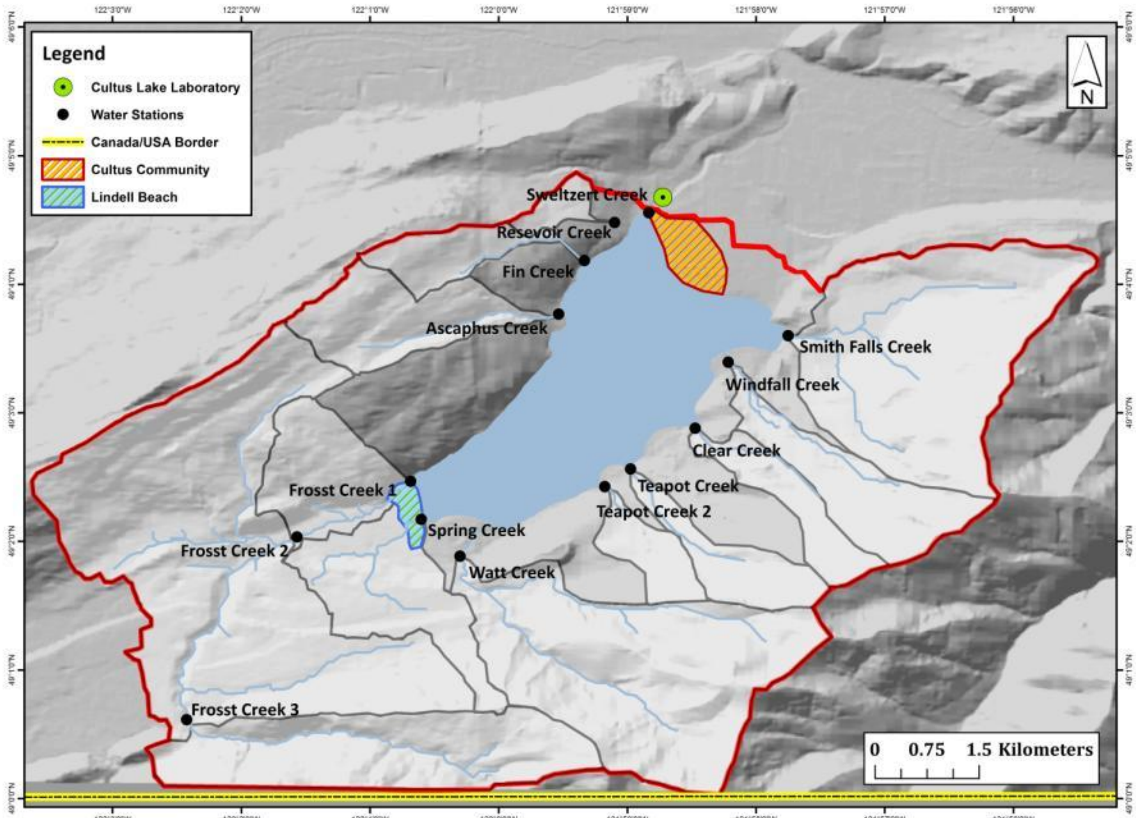

Figure 2-2 Cultus Lake watershed map including the locations of tributary sampling stations (black circles) and stream catchment boundaries (grey lines).

Table 2-1 Physical parameters of monitored tributaries and subwatersheds in the Cultus Lake watershed.

Stream	Abbrev.	Gauging Station (°N, °W)	Mean Elevation (m)[a]	Mean Slope (Degrees)[a]	Area (km^2)[a,c]	Primary Cover Type[b]	Geology	Sample Regime
Vedder Mountain			**386**	**16**	**7.18**	**Broadleaf dense**	**Sandstone, shale**	
Ascaphus	ASC	49.063, -121.992	554	17	2.01	Broadleaf dense		WQ, DL
Fin	FIN	49.067, -121.991	541	15	0.93	Broadleaf dense		WQ
Reservoir	RSV	49.075, -121.986	244	10	0.44	Broadleaf dense		WQ
Smith Falls			**368**	**19**	**6.49**	**Coniferous open**	**Argillite, shale**	
Smith Falls Creek	SMI	49.060, -121.962	368	19	6.49	Coniferous open		WQ, DL
International Ridge			**625**	**24**	**16.15**	**Coniferous open**	**Argillite, shale**	
Windfall	WIN	49.056, -121.971	697	25	2.08	Coniferous open		WQ
Clear	CLE	49.056, -121.968	599	24	1.13	Coniferous open		WQ
Teapot	TEA	49.043, -121.983	535	25	2.01	Coniferous open		WQ
Watt	WAT	49.031, -122.005	887	27	6.58	Coniferous open		WQ, DL
Columbia Valley			**415**	**18**	**31.60**	**Broadleaf Dense**	**Glaciofluvial outwash**	
Spring	SPR	49.035, -122.010	202	10	2.45	Broadleaf dense		WQ
Frosst (downstream site)	FRO2	49.034, -122.012	466	19	27.12	Coniferous open		WQ, DL
Frosst (upstream site)	FRO3	49.011, -122.041	705	27	4.06	Coniferous open		WQ
Sweltzer Creek Outflow			**69**	**4**	**1.36**	**Residential**	**Glaciofluvial outwash**	
Sweltzer Creek	SWE	49.078, -121.978	69	4	1.36	Residential		WQ, DL

Sample regime Codes: WQ (water quality), DL (stream flow data logger)

a. Source: Canadian Digital Elevation Data; Government of Canada, 2000

b. Source: Land Cover Circa 2000; Government of Canada, 2009

c. Subwatershed area totals include both gauged and ungauged catchment areas.

3. Materials and Methods

3.1. Water balance

We developed an annual average water budget for Cultus Lake based upon the general equation:

$$I + G_{in} + P - O - G_{out} - E \pm \Delta S = 0 \quad (1)$$

Where *I* represented inflows, including stream flow and non-channelized surface runoff; G_{in} was groundwater inflow; *P* was direct precipitation on the surface of Cultus Lake; *O* was outflow in Sweltzer Creek; G_{out} was direct groundwater outflow; *E* was evaporation directly from the surface of the lake; and ΔS was the change in lake storage over the measured time period. For this study we assumed ΔS to be 0 due to a lack of sufficient lake level data.

To determine stream inflows, we installed continuous hydrometric discharge stations on 4 tributaries (Frosst Creek, Ascaphus Creek, Smith Falls Creek, and Watt Creek) and the lake outlet (Sweltzer Creek; Figure 2-2, Appendix B). We calculated continuous discharges for monitored streams by developing logpower stage-discharge rating curves (Baty and Delignette-Muller 2012). We measured biweekly instantaneous discharges for streams without hydrometric stations and estimated discharge using linear regressions with a neighbouring continuously-monitored stream. Surface runoff from the ungauged portions of the subwatersheds was calculated using the area-weighted average flow for all monitored streams in the subwatershed. We estimated groundwater runoff from each subwatershed as the difference between the areal surface runoff estimated as above for each subwatershed and the average areal runoff measured for the entire Cultus Lake watershed at Sweltzer Creek. For Vedder Mountain and International Ridge, groundwater flows include shallow interflows in unsaturated tills, shale, and soils along the base of the ridges, while direct aquifer outflow was likely the predominant groundwater runoff from the Columbia Valley. Direct groundwater outflow from Cultus Lake was obtained from a numerical groundwater flow model developed by Holding and Allen (2012).

We measured direct precipitation on the surface of Cultus Lake at a meteorological station located at the Cultus Lake Laboratory (Figure 2-2). Daily temperatures (C), rainfall (mm), and relative humidity (ϕ) were monitored during the study and verified using data from an Environment Canada station located in Chilliwack, Canada (Environment Canada 2013a). We estimated evaporative losses from the surface of Cultus Lake using data from the nearby Agriculture and Agri-Foods Canada station in Agassiz, Canada which were scaled to the area of Cultus Lake (Zubel 2000). Detailed water balance methods and results can be found in Appendix C.

3.2. Nutrient budget

We identified potential sources of nitrogen and phosphorous loadings to Cultus Lake and calculated average annual and seasonal loads using our water quality data, or estimated loads using literature values and expert knowledge (Appendix E). Nutrient loading sources included gauged tributaries, ungauged overland flows, groundwater flows and interflows, atmospheric deposition, migratory gull guano, septic leachate, and sockeye salmon carcasses.

Total nitrogen (TN) and total phosphorous (TP) loading from tributary inflows and direct precipitation were calculated using the weighted sample mean averaging method, where instantaneous loads (i.e., concentration multiplied by discharge) were scaled by average discharges over the desired time period (Walling and Webb 1981). TN loads were calculated for subwatershed runoff and groundwater loading using TDN concentrations because particulate nitrogen data were not available at the time of the analysis. Although subwatershed loads are therefore underestimated, particulate nitrogen likely contributes a relatively small portion of TN loading in the streams except during fall high flows when detrital transport can be high. We sampled water chemistry at the outflow of each of the 11 tributaries and the Sweltzer Creek outflow on a biweekly basis from May 2011 to May 2013 (Appendix B). In Frosst Creek, 3 stations were located on a transect along the stream reach to determine nutrient levels and water quality parameters as the creek flowed from the forested mountain ridge through agricultural lands to the lake. Replicate water samples were syringe-filtered in the field through sample-washed glass-fibre filters (Pall Acrodisc, 1.0 μm) for analysis of dissolved organic matter (DOM), dissolved organic nitrogen (DON), nitrate (NO_3^--N), ammonium (NH_4^+-N), dissolved inorganic phosphorus (DIP), and total dissolved phosphorus (TDP) (Stephens and Brandstaetter 1983). Particulate phosphorus samples (PP) were filtered onto ashed borosilicate microfiber filters (equivalent to a Whatman GFF), frozen in a clean vial, and analyzed using the method of Stephens and Brandstaetter (1983). Particulate nitrogen samples (PN) were also filtered onto ashed borosilicate microfiber filters and stored frozen for later analysis. Total phosphorous was calculated as the sum of TDP and PP in water chemistry samples. Water chemistry analyses were performed at Fisheries and Oceans Canada's Cultus Lake Salmon Research Laboratory.

The average nutrient concentrations measured in the tributaries were used as average nutrient values for ungauged and groundwater inflows in each of the subwatersheds, and the groundwater-fed Spring Creek tributary was used as an estimate of groundwater chemistry for the Columbia Valley (Appendix D). We also sampled groundwater directly in 3 Columbia Valley wells (British Columbia tag numbers 18149, 37208, and 92975) and compiled historical well data from Fraser Health for comparison and to examine spatial nutrient variations in the Columbia Valley aquifer (Sivia B, Fraser Health, September 2012, pers. comm.). A two end-member mixing model of conductivity and DOM was also developed for Frosst Creek to separate seasonal groundwater and surface water source contributions (Appendix D).

We sampled precipitation chemistry at the Cultus Lake Salmon Research Laboratory meteorological station to estimate wet deposition of nitrogen and phosphorous using 25 cm funnels in light-excluded vessels (year 2 only). Weekly precipitation samples were pooled and analyzed at the Cultus Lake Laboratory for DIP, TDP, nitrate, and ammonium using the same methods as for stream samples. Dry deposition of nitrogen and phosphorous was estimated from the proportion of the annual deposition rates measured in nearby Abbotsford and Chilliwack (Belzer et al. 1997, Vingarzan at al. 2000).

Another source of nutrient loading into Cultus Lake is guano from migratory gulls (primarily glaucous-winged gulls; *Larus glaucencens*) that use the lake as a winter roosting site. Cultus Lake resident observations and data from the National Audubon Society Christmas Bird Count (CBC) in Chilliwack indicate increasing gull populations in the area since at least the late-1970's (National Audubon Society 2010, Robinson 2012). Gulls spend the daylight hours feeding outside of the watershed at agricultural fields, waterbodies, and nearby waste disposal sites, and excrete nutrients into Cultus Lake while they roost on the lake overnight. We estimated nutrient loading from migratory gull guano using population estimates of 9,500-12,500 gulls/yr obtained from visual surveys (tallies and photograph counts), and existing literature values of nutrient production rates for herring gulls (*Larus argentatus*), a close relative of glaucous-winged gulls (Gould and Fletcher 1978, Portnoy 1990, Marion et al. 1994, Hahn et al. 2007). Literature values of gull nutrient production were highly variable (0.44 to 1.82 g/gull/d for total Kjeldahl nitrogen [TKN], and 0.12 to 0.76 g/gull/d for TP), and we calculated a median load based on a range of literature rates to estimate guano-sourced nutrient loadings to Cultus Lake.

Sockeye salmon carcasses are a natural source of nutrient loading to Cultus Lake, importing nutrients when they spawn and die in the fall. We estimated nutrient loads from salmon carcasses using historic escapement data from Fisheries and Oceans Canada (DFO), nutrient contents of 3.04% for nitrogen and 0.36% for phosphorous by weight (Larkin and Slaney 1995), and the average weight (minus gonad weight) of an adult Cultus Lake sockeye salmon carcass (1.55 kg, 2010 data; Patterson D, DFO, *unpublished data*).

Septic leaching from both private and centralized on-site wastewater treatment systems occurs from numerous small communities and resort developments in the Columbia Valley and provincial campgrounds located along the shoreline of International Ridge. Concentrations of septic systems are located downstream or distant from stream sampling sites located in these subwatersheds, so septic loading to the lake was estimated separately from stream loading. Septic systems in the watershed use buried leaching fields, and the nutrient leaching potential is high due to the shallow depth of the water table relative to the depth of the fields, the low filtration capacity of the coarse-textured gravelly sub-soils, the potential for high nutrient saturation in aging septic systems and soils, and the high precipitation and leaching rates in the region (Zubel

2000, McCray et al. 2005, Urban Systems Ltd 2012). We estimated loads from septic systems in the Columbia Valley and International Ridge subwatersheds using sewage flow rates obtained from the British Columbia Sewerage Standards Practice Manual for residential (175 L/cap/d), campgrounds (90 L/cap/d), and day use areas (20 L/cap/d; BC Ministry of Health 2006), and sewage outflow nutrient concentrations measured in the Okanagan, BC (32 mg/L for TN and 7.8 mg/L for TP; Kennedy and Oldham 1982). We used recently-derived residential population estimates for the Columbia Valley (Urban Systems Ltd (2012) and camping and day use statistics for Cultus Lake Provincial Park (BC Parks 2012). We estimated soil retention coefficients using available soil composition data (Comar et al. 1962) and coefficients from the Spokane Valley-Rathdrum Prairie Aquifer in northeastern Washington that has similar soil characteristics to the Cultus Lake watershed (HDR Consulting 2006). Retention coefficients of 15% for TN and 60% for TP were used as primary model input parameters, and a sensitivity analysis of high and low coefficients (i.e., ±10%) was performed to examine uncertainty in soil retention.

3.3. BATHTUB modelling

We used a lake and reservoir eutrophication model to estimate steady state epilimnetic TP, TDN, and chlorophyll *a* (chl-*a*) concentrations in Cultus Lake relative to nitrogen and phosphorous loadings from the watershed and airshed. TDN was used for TN for subwatershed runoff and groundwater loading as well as for in-lake nitrogen concentrations due to a lack of particulate nitrogen data at the time of modelling. The BATHTUB Simplified Techniques for Eutrophication Assessment & Prediction model (version 6.1; Walker 1985, 2004) is composed of nonlinear mass balance equations solved iteratively for water and nutrient balances to empirically relate nutrient loading to lake water quality parameters. We used annual flow volumes from the water balance and time-weighted concentrations of TDN and TP for point and non-point sources of nutrient loading into Cultus Lake. Point source loading inputs were generated using the total annual nutrient loads and a nominal inflow volume of 0.01 hm^3/yr. Epilimnetic water quality and chl-*a* data for Cultus Lake collected by Fisheries and Oceans Canada’s Lakes Research Program (2011 and 2012) were used to calibrate the nutrient sedimentation and chl-*a* model parameters and specific conductivity was used as a conservative tracer to verify the Cultus Lake water balance. Although the BATHTUB model can be calibrated to accurately predict epilimnetic nutrient concentrations, it should be noted that the resulting whole-lake effects of eutrophication may be more severe in Cultus Lake relative to other lakes and reservoirs due to the presence of a deep chlorophyll maximum during the growing season, which would result in greater total primary productivity than in a lake with epilimnetic-dominated primary productivity. Once calibrated against current conditions, the BATHTUB model was used to predict changes in epilimnetic nutrient and chl-*a* concentrations under 4 scenarios: historic watershed conditions before anthropogenic influences (i.e., pre-European); a current watershed conditions scenario with potential nutrient abatement strategies enacted; a development scenario projected 25 years into the future using projected population increases, land use changes, and gull population expansion for the region; and the 25-year future development scenario with potential nutrient abatement strategies enacted to mitigate the effects of increased development and gull population expansion.

For modelling pre-European contact and future nutrient loading scenarios, we required estimates of the background atmospheric deposition rates for TN and TP directly to Cultus Lake from non-anthropogenic sources. We assumed the difference between our measured deposition rate and the estimated background rate was the anthropogenic load which we varied for the future development and mitigation scenarios modelling. While there likely is no true modern analog for levels of pre-anthropogenic atmospheric deposition due to the diffuse global distribution of environmental contaminants via the atmosphere (Elser 2011, Holtgrieve et al. 2011), we based our estimates on nitrogen and phosphorous deposition rates measured or modelled within relatively pristine regions of the PNW.

There have been many air quality studies of atmospheric nitrogen deposition in the PNW but few in pristine watersheds comparable to the Cultus Lake watershed. For a background estimate of non-anthropogenic nitrogen loading, we used an annual average TN deposition rate of 2.0 kg-N/ha/yr (1996-2007; range 1.4-2.7 kg-N/ha/yr) from the Clean Air Status and Trends Network (CASTNET; http://epa.gov/castnet/javaweb/index.html) for monitoring site NCS415, located approximately 70 km southeast of Cultus Lake in the North Cascades National Park of Washington State (Fenn et al 2013). This deposition rate is in the range of the values

(<2.1 kg-N/ha/yr) estimated by Raymond et al. (2010) using a nitrogen deposition model for areas of southwest British Columbia that are remote and unaffected by anthropogenic TN emissions from the city of Vancouver. Martin and Harr (1988) also reported similar TN deposition rates of 2.0-2.1 kg-N/ha/yr in the H.J. Andrews Research Forest, 550 km south in the western Cascade Mountain Range of Oregon (Figure 2-1), that the authors considered to be relatively unaffected by anthropogenic sources. For comparison, the background TN deposition value we used is much lower than the recent atmospheric nitrogen deposition rate of 25.7 kg-N/ha/yr measured by Vingarzan et al (2000) in the nearby Fraser Valley agricultural region and transportation corridors.

We could find few published studies of phosphorous deposition in pristine watersheds of the PNW to estimate a background non-anthropogenic atmospheric TP load for Cultus Lake. Precipitation chemistry has been measured for more than 40 years in the undisturbed watersheds of the H.J. Andrews Research Forest in the western Cascade Mountains of Oregon (Figure 2-1), however, we used the recent 10-year average (2000-2009) TP deposition rate for both monitoring stations of 0.02 kg-P/ha/yr as our background estimate of non-anthropogenic atmospheric phosphorous loading directly to the lake from wet deposition (Johnson and Fredriksen 2012). Total wet and dry phosphorus was estimated as 0.04 kg-P/ha/yr based on Elk Creek (Figure 2-1) wet and dry deposition ratios (i.e., 50%) in Vingarzan et al. (2000). Global P deposition models project similar levels of background phosphorous deposition for the PNW (Mahowald et al. 2008). Similar to nitrogen, the background TP deposition value used is much lower than the 0.15 kg-P/ha/yr atmospheric phosphorous deposition rate measured by Vingarzan et al. (2000) for the Fraser Valley[1].

Nitrogen exported from watersheds that are unaffected by anthropogenic sources originates almost entirely from natural deposition and biological fixation of atmospheric nitrogen. Exported phosphorous originates from both mineral weathering and atmospheric deposition in the watershed. We required estimates of these background, non-anthropogenic nutrient export rates for the Cultus Lake watershed to partition the current natural and anthropogenic loadings of nitrogen and phosphorous for the historic

[1] Based on Tables 5 and 6 in Vingarzen et al. (2000); total deposition in Table 10 of Vingarzen et al (2000) was miscalculated.

and future projection model scenarios. As an estimate of the non-anthropogenic nitrogen export rate for Cultus Lake watershed, we examined literature values from forested watersheds in the Pacific Northwest (PNW) located outside of urban and agricultural airsheds with similar climates and forest covers. Nitrogen export rates for 2 forested watersheds located on Vancouver Island (Leech River and Sooke Lake watersheds; Figure 2-1) had TN areal export rates of ~2 kg-N/ha/yr for mature and old growth forests (Zhu and Mazumder 2008). According to nitrogen deposition modelling and lichen tissues, the Vancouver Island watersheds are relatively unaffected by regional anthropogenic nitrogen deposition (Raymond et al. 2010). Undisturbed forested watersheds in the H.J. Andrews Research Forest of Oregon exhibited similarly low areal TN exports of <1.5 kg-N/ha/yr (Martin and Harr 1988, Schaefer et al. 2009). We set the background export rate of TN from the Cultus Lake watershed at 2 kg-N/ha/yr which is likely a reasonable estimate of nitrogen loading from natural, background nitrogen fixation and atmospheric deposition.

Determining the portion of areal phosphorous loading attributable to natural background geologic sources and atmospheric deposition for Cultus Lake was more difficult due to a lack of available high quality regional data and the geologically-specific nature of phosphorous mineral weathering. BATHTUB was used with limnological data collected by the Fisheries and Oceans Canada's Lakes Research Program (Selbie D, DFO, *unpublished data*.) to estimate an average areal TP export for Chilliwack Lake, which is located in a similar biogeoclimatic setting 41 km east of Cultus Lake in a forested watershed of the Northern Cascade Mountains (Figure 2-1) that is not heavily influenced by regional atmospheric deposition (Raymond et al. 2010). Estimated areal export of TP for the Chilliwack Lake watershed was 0.065 kg-P/ha/yr and used as our background export rate from natural atmospheric and mineral weathering sources for Cultus Lake (accounting for 45% of the average annual TP export from Cultus Lake subwatersheds). Our estimation for Chilliwack Lake was similar to TP areal exports for 2 watersheds (Roberts and Blackburn Lakes) located in a relatively undisturbed region of Vancouver Island with similar climate and forest cover to the Cultus Lake watershed, which ranged from 0.08 to 0.10 kg/ha/yr (Sprague 2007).

3.3.1. *Pre-development scenario*

We used the estimates of background non-anthropogenic atmospheric deposition and watershed export of nitrogen and phosphorous as estimates of nutrient loading to Cultus Lake prior to European settlement of the region for the pre-development BATHTUB model scenario. Using background areal exports eliminated anthropogenic inputs from both watershed sources (i.e., agricultural inputs and export changes due to deforestation) and regional airshed sources (i.e., vehicle and industrial emissions, agricultural volatilization, and dust emissions) and allowed for an approximation of watershed conditions prior to settlement. In addition, all septic loadings were eliminated from the Columbia Valley and International Ridge subwatersheds. Nutrient loadings from gulls were removed because local long-term residents report that the extensive use of Cultus Lake by migratory gulls is a relatively recent phenomenon (Robinson 2012), an assertion supported by available bird count data since the late 1970's (National Audubon Society 2010). Although aquatic birds other than gulls would have been resident at Cultus Lake before European settlement, they would have likely remained and recycled nutrients within the watershed. To estimate pre-development loading from salmon carcasses (the only load to increase for this scenario) the average annual escapement was calculated for the earliest 10 years on record (1953 to 1962; i.e., the highest escapement levels recorded since enumerations began) as an estimate of historical nitrogen and phosphorus loads.

3.3.2. *Future development scenario*

We projected nitrogen and phosphorous loadings to Cultus Lake 25 years into the future as a status quo scenario of future watershed development and occupation. For the future development BATHTUB scenario, loads from atmospheric deposition, migratory gulls, septic sources, agricultural leaching, and watershed runoff were increased.

The populations of Greater Vancouver and the Fraser Valley are projected to increase by >40% over the next 25 years (FVRD 2004). The increased vehicle traffic and urban combustion sources, agricultural intensification to meet local food demands, and more human activity in proximity to Cultus Lake would be expected to increase potential sources of wet and dry atmospheric deposition of TN and TP to the lake and watershed. As a realistic future scenario for modelling the atmospheric component of future development impacts, we increased both direct deposition of TN and TP to the lake and the portion of subwatershed TN and TP runoff loading attributed to atmospheric sources by 30%, accounting for a combination of increased population densities and advancements in pollution capture technologies.

To estimate future loading from migratory gulls, bird population growth was projected 25 years into the future using Christmas Bird Count (CBC) data for the Chilliwack area. CBC data for Chilliwack (National Audubon Society 2010) and the North American Breeding Bird Survey for the coast region (Environment Canada 2013b) both indicate increasing trends in glaucous-winged gulls. CBC data from the Chilliwack area were used as a best estimate of population trends at Cultus Lake because they represent the closest available estimate for the area. Logarithms of count data were fit using a linear time trend model ($R^2 = 0.36$, $p < 0.001$, $n = 32$), which predicted a current gull population size of 9,030 gulls/yr that approximated the range observed in the preliminary bird counts of this study (9,500 to 12,500 gulls/yr; Appendix E). Carrying capacity was not considered to be a factor for future populations as the birds do not currently feed or breed on the lake and therefore are not limited by these constraints. The CBC model predicted an increase to 30,800 gulls/yr or a 180% increase, and the associated future nitrogen and phosphorus loads were calculated.

Future septic loads from the Columbia Valley were predicted assuming a total increase in residential units of 804, as estimated in the Cultus Lake South Sewerage Planning Study based on current development plans and proposals (Urban Systems Ltd 2012). Park use statistics from Cultus Lake Provincial Park indicate that camping and day use has been relatively stable in recent years (BC Parks 2012), but we predict day visitation to increase in the next 25 years as a result of population growth in the Fraser Valley (i.e., a 47% increase from 2001 levels by 2030; FVRD 2004). To represent this trend, we increased total person days of day users by 45% for the future development scenario.

Agricultural nutrient loading to fields in the Columbia Valley is likely to increase the future nutrient loads to Cultus Lake as a result of ongoing conversion from forage to berry production in the area. Land use projections suggest berry production may increase to a maximum of 30% of the total cropped area (i.e., a tripling of the current area), forage production may increase to 40%, and there will likely be a slight increase in hobby farms and niche crop production (Sutherland K., BC Ministry of Agriculture, March 2014, pers. comm.). To account for the projected increase in berry and livestock production, current loads estimated for Columbia Valley agricultural sources were doubled. Although the area of berry cropping is projected to triple, not all nutrient export from the Columbia Valley can be attributed to berries and manure spreading (i.e., natural sources, septic leaching, atmospheric deposition, and other sources likely contribute), and a tripling of the current load would likely overestimate the true future load.

To increase agricultural nitrogen loadings in the Columbia Valley, we separated current anthropogenic subwatershed loadings from agricultural inputs and anthropogenically-sourced atmospheric nitrogen deposition. The difference between current and pre-developed Columbia Valley subwatershed export was assumed to originate primarily from anthropogenic sources (i.e., agricultural loadings or atmospheric deposition). To determine what proportion of nutrient loading to Cultus Lake from the Columbia Valley was attributable to agriculture, we calculated nutrient loadings using water chemistry data from the Frosst Creek station upstream of agricultural influences. The difference between loadings calculated using chemistry data from the two Frosst Creek stations was assumed to be agriculturally-derived (10% of total anthropogenic loadings for TP and 73% for TN). Agricultural nitrogen and phosphorous loadings were then doubled to account for estimated future intensification (Sutherland K., BC Ministry of Agriculture, March 2014, pers. comm.).

3.3.3. Current mitigation scenario

To explore the benefits of reasonably-achievable nutrient management and mitigation strategies on the current trophic status of Cultus Lake, current loadings from migratory gull guano and agricultural runoff were reduced and septic leaching was removed entirely. Septic leaching was removed assuming most septics in the watershed could be diverted to a sewer system and exported from the watershed. Sewerage options for the Cultus Lake watershed are currently under review by the Fraser Valley Regional District, and export via sewer infrastructure is being considered (Urban

Systems Ltd 2012). Mitigation of atmospheric deposition was not considered because capture technologies for emissions and improved agricultural management are not likely to be imminently achievable.

Although gulls are protected under the Migratory Birds Convention Act (MBCA), we included an option for deterring or culling of birds that are overpopulated or threaten environmental quality (Government of Canada 2014). Public acceptance of culling is generally low, and although the MBCA legislation enables culling permits to be issued in some situations, permit issuance is uncommon (Government of Canada 2014). For this reason, non-lethal methods of deterring birds along the flight path to the lake and at nearby landfill sites would likely be the preferred methods of control. The use of falcons (a lethal but more publically accepted method), non-lethal shot, and gull distress calls have resulted in 40% to 50% long-term reductions in gull numbers at landfill sites (Baxter and Robinson 2007, Cook et al. 2008, Thiériot et al. 2012). Thus gulls were reduced by 45% in the mitigation scenario, assuming that gulls scared from nearby landfill sites would not return to roost on Cultus Lake at night. Although this is likely a larger reduction than could be achieved for the Cultus Lake watershed, it allows for the examination of an optimal scenario of mitigating gull guano loading in combination with other management strategies.

Nitrogen and phosphorous loadings to Cultus Lake from the Columbia Valley were also reduced assuming improvements could be made to fertilizer and manure management practices. Improved fertilizer management could reduce nutrient leaching from berry crops by 70% to 80% while leaching from forage and hobby farms may decline up to 50% (Sutherland K, BC Ministry of Agriculture, March 2014, pers. comm.). Nutrient loads attributed to agriculture were determined as they were for the future development scenario, and the agricultural load was reduced by 50% to account for potential improvements in nutrient management practices. Delays would likely occur between loading reductions and water quality improvements due to watershed retention processes; however, for simplicity all mitigation measures were assumed to have immediate effects on water quality in the watershed.

3.3.4. Future development with mitigation scenario

A final scenario was examined that combined increased nutrient loads as a result of future development projections with realistic mitigation measures. We used the increased nutrient loads from the future development scenario and then reduced these loads using the mitigation measures from the current mitigation scenario. More specifically, migratory gull populations were projected 25 years into the future and then reduced by 45%; agricultural inputs were doubled as a result of intensification then decreased by 50% assuming improved fertilizer management; atmospheric deposition was increased by 30% as was the resulting runoff from the subwatersheds attributed to atmospheric deposition; sockeye salmon carcass loads were unchanged; and septic leaching was eliminated.

4. Results

4.1. Water balance

Total inflow into Cultus Lake from watershed sources and direct precipitation was approximately 110 hm^3/yr, with the largest inflow source being the Columbia Valley subwatershed which contributed 47% (Table 4-1; Appendix C). Groundwater sources contributed 33 hm^3/yr of total inflow to the lake with the Columbia Valley accounting for 32% of groundwater inflows. Although the aquifer represents a large stored volume of groundwater, 80% of the runoff from the Columbia Valley subwatershed to the lake is surface runoff largely in Frosst Creek. Outflow from Cultus Lake was dominated by Sweltzer Creek, while evaporation and direct groundwater outflow together accounted for 3.3% of the total. Seasonal discharge patterns of streams throughout most of the watershed followed wet and dry seasons typical of the Pacific Northwest (PNW), with maxima occurring October through May, and minima occurring July through September. Low flow periods were less pronounced in Frosst Creek in the Columbia Valley, reflecting a later snowmelt freshet in its mountain ridge headwaters and higher groundwater baseflow contributions from the Columbia Valley aquifer during normally low flow periods (Appendix D).

Table 4-1 Cultus Lake average annual water balance.

		Annual Average (m^3/yr)	% Total
INFLOW			
I	**Subwatershed surface runoff**		
	Vedder Mountain	6,401,307	5.8
	International Ridge	14,850,751	13.4
	Smith Falls	5,264,991	4.8
	Columbia Valley	41,891,643	37.9
G_{in}	**Subwatershed groundwater inflow**		
	Vedder Mountain	5,515,793	5.0
	International Ridge	11,594,062	10.8
	Smith Falls	5,500,508	5.0
	Columbia Valley	10,482,789	9.4
P	**Direct precipitation**	8,564,850	7.8
OUTFLOW			
O	**Sweltzer Creek outflow**	106,788,407	96.7
G_{out}	**Groundwater outflow**	39,366	<0.1
E	**Evaporative loss**	3,629,755	3.3

4.2. Nutrient budget

4.2.1. Stream water and precipitation chemistry

The Vedder Mountain streams in the most northern part of the Cultus watershed generally had the highest mean annual flow-weighted (MAFW) concentrations of TDN and TDP. Ascaphus and Reservoir streams averaged 557 and 690 µg-N/L TDN, respectively, while the other Cultus Lake tributaries ranged from 148 to 452 µg-N/L. Frosst Creek, which flows through the agricultural Columbia Valley, was intermediate at 379 µg-N/L. The Vedder Mountain streams and Smith Falls Creek had the highest MAFW TDP concentrations of all the tributaries at 9.3 to 13.0 µg-P/L while the

International Ridge streams ranged from 7.3 to 9.6 µg-P/L with the agriculturally influenced Frosst Creek at 6.9 µg-P/L. DIN was the primary component of the TDN, contributing 74 to 84% of the TDN, with the exception of Smith Falls Creek which had a higher dissolved organic component and only 58% DIN. DIP contributed 20 to 39% of the TDP among all the Cultus Lake tributaries, with organic phosphorus forms dominating the dissolved fraction.

Seasonal variations in TDN concentrations among streams largely reflect differences in seasonal nitrogen availability, leaching of nitrogen from soils during high fall and winter precipitation, and the moderating or enriching effects of local groundwater sources and wetlands in the catchments. Seasonal TDN variations were greatest in Vedder Mountain streams, where TDN in Ascaphus and Reservoir Creeks ranged from ~250 µg-N/L during the low flow period (July through September) to a spike of >1,200 µg-N/L at the onset of fall precipitation (Figure 4-1). This spike in nitrogen likely occurred when soluble nitrogen accumulated in catchment soils over the dry growing season flushed to the streams as soils became water saturated and vegetative uptake slowed (Hudson and Fraser 2001). TDN levels remained relatively high in all of the Vedder Mountain streams during the winter months when precipitation and stream discharges were high and vegetative uptake in the watershed remained low. Some of the International Ridge streams had similar seasonal patterns but concentrations were much lower and seasonal variations were muted relative to the Vedder Mountain streams. There are extensive deposits of glacial tills and outwash sediments and colluvial and alluvial sediments at the base of International Ridge near the lake compared to Vedder Mountain and several of the streams flow subsurface in some lower reaches and during summer low flow periods. Hydrologic exchange with groundwater may moderate seasonal variations in TDN compared to the Vedder Mountain streams. The Smith Falls subwatershed exhibited similarly low TDN concentrations with even less seasonal variation (150 to 350 µg-N/L) compared to the neighbouring International Ridge catchments, likely due to wetlands in the upper watershed of the stream that can retain nitrogen and buffer the export of TDN (Gilliam 1994).

High TDN levels were found in precipitation in the Cultus Lake watershed, and the seasonal pattern implicates agriculture as a primary source. The seasonal pattern was opposite to TDN patterns recorded in the Vedder Mountain streams, with minima during high rainfall from November through April (80 µg-N/L) and maximum concentrations occurring during the low precipitation period (1,200 µg-N/L; May through October). The seasonal peaks correspond with the timing of early summer and fall manure and fertilizer applications in the Fraser Valley (Belzer et al. 1997, Vingarzan et al. 2000). Peak TDN concentrations in precipitation were higher than any of the streams with the exception of Ascaphus and Reservoir streams on Vedder Mountain, but not as high as peak DIN concentrations that have been measured for rainfall in the central Fraser Valley (Vingarzan et al. 2000).

Frosst Creek TDN concentrations did not follow the same seasonal pattern observed in most of the other Cultus Lake streams. A comparison of TDN levels measured at the lower and upland Frosst Creek stations combined with the high TDN levels recorded during low flows both implicate nitrogen-enriched groundwater from agricultural sources in the Columbia Valley as the dominant influence on nitrogen levels in the stream. The upland Frosst Creek station, upstream of any direct agricultural influences in the valley and the furthest catchment from atmospheric sources in the Fraser Valley, had the lowest TDN concentrations of all the Cultus Lake watershed streams and did not exhibit the marked seasonal peaks or patterns found in any of the other streams. In contrast, TDN concentrations at the lower Frosst Creek station (downstream of the Columbia Valley agricultural region) were highest throughout the summer and early fall (>800 µg-N/L) when nitrogen-enriched groundwater dominated baseflows (Figure 4-1). According to the Frosst Creek end-member mixing analysis, TDN concentrations were highest in the creek when the groundwater proportion approached 100%, and were correlated with the proportional contribution of aquifer-sourced groundwater in Frosst Creek flow ($R^2 = 0.74$, $p < 0.001$, n = 48; Appendix D). Additional sampling conducted along an upstream transect in Frosst Creek on 27 August 2012 also documented substantial groundwater seepage into the creek from the upslope banks along the incised gorge between the upland and downstream Frosst Creek sampling stations. Samples collected upstream of this groundwater seepage had low concentrations of nitrate-nitrite (<50 µg-N/L) similar to the upland Frosst Creek station, while downstream sampling had highly elevated nitrate concentrations (850 µg-N/L). TDN concentrations in the groundwater-sourced Spring Creek were also elevated (>300 µg-N/L) and exhibited little seasonal variation. Columbia Valley well water sampling provided further evidence of high concentrations of TDN in the Columbia Valley groundwater (i.e., mean DIN 458 μg-N/L, maximum 1,890 μg-N/L) being the source of elevated TDN for lower Frosst Creek.

The seasonal variations in TDP concentrations in precipitation were similar to those for TDN, suggesting similar agricultural atmospheric sources may account for the high levels of phosphorus in dry season rainfall. TDP concentrations were lowest during the wet season from November through April (<1 μg-P/L) and peaked during the May to October dry growing season at 30 to 60 μg-P/L, well above concentrations recorded in any of the Cultus watershed streams and more than double peak levels measured in the nearby Fraser Valley (Vingarzan et al 2002). The seasonal patterns we found in precipitation chemistry for TDN and TDP were similar to those found by Vingarzan et al. (2002) and Belzer et al. (1997) in the nearby Fraser Valley.

Seasonal variations in stream TDP concentrations were more muted than TDN. The highest concentrations and largest seasonal variations occurred in Smith Falls (5 to 25 μg-P/L), Ascaphus (5 to 32 μg-P/L) and Reservoir creeks (6 to 22 μg-P/L) (Figure 4-2). As with TDN, most of the streams showed some elevation of TDP stream concentrations during periods of fall flushing following the end of the dry season. Unlike TDN, seasonal TDP concentration patterns in the Columbia Valley were similar to those of the remaining subwatersheds, and there was no difference between phosphorous concentrations in Frosst Creek upstream and downstream of agricultural influences (Figure 4-2). TDP ranged from 3 to 18 μg-P/L in the upstream forested station, and 4 to 14 μg-P/L in the valley bottom, with maxima at both stations occurring in November at the onset of winter precipitation, indicating that, unlike nitrogen, Columbia Valley groundwater is not significantly enriched with phosphorous by agriculture in the valley.

4.2.2. Total nutrient loading into Cultus Lake

Total TN loading to Cultus Lake was 47 tonnes-N/yr with 75% of the nitrogen load coming from surface and groundwater runoff from the watershed and 19% arising from direct atmospheric deposition. 61% of the TN was retained in the lake, presumably attenuated by autotrophic production and exported to the sediments. The largest single source of TN loading was runoff from the Columbia Valley subwatershed, which delivered 20 tonnes-N/yr, or 43% of the total TN load to the lake, largely via surface runoff (Table 4-2). Nitrogen from direct wet and dry atmospheric deposition onto the lake contributed 8.7 tonnes-N/yr or 19% of the total nitrogen load, a high proportion given that the lake surface area is about 10% of the total watershed area. Gull guano and salmon carcasses were minor sources of TN to the lake (<2% of the total load). Although near-shore septics can be an important source of nitrogen loading to lakes, they contributed 4% to the overall TN load to Cultus Lake, roughly a quarter of the nitrogen load coming from atmospheric deposition.

Total TP loading to the lake was 2,199 kg-P/yr with 66% coming in surface and groundwater runoff from the subwatersheds and 6% via direct atmospheric loadings. 43% of TP loading was retained in the lake, an 18% lower retention rate than TN. Septic leaching and migratory gull guano contributed 238 and 355 kg-P/yr respectively, or a combined 27% of the total annual load to the lake (Table 4-2). Gull guano represented a substantial phosphorous source to Cultus Lake only in the fall and winter seasons when gulls roosted on the lake. In contrast, leaching of phosphate from septic systems likely occurred primarily during peak summer visitation and lake stratification, potentially contributing disproportionately to lake productivity. Direct wet and dry atmospheric deposition on the lake surface was also a significant source of phosphorous loading, contributing 124 kg-P/yr or about 6% of the total load, approximately proportionate to its share of the total watershed area. Considering that a portion of the phosphorous delivered by runoff from the subwatersheds can also be attributed to these high atmospheric deposition rates on land, atmospheric deposition may be one of the largest sources of phosphorous loading to the lake.

The relative contributions of inorganic and organic forms of dissolved nitrogen and phosphorous differed among nutrient sources. TDN loading in watershed runoff into Cultus Lake was 81% dissolved inorganic forms (DIN, predominantly nitrate), while dissolved inorganic phosphorous (DIP) accounted for 32% of the TDP loading. It was not possible to partition nitrogen and phosphorus loading from gulls, septics, and sockeye carcasses into dissolved inorganic and organic forms. However, nitrogen and phosphorous from septic effluents are delivered to watercourses predominantly as nitrate and phosphates after percolation through soils (McCray et al. 2005), while gull guano and decomposing salmon carcasses release a variety of organic and inorganic particulate and dissolved forms into water. Total wet and dry atmospheric deposition (TN and TP) was estimated from our precipitation sampling and dry deposition measurements made in the nearby Fraser Valley (Belzer et al. 1997, Vingarzan et al. 2000). TDP in precipitation was 67% DIP, while atmospheric TDN was 95% DIN, with nitrate and ammonium contributing roughly 30% and 70% of DIN, respectively. Of the atmospheric phosphorous deposition, 33% was attributed to dry deposition of dust and aerosol particles, while the remaining 67% occurred dissolved in precipitation. In contrast, 59% of TN deposition occurred in the dry form due to high volumes of dry ammonia deposition originating from volatilization of agricultural ammonia sources.

4.2.3. Areal nutrient export in the Cultus Lake watershed

Areal TN and TP export rates were compared among subwatersheds to determine how land use and atmospheric deposition may be affecting nutrient export to the lake. Atmospheric deposition of TN to the entire watershed was estimated at 13.70 kg-N/ha/yr while export of TN to the lake from all watershed runoff averaged less than half that at 5.76 kg-N/ha/yr. Average atmospheric input of TP to the watershed was 0.20 kg-N/ha/yr while average export of TP to the lake was higher at 0.24 kg-P/ha/yr (Table 4-3). Atmospheric deposition is not the only source for the TN exported from the watershed (e.g. soil nitrogen fixation, agriculture) , so the differences between average input and export suggest that >58% of annual atmospheric TN inputs are being retained in the soils and vegetation of the Cultus watershed. Export of TP from the subwatersheds was greater than atmospheric deposition, indicating that mineral weathering sources are also a major contributor of TP loading from the watershed.

Comparing the average areal TN atmospheric deposition rate of 13.70 kg N/ha/yr to the areal export rates of TN for each of the subwatersheds, all had export rates that were less than 60% of the deposition rate. The highest areal nitrogen exports for the subwatersheds originated from the Vedder Mountain and the Columbia Valley at 7.92 and 6.35 kg-N/ha/yr respectively. As noted previously, the higher rate of nitrogen export from the Columbia Valley is due to agricultural enrichment of stream groundwater sources. The Columbia Valley subwatershed includes high elevation forested areas on the southern flanks of International Ridge and Vedder Mountain and the areal TN export rate from just the agricultural part of the watershed would be much higher than the average for the entire subwatershed.

Vedder Mountain is forested, but its proximity to the atmospheric emission sources in the Fraser Valley and historic logging with recolonization by nitrogen-fixing alder species (*Alnus* sp.) in the subwatershed, likely account for its elevated nitrogen export rate. Vedder Mountain is east of regions of high atmospheric nitrogen deposition in the Fraser Valley mapped by the CMAQ spatial nitrogen deposition model (Nasr et al. 2010). For the nutrient budget, we assume that deposition rates measured at the outlet of Cultus Lake are representative of the entire watershed but geographic homogeneity is unlikely given airflow and orographic effects in mountainous terrain. Another contributing factor may be differences among subwatersheds in vegetative land cover. Vedder Mountain was logged extensively up until the 1930s and it may have a relatively high density of secondary growth broadleaf species, including nitrogen-fixing alder species, which naturally revegetated the clear-cut slopes and may be contributing to the higher export rates. Smith Falls subwatershed had the lowest TN export rate at 4.02 kg-N/ha/yr despite its proximity to the Fraser Valley, perhaps reflecting significant nitrogen retention by the wetlands in its upper catchment.

Individual TP export rates for International Ridge and Columbia Valley subwatersheds were similar to the average areal TP deposition rate of 0.20 kg-P/ha/yr for the entire watershed while Vedder Mountain and Smith Falls were both 30% higher than the average deposition rate. Given that mineral weathering, which is unaccounted for in our study, is another important contributing source of phosphorous export from watersheds, Vedder Mountain and Smith Falls subwatersheds may be either phosphorous saturated, have higher than average atmospheric P deposition rates due to orographic effects or have alternative mineral TP sources within the subwatersheds. Both subwatersheds are the Cultus Lake catchments nearest to anthropogenic phosphorous sources in the Fraser Valley.

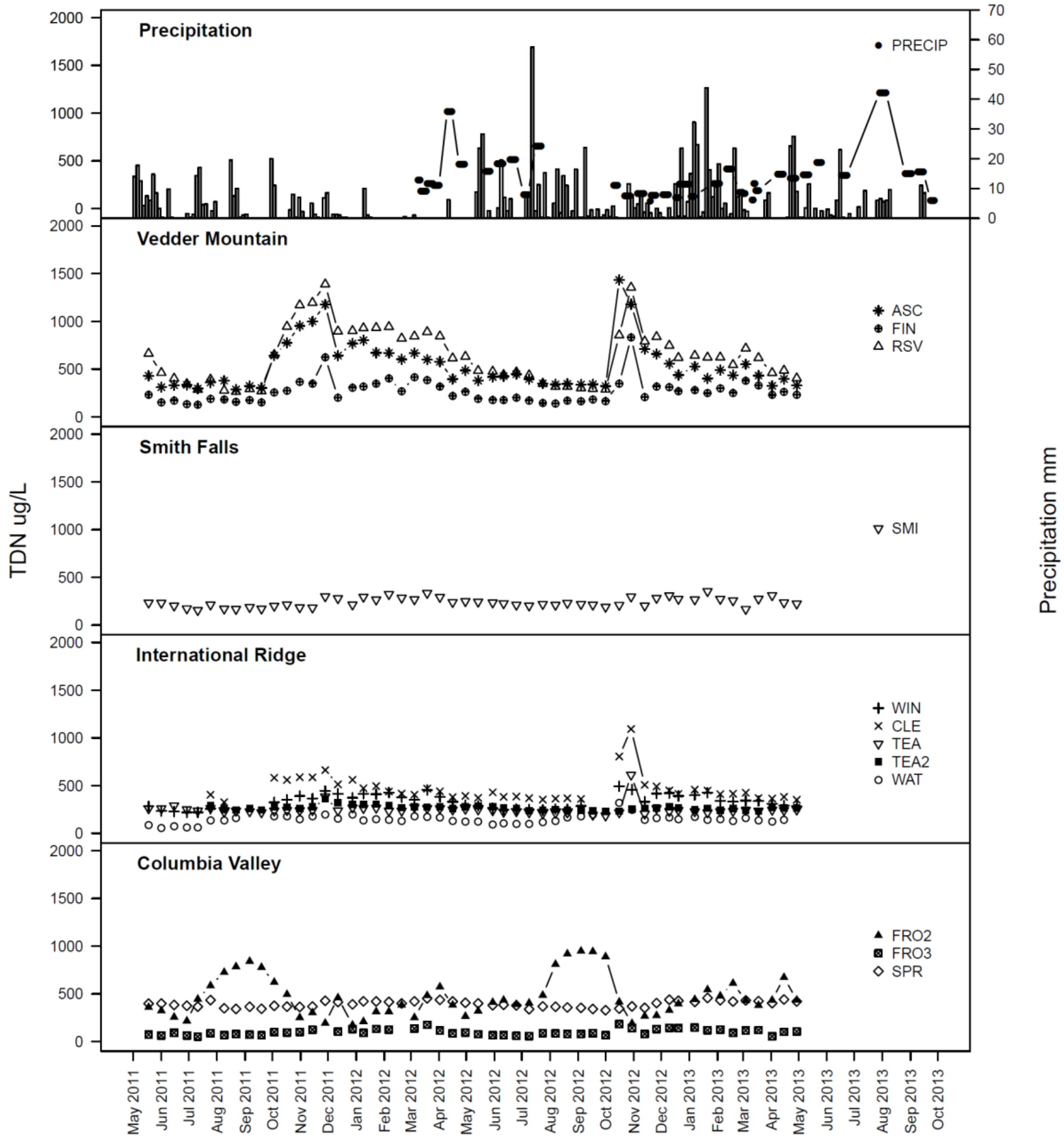

Figure 4-1 Time series of TDN concentrations (µg-N/L) in Cultus Lake streams separated into subwatershed clusters and direct precipitation on the lake (May 2011 to May 2013). Teapot Creek has been separated into its two original streams: TEA and TEA2.

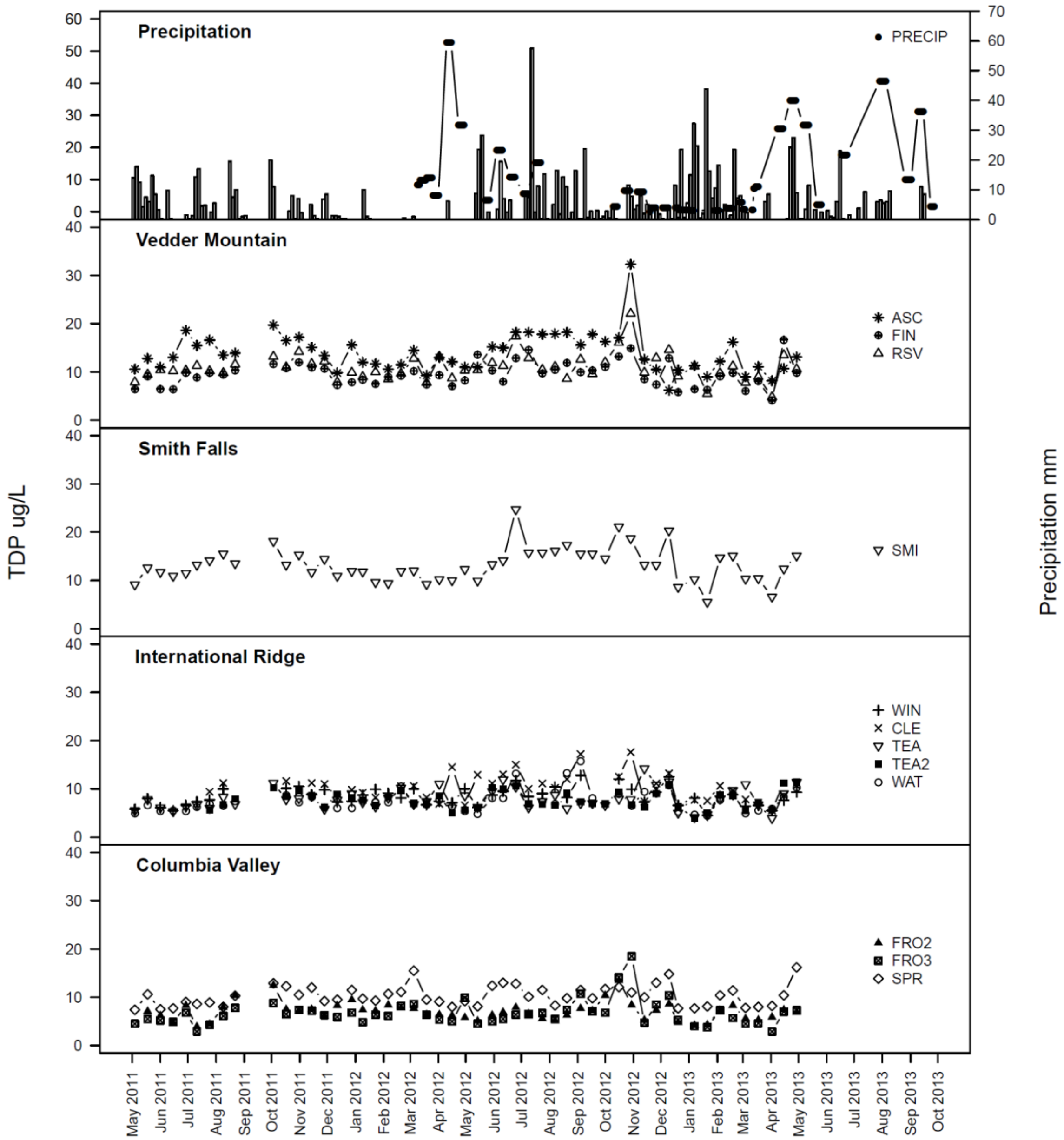

Figure 4-2 ***Time series of TDP concentrations (µg-P/L) in Cultus Lake streams separated into subwatershed clusters and direct precipitation on the lake (May 2011 to May 2013). Teapot Creek has been separated into its two original streams: TEA and TEA2.***

Table 4-2 ***Annual nitrogen and phosphorous loads into Cultus Lake. Totals for individual subwatersheds are broken into surface water and groundwater loads, and septic leaching is separated into the two subwatersheds with the majority of septic systems. Nitrogen loads for surface and groundwater loading were calculated using TDN only.***

	Avg Annual Load (kg/yr)	
Source	**TP**	**TN**
Vedder Mountain Total	**221**	**5,688**
Surface	118	3,063
Groundwater[a]	103	2,625
International Ridge Total	**305**	**7,049**
Surface	164	3,613
Groundwater[a]	141	3,436
Smith Falls Total	**209**	**2,605**
Surface	101	1,296
Groundwater[a]	107	1,309
Columbia Valley Total	**724**	**20,026**
Surface	582	15,902
Groundwater	142	4,124
Atmospheric Deposition[b]	**124**	**8,673**
Measured wet deposition	83	3,573
Estimated dry deposition	42	5,100
Migratory Gulls[c]	**355**	**585**
Septic Leaching	**238**	**2,070**
Columbia Valley Septics	170	1,485
International Ridge Septics	67	586
Sockeye Carcasses	**23**	**191**
TOTAL LOAD	**2,199**	**46,866**
Sweltzer Export	-1,258	-18,467
% Retention	42.8%	60.6%

a. Includes shallow soil interflow

b. Lake surface area only

c. Total Kjeldahl nitrogen (TKN; excludes nitrate-nitrate); however, nitrate-nitrite is expected to be low in guano

Table 4-3 Average annual export rates of nitrogen and phosphorous in the Cultus Lake watershed and annual atmospheric deposition rates.

	Average Annual Export (kg/ha/yr)					
Source	**TP**	**DOP**	**DIP**	**TN[a]**	**DON**	**DIN**
Average Watershed Export	**0.24**	**0.08**	**0.06**	**5.76[a]**	**1.07**	**4.69**
Vedder Mountain	0.31	0.10	0.09	7.92[a]	1.31	6.62
International Ridge	0.19	0.08	0.06	4.37[a]	0.75	3.62
Smith Falls	0.32	0.13	0.08	4.02[a]	1.66	2.36
Columbia Valley	0.23	0.07	0.05	6.35[a]	1.06	5.29
Atmospheric Deposition	**0.20**			**13.70**		

a. TN export for average watershed export are calculated using TDN only.

4.3. BATHTUB modelling

Parsimony between BATHTUB model predictions and observed in-lake conductivity measurements suggests the calculated water balance is appropriate for the Cultus Lake watershed and supports our groundwater runoff estimates for the Columbia Valley. Previous estimates of groundwater discharge in the Columbia Valley are variable, ranging from 4 to 73 hm^3/year (Holding and Allen 2012, Urban Systems Ltd 2012, Zubel 2000). The differences between modelled and estimated groundwater flows and the water balance estimate from this study are largely due to differences in apportioning runoff to aquifer groundwater or Frosst Creek stream water sources. Previous methods are sensitive to hydraulic assumptions, model boundary conditions, and physical parameter estimates, but the water balance method used in this study is the best estimate of aquifer discharge as it avoids many of the assumptions and uncertainties of previous methods.

With minimal calibration, the BATHTUB model accurately predicted current Secchi depth and epilimnetic TDN, TP, and chl-*a* concentrations in Cultus Lake (Table 4-4). The model predictions suggested the trophic status of Cultus Lake is oligotrophic under both pre-development and current conditions (CCME 2004), but that the lake has undergone significant eutrophication from its natural state prior to European settlement (TP +91%, TDN +103%, chl-*a* +183%; Table 4-5). The doubling of epilimnetic TP concentrations from a pre-development seasonal mean value of 4.3 µg-P/L to current concentrations of 8.2 µg-P/L were primarily due to the introduction of migratory gull guano, septic leaching, and anthropogenic atmospheric phosphorous deposition. A similar doubling of TDN from 68 to 138 µg-N/L can be attributed to the addition of agricultural loadings from the Columbia Valley and anthropogenic atmospheric nitrogen deposition.

Under the future development scenario (without nutrient mitigation), the model predicted 30%, 22% and 47% increases in epilimnetic TP, TDN and chl-*a* concentrations, respectively, relative to the current state (Table 4-5). The modeled increases in epilimnetic nutrient and chl-*a* concentrations were due to increases in both watershed and airshed loadings, particularly from septic systems, migratory gulls, and wet and dry atmospheric deposition. Mean growing season phosphorous increases up to

10.7 µg-P/L (predicted as a result of future development) suggest that Cultus Lake will shift to a mesotrophic state if the future development scenario unfolds without targeted mitigation (CCME 2004). However, it is important to consider that although the model accurately predicted epilimnetic nutrient concentrations, the resulting eutrophication and increased primary productivity may be more severe than predicted based upon these predicted nutrient concentrations due to the presence of a deep chlorophyll maximum and elevated metalimnetic production in Cultus Lake.

Modelling the proposed realistic mitigation of current watershed nutrient loads from septics (-100%), agriculture (-50%) and gulls (-45%) elicited marginal water quality improvements for Cultus Lake. Epilimnetic phosphorus concentrations were predicted to be 10% lower than current conditions, epilimnetic TDN was reduced by 8%, and there was an 18% decrease in epilimnetic chl-*a* (Table 4-5). Reductions in epilimnetic phosphorous concentrations primarily resulted from the elimination of all septic system leaching, one of the largest sources of phosphorous loadings to Cultus Lake, while reduced agricultural loadings from the Columbia Valley were largely responsible for predicted decreases to epilimnetic TDN concentrations in Cultus Lake.

Under the scenario of increased future nutrient loading from development combined with realistic nutrient mitigation measures (as in the current condition mitigation scenario), the model predicted further degradation of water quality relative to current conditions; however, declines were considerably less pronounced than predicted for the unmitigated future development scenario. Epilimnetic TP concentrations were predicted to increase by 12%, epilimnetic TDN increased by 13%, and chl-*a* increased by 18% compared to the 30%, 22% and 47% increases predicted without mitigation. The model did not predict water quality improvements in Cultus Lake because atmospheric deposition, one of the largest sources of both TDN and TP, was not mitigated in the scenario and is expected to increase in the next 25 years.

In all cases, the model predicted little change in the nitrogen to phosphorous loading ratio from the pre-development condition of 35 (molar) under current and future loading scenarios (Table 4-5). A decrease in the TDN:TP loading ratio can seriously affect the quality of nutrient limitation and algal growth in a lake if nitrogen becomes limiting to production (Schindler 2012).

Table 4-4 Calibration results for the BATHTUB model with observed and predicted epilimnetic concentrations of TP, TDN, chl-a, and Secchi depth for Cultus Lake (growing season averages), calibration factors, and descriptions of the model equations used.

Parameter	Observed[a]	Predicted[a]	Calibration Factor	Model Equation
TP (µg/L)	8.25	8.2	0.95	Second order available phosphorus
TDN (µg/L)	137.80	138.8	2.64	Second order available nitrogen
Chl-*a* (µg/L)	1.68	1.7	0.95	Exponential as a function of phosphorous (Jones & Bachman, 1976)
Secchi Depth (m)	7.50	7.0	1.00	Linear as a function of chlorophyll *a* and turbidity

a. Epilimnetic growing season averages; mean of 2011 and 2012

Table 4-5 ***BATHTUB model results for current steady state water quality conditions in Cultus Lake, the estimate of water quality conditions prior to European settlement and land development, predicted water quality if current nutrient sources are mitigated, and water quality predictions for two future development scenarios with and without nutrient mitigation. TP, TDN, and* chl-*a* *are model estimates of epilimnetic growing season averages.***

Scenario	TP (µg/L)	TDN (µg/L)	Chl-*a* (µg/L)	$TDN:TP_{molar}$
Current	8.2	137.8	1.7	37.2
Pre-development	4.3	68.0	0.6	35.0
Future development	10.7	167.6	2.5	34.6
Mitigated	7.4	126.6	1.4	37.8
Mitigated Future	9.2	155.9	2.0	37.5

5. Discussion

Integrated watershed management, which requires broad stakeholder cooperation to manage aquatic resources at the watershed scale, is necessary for lakes near urban and agricultural areas to address the variety of anthropogenic stressors and diverse stakeholder interests associated with these ecosystems (Ghadouani and Coggins 2011). Our analysis identified substantial nutrient loading to Cultus Lake from multiple sources both within the lake watershed and the regional airshed, highlighting the need for a multijurisdictional management approach encompassing the British Columbia Lower Mainland (Fraser Valley and Metropolitan Vancouver) to conserve water quality and ecosystem services in Cultus Lake and other potentially impacted regional watersheds. The nutrient sources identified in this study account for the range of eutrophication-related water quality degradation in Cultus Lake over the past century (Shortreed 2007), and lake modelling predicted that water quality declines will continue with expanding regional development and population growth. By virtue of their geographical position and the predominant westerly atmospheric flows, lakes in the British Columbia Lower Mainland may be disproportionately influenced by atmospheric nutrient loading from intensive regional agriculture, transportation corridors and urban development. Our exploration of potential nutrient mitigation for Cultus Lake indicated that although mitigating watershed sources are a necessary step to slow the progress of eutrophication, a multifaceted approach that targets airshed sources within the Lower Mainland is required to halt or reverse eutrophication trends.

5.1. Nutrient sources and loadings to Cultus Lake

By constructing detailed water and nutrient budgets for Cultus Lake, we were able to identify the most important annual and seasonal sources of nitrogen and phosphorous loadings. Atmospheric deposition of nitrogen and phosphorous, both directly to the surface of Cultus Lake and exported in runoff from its subwatersheds, proved to be one of the largest sources of nutrient loadings. Using regional nutrient export coefficients for other pristine watersheds, we estimated that a substantial portion of the nutrients in subwatershed runoff could be attributed to atmospheric deposition of nitrogen and phosphorous on land. High atmospheric deposition is likely due to the westerly atmospheric flows that transport pollution from Metro Vancouver, the Fraser Valley, and possibly Whatcom County, USA up the Fraser Valley and into the Cultus Lake watershed (Vingarzan and Li 2006). In general, the Vedder Mountain subwatershed in the north part of the Cultus Lake watershed closest to atmospheric sources in the Fraser Valley exhibited higher nutrient concentrations and export rates than the upper Columbia Valley or International Ridge subwatersheds that are furthest from these atmospheric sources.

In addition to atmospheric deposition and subwatershed runoff, substantial sources of TP loading to Cultus Lake were from migratory gull guano and leaching from septic systems. Nutrient loadings from septic systems were highest during the summer growing season when cottage residents and tourist visits reach their seasonal peak. In contrast, guano nutrient loading primarily occurs in winter, the period of highest lake flushing due to seasonal precipitation, and may exhibit enhanced winter export from the lake that reduces availability to primary producers during the stratified growing season (Jeppesen et al. 2005, Koiv et al. 2010). Winter primary production is high in Cultus Lake relative to other British Columbia sockeye salmon lakes (Shortreed et al. 2001), and year-round nutrient loading likely contributes to the enhanced productivity of Cultus Lake and associated impacts on lake ecology (e.g., hypolimnetic oxygen demand).

We identified groundwater in subwatershed runoff from the Columbia Valley as being highly enriched with agriculturally-sourced nitrogen, but not phosphorous (Table 4-2). While nitrogen levels in runoff from the other subwatersheds were generally highest during the onset of the fall wet season (Appendix E), nitrogen levels in Frosst Creek were elevated during the dry summer period due to nitrogen rich groundwater from the Columbia Valley aquifer comprising most of the baseflow. Nitrogen levels in groundwater spring-fed Spring Creek were also elevated and varied little through the season. The relatively constant concentration of nitrogen in Columbia Valley groundwater suggests that agriculturally-derived nitrogen is relatively well mixed in the aquifer before reaching the creeks and discharging into Cultus Lake. Our examination of water quality in three groundwater-dominated sources (i.e., Spring Creek, Frosst Creek during baseflow, and Lindell Beach groundwater wells) suggested decreasing nitrogen concentrations with proximity to Cultus Lake (Appendix D). As agriculturally-sourced nitrogen travels north along the groundwater gradient to Cultus Lake, it is likely diluted by forested runoff from the valley ridges that infiltrates valley soils and contributes to aquifer flow (Zubel 2000).

Agriculture in the Columbia Valley was a major source of nitrogen but not phosphorous for Cultus Lake. High phosphorous export has been documented in other agricultural catchments (Jones et al. 2001, Coulter et al. 2004, Domagalski and Johnson 2011, Wise and Johnson 2011), suggesting that the phosphorous, unlike nitrogen, is being retained in the deep glacial outwash sediments of the Columbia Valley. Zubel (2000) noted a lack of surface water pathways in the valley, and hypothesized that >2.5 yrs would be required for the vertical infiltration of water through the unsaturated sediments into the Columbia Valley aquifer (30 to 50 m below the soils surface). Nitrates have been shown to freely leach into groundwater through similar soils and sediments (Chesnaux and Allan 2007), but phosphates can be sorbed and retained by iron and aluminum oxides and clay and calcium minerals (Domagalski and Johnson 2011). However, phosphorous leaching to the aquifer may increase in the event of continued or increasing agricultural inputs and soil saturation. The degree of soil phosphorous saturation in the Columbia Valley is a source of uncertainty that could have major implications for future nutrient loadings to Cultus Lake, and studies should be undertaken to quantify the risk to Cultus Lake from current and future agricultural development.

Nitrogen and phosphorous areal export rates are routinely used to assess the effects of local and regional anthropogenic nutrient sources on freshwater ecosystems, as they integrate atmospheric and landscape nutrient sources (Campbell et al. 2003). We relied on areal export rates measured in pristine watersheds of the Pacific Northwest to estimate the background levels of nutrient export expected from the Cultus Lake watershed without anthropogenic inputs. Catchment export rates have been measured in undeveloped, mixed-use, and agricultural watersheds in the Pacific Northwest (PNW), with the highest areal loads generally occurring in agricultural catchments, or in watersheds located within urban airsheds (Schaefer et al. 2009, Wise and Johnson 2011). Nitrogen exports are low (<5 kg-N/ha/yr) in pristine watersheds such as those located in the Oregon Cascade Mountains (Martin and Harr 1988, Vanderbilt et al. 2002) and on Vancouver Island (i.e., Sooke Lake; Zhu and Mazumder 2008) (Figure 2-1), while exports from undeveloped watersheds within urban airsheds can reach 10 kg-N/ha/yr (Schaefer et al. 2009, Wise and Johnson 2011). Agricultural development results in higher atmospheric and landscape nutrient loads, with TN exports >10 kg-N/ha/yr, due to excess fertilizer inputs, livestock production, and soil erosion (Schindler, Dillon and Schreier 2006).

TN exports from the Cultus Lake watershed (5.8 kg-N/ha/yr) were high relative to regional undeveloped areas, but were within the nitrogen export ranges measured by Schaefer et al. (2009) and Wise and Johnson (2011) in mixed-use watersheds in similar climatic settings. Phosphorous exports within the Cultus Lake watershed were more difficult to compare to regional values, due to the highly site-specific nature of geologically-sourced phosphorous (Mahowald et al. 2008). Two watersheds on Saltspring Island (Roberts and Blackburn Lakes climatically and geologically similar to Cultus Lake but outside of substantial urban and agricultural airshed influences; Figure 2-1) exhibited TP export rates 60% lower than at Cultus Lake (i.e., 0.08 to 0.10 kg-P/ha/yr; Sprague 2007), highlighting the substantial anthropogenic- airshed contributions to the Cultus Lake watershed.

5.2. The past, present, and future nutrient status of Cultus Lake

Cultus Lake is currently oligo-mesotrophic (i.e., epilimnetic TP ranges from 6 to 15 µg-P/L; CCME 2004) but surface water (epilimnetic) nutrient concentrations in Cultus Lake have increased relative to baseline conditions prior to Euro-American arrival in response to nutrient loading from agricultural development, atmospheric deposition, septic leaching, and migratory gull guano (Table 4-5). The BATHTUB model estimated that current TP and TDN concentrations have roughly doubled since Euro-American settlement, while chlorophyll *a* has increased by 183%. The model estimates were consistent with limnological research and observations by long-term watershed residents that indicate deteriorating water quality in Cultus Lake. Comparative limnological research suggests that lake productivity has increased over the past century, and hypolimnetic oxygen has decreased relative to the 1920's and 1930's (Ricker 1937, Shortreed 2007).

The model predictions indicate Cultus Lake may shift to a mesotrophic state (i.e., >10 µg-P/L, CCME 2004) due to unmitigated increases in nutrient loadings from septic systems, migratory gulls, and atmospheric deposition (Table 4-5). Eutrophication-induced hypoxia has altered cold-water fish distributions in freshwater lakes globally, generally forcing fish to occupy the upper water column where enhanced predation and potentially detrimental water temperatures can elicit deleterious effects (Ficke et al. 2007, Jeppesen et al. 2010). In Cultus Lake, further eutrophication will negatively impact hypolimnetic oxygen levels during stratification and reduce the quality of deepwater thermal refuges (i.e., shift towards hypoxia) for resident species at risk (coastrange sculpin and sockeye salmon). Climate change can exacerbate hypoxia if warming continues by extending the stratified growing season. Hypoxia may also alter food webs in Cultus Lake critical for the persistence of these species (COSEWIC 2010, Bradford et al. 2011, Chiang et al. in press). Hypolimnetic anoxia can also lead to internal nutrient loading (phosphorous and ammonia) from lake sediments, which accelerates eutrophication (positive feedback) and can eventually shift lakes into a self-sustaining hyper-eutrophic state (Carpenter et al. 1999, Anderson et al. 2009). Sequestration of both nitrogen and phosphorous in lake sediments is high in Cultus Lake with 61% and 43% of total nitrogen and phosphorous loading respectively retained in the lake (Table 4-2), and anoxia-induced internal loading represents a substantial risk to future lake water quality, and the persistence of species at risk.

Eutrophication can reduce ecosystem services derived from lakes close to urban centres through decreased water clarity, unsightly and potentially toxic cyanobacteria blooms, reduced recreational fisheries, and nuisance macrophytes in swimming areas (Dodds et al. 2009). Reduced ecosystem services can negatively affect the economic and cultural benefits derived from freshwater lakes (Wilson and Carpenter 1999, Mossop and Bradford 2004, Carmago and Alonso 2006). Cyanobacteria blooms have led to beach closures and health advisories in tourist areas, fisheries closures, and reduced tourism, negatively impacting economies of nearby communities (Camargo and Alonso 2006, O'Neil et al. 2012). Cultus Lake may remain phosphorous limited in response to continued or enhanced atmospheric nitrogen deposition (Table 4-5) but cyanobacteria and other nuisance algae may increase due to proximate epilimnetic nitrogen limitation or increased phosphorous availability as a result of internal loading (Davies et al. 2004, Shortreed 2007). Spatially-isolated heterocystous cyanobacteria blooms (*Anabaena* spp.) were observed in Cultus Lake in 2012, suggesting that proximate epilimnetic nitrogen limitation occurs and may increase with anticipated future nutrient loads in the absence of mitigation. Cultus Lake residents and visitors have already observed deteriorating water quality and increasing macrophytes in swimming areas (Robinson 2012), and further eutrophication may negatively affect tourism-based economies at Cultus Lake and in the surrounding area.

Eutrophication-induced changes in freshwater ecosystems will likely be exacerbated by the cumulative effects of other anthropogenic stressors, and in particular, a warming climate (Ficke et al. 2007, Moss 2012). Climate change represents a threat to global water quality as it can exacerbate habitat degradation, change flow regimes, encourage the spread of invasive species, and enhance the impacts of industrial contamination (Schindler 2001, Ficke et al. 2007). Climate modelling projections for the South Coast Region of British Columbia predict increasing air temperatures (1.1-2.5 C increase) and total annual precipitation volumes (6% increase) by 2050 (PCIC 2013). Precipitation is projected to increase in spring and winter, with corresponding decreases in snowfall (winter -24%, spring -52%) and summer precipitation (-14%; PCIC 2013), potentially altering freshet characteristics, hydrological flow regimes and seasonal lake flushing (Pike et al. 2008).

The cumulative effects of future climate change on Cultus Lake are uncertain; the effects and interactions of climate change may serve to further degrade Cultus Lake water quality and fish habitat, as increasing nutrients and temperatures tend to intensify the ecological effects of eutrophication (Moss et al. 2011). Warmer temperatures and increased spring and winter precipitation may result in earlier, more pronounced lake stratification that may enhance the influence of summer loadings, particularly from septic leaching. Warmer temperatures may also prolong stratification, thereby increasing algal production and hypolimnetic oxygen depletion beyond the scope of what has been considered in this study, degrading and reducing habitat for cold-water fish species (Schindler 2001, Ficke et al. 2007, Moss 2012). Enhanced biological turbidity (i.e. algae, bacteria) may increase heat retention, with the potential to induce food web reorganization and enhance thermal stresses on coldwater fish species such as sockeye salmon and Cultus Lake pygmy sculpin. Warmer surface temperatures and enhanced deepwater biological oxygen demands may also result in a temperature-oxygen squeeze in Cultus Lake, where hypoxic bottom waters and sub-lethal to lethal surface water temperatures encroach upon one another and lead to an overall reduction in suitable fish habitat. Cultus Lake sockeye salmon, in particular, already face threats of overexploitation and increasing river temperatures during migration (Morrison et al. 2002), and eutrophication in Cultus Lake could interact to enhance the risk of extinction of this species.

5.3. Nutrient mitigation recommendations for Cultus Lake

Mitigating phosphorous loading to Cultus Lake will be critical to slowing eutrophication and protecting resident species at risk. We examined two separate scenarios of mitigation for Cultus Lake: mitigation of current loadings from septics, gulls and Columbia Valley agriculture, and mitigation of the increasing loads expected from projected future development and gull populations. Mitigating current loadings resulted in decreased concentrations of epilimnetic phosphorous and nitrogen in Cultus Lake; however, mitigation of future development still predicted increasing epilimnetic nutrient concentrations relative to current lake conditions (Table 4-5). Development and increased airshed loadings will likely outpace efforts to mitigate watershed sources alone (i.e., septic, gull, and agricultural sources), making management of atmospheric sources essential to halt or reverse eutrophication in the lake. Although targeting reductions in atmospheric nutrient loads is necessary, reducing nutrient loadings from sources within the watershed will improve or slow the degradation of water quality and should be a key component of future watershed nutrient abatement strategies. Mitigation of these local watershed sources can be undertaken without substantial cross-jurisdictional cooperation, while reducing atmospheric deposition is a regional issue that will require a multifaceted and integrated management approach.

One of the largest phosphorous sources to Cultus Lake that is likely to increase with development is septic leaching. Septic systems and sewage inflows have been found to contribute heavily to the global eutrophication of lakes with intensive shoreline development (Stollenwerk 1996, Carpenter et al. 1998, Moore et al. 2003), and removing septic sources (i.e., sewer export to treatment facilities) has led to significant water quality improvements (Smith 1998; Ockenden et al. 2014). In Cultus Lake, substantial phosphorous loadings may be occurring from septic systems due to high septic use in the summer, coupled with the potential for shoreline groundwater infiltration through the pervious soils and glacial tills that comprise the shoreline of the lake. We used relatively conservative assumptions for soil retention to estimate septic inputs, but the exact magnitude of septic leaching into Cultus Lake is relatively uncertain given the nature of the shallow soils and age of many of the septic systems and requires detailed studies to quantify further. Despite these uncertainties, using conservative estimation, septic systems were identified as a large source of phosphorous loading into Cultus Lake. The lake modeling suggests reducing the contribution of septic leaching to total nutrient loadings would likely result in water quality improvements in Cultus Lake.

Another large source of phosphorous loading for which mitigation measures could lead to improved water quality in Cultus Lake is guano from high densities of migratory gulls, which have been found to disrupt nutrient cycling and result in eutrophication of other temperate lakes (Payne and Moore 2006, Hahn et al. 2007). The absolute guano-sourced phosphorus loading from migratory birds and its impact on Cultus Lake water quality is uncertain due to intra-specific variations in gull guano production rates, uncertainty in the bioavailability and remineralization of guano-derived nutrients, and somewhat variable intra-annual population estimates (9 - 12.5K). While our estimates of avian-derived nutrients could be improved with further guano sampling and population monitoring, our models indicate guano represents a substantial phosphorus load to Cultus Lake annually. Glaucous-winged gulls are protected under the Migratory Bird Convention Act (MBCA; Government of Canada 2014), and reducing Cultus Lake gull populations will be challenging because of their migratory nature, the richness of nearby feeding areas in the Fraser Valley, and the negative social connotations of noise-related gull deterrent tactics and lethal control methods (Baxter and Robinson 2007, Government of Canada 2014). Despite these challenges, the use of non-lethal tactics has successfully reduced gull numbers at landfills and agricultural areas (Baxter and Robinson 2007, Cook et al. 2008, Thiériot et al. 2012), and these tactics could be considered for daytime feeding sites located near Cultus Lake.

Agricultural nutrient loading represents one of the largest non-point sources of nutrient loading to aquatic ecosystems worldwide, and reducing agricultural contributions is often a critical step to improving water quality in heavily impacted areas (Carpenter et al. 1998). Agricultural nutrients contribute substantially to loadings to Cultus Lake from its watershed and airshed, and mitigation should be considered that reduces excess agricultural loadings to soils and groundwater in the Columbia Valley. The unique geology and depth of sediments above the water table in the Columbia Valley relative to the rest of the Cultus Lake watershed suggest that Columbia Valley soils may geochemically retain agriculturally-derived phosphorous. However, phosphorous loading into Cultus Lake may increase if soils in the Columbia Valley become saturated with phosphorous, and a precautionary approach should be considered that minimizes excess nutrient loading from current and future agricultural development (Sims et al. 1998, McDowell et al. 2001). Improved fertilizer application and altered agricultural management practices (e.g., deep cropping, soil nutrient testing conservation tillage, livestock control) can decrease future agricultural loadings (Sims et al. 2000, Dinnes et al. 2002), and these strategies should be implemented in the Cultus Lake watershed to mitigate the risk of future phosphorous loadings to the lake.

Modeled lake water quality continued to decline under a scenario of future development combined with watershed mitigation measures (i.e., partially mitigating gull guano, eliminating septic leaching, and reducing agricultural inputs), indicating that the atmospheric sources outside of the watershed can override the benefits of mitigation efforts for watershed sources alone. Increased atmospheric deposition, as a result of urban and agricultural growth in the Fraser Valley, represents one of the largest impediments to effective nutrient abatement in Cultus Lake, and potentially in similarly impacted watersheds throughout the Lower Mainland of British Columbia. The Fraser Valley is undergoing agricultural intensification and increasing urban densification, and nitrogen (particularly ammonia) and particulate phosphorous deposition may increase throughout the Lower Mainland (Metro Vancouver 2013). Reducing current and future atmospheric deposition should be a priority due to the widespread nature of atmospheric pollution and the potential for interactive effects with industrial pollutants, aerosols from regional and trans-Pacific sources, and changing climate patterns. The Lower Mainland represents a uniquely sensitive system due to its complex topography and high urban and agricultural emissions, and a precautionary approach is recommended that considers the interactive effects of atmospheric pollution and climate change on regional ecosystems such as Cultus Lake. Ozone and particulate matter reductions have been the focus of emissions management in the Lower Mainland due to human health effects (e.g., FVRD 1998, Metro Vancouver 2008); however, our research indicates that nutrient emissions should also be targeted due to their potential to contribute to the eutrophication of aquatic ecosystems, impact the socioeconomic values of these ecosystems, and disrupt the biogeochemical cycles in natural ecosystems throughout the Lower Mainland.

5.4. Nutrient pollution throughout the Lower Mainland and Pacific Northwest

High levels of atmospheric deposition identified in the Cultus Lake watershed and throughout the Lower Mainland suggest that urban and agricultural emissions are impacting valuable ecosystems throughout the region. Atmospheric deposition in the Lower Mainland is substantial in both developed and undeveloped areas, with TN deposition in Abbotsford and the Elk Creek watershed (Figure 2-1) averaging 8.6 and 25.7 kg-N/ha/yr, respectively (Belzer et al. 1997, Vingarzan et al. 2000). Evidence of elevated TN deposition has also been found in the East Creek watershed (~6 kg-N/ha/yr from 2000 to 2010) and at Loon Lake, two undeveloped forested watersheds in the University of British Columbia's Malcolm Knapp Research Forest (Figure 2-1), located within the airshed of Metro Vancouver (Feller 2010, Holtgrieve et al. 2011). Nitrogen saturation, primarily as a result of atmospheric deposition, has been observed in the East Creek watershed (Feller 2010), suggesting that nutrient emissions from Metro Vancouver and the Fraser Valley are altering biogeochemical cycles in terrestrial and freshwater ecosystems throughout the region.

Atmospheric TN and TP deposition are major sources of nutrient loading to watersheds located in areas downwind of urban centres and agricultural development throughout North America (Mahowald 2008, Wise and Johnson 2011). Nitrogen deposition is >20 kg-N/ha/yr in most of the northeastern United States as a result of emissions from high density urban areas (Zhang et al. 2012), and although western

North America is characterized by fewer urban and industrial sources, atmospheric deposition in catchments located within urban airsheds can surpass 20 kg-N/ha/yr (Schaefer et al. 2009, Fenn et al. 2013). In addition to high deposition rates in urban and agricultural airsheds, anthropogenic nitrogen deposition has been identified as a low-level source of global nutrient loading in pristine watersheds located far from emissions sources (Perakis and Hedin 2002, Holtgrieve et al. 2011, Grigal 2012). Widespread TN deposition represents a shift in the global nitrogen cycle that may be responsible for increased nitrogen saturation in terrestrial and aquatic ecosystems, increased phosphorous limitation in lakes, and changes to ecosystem biodiversity (Goldman 1988, Perakis and Hedin 2002, Elser et al. 2009, Holtgrieve et al. 2011, Elser 2011). Our research indicates that atmospheric pollution in Metro Vancouver and the Fraser Valley has likely altered conditions in Cultus Lake and ecosystems throughout the valley, and nutrient deposition will continue to degrade the lake ecosystem if mitigation measures in the airshed and watershed are not initiated.

5.5. Conclusion

Population growth and agricultural expansion in Metro Vancouver and the Fraser Valley will increase development pressures throughout the Lower Mainland, likely with negative effects on the structure and functioning of both terrestrial and aquatic ecosystems. Declining water quality has been observed in freshwater lakes in the Lower Mainland (e.g., Cultus Lake, this study; Loon Lake; Holtgrieve et al. 2011), and in areas of the Pacific Northwest downwind of urban and agricultural sources (e.g., lakes in Mount Rainer and North Cascades National Parks in Washington, USA, and Lake Washington; Edmondson 1981, Clow and Campbell 2008). Our research indicates that although local watershed sources contribute heavily to Cultus Lake nutrient loadings, atmospheric nutrient deposition originating from urban and agricultural activities is likely the primary component of elevated nutrient loadings, particularly of nitrogen. Scenario-based lake modelling suggests that although mitigating local watershed sources will improve water quality and should be a focus of watershed management, reducing loadings from atmospheric deposition will be necessary to reverse eutrophication in the context of increased future loadings. Freshwater lakes in the Lower Mainland provide valuable ecosystem services and habitat for important species at risk, and mitigating atmospheric nutrient deposition is likely critical for sustaining ecosystem services, and future use and enjoyment of lakes throughout the region.

Due to the cross-jurisdictional nature of nutrient loadings to Cultus Lake, an integrated management approach that brings together all stakeholders and levels of government to mitigate nutrients at both the local and regional scales will be required. Stakeholder interests in Cultus Lake are diverse, and water quality requirements for ecosystem services and species at risk must both be considered in management initiatives. Realizable water quality goals and mitigation approaches that address phosphorous sources to Cultus Lake (particularly septic leaching and migratory gull guano) are necessary to slow current eutrophication trends. Eutrophication is a reversible phenomenon, and mitigating watershed sources has resulted in near complete water quality recovery in lakes where local sources contributed the bulk of nutrient loadings (e.g., Lake Washington; Edmondson 1981). Reversing eutrophication will be challenging at Cultus Lake and similarly impacted systems in the Lower Mainland due to the regional nature of elevated atmospheric nutrient deposition. However, an integrated management approach that accounts for diverse stakeholder interests and manages nutrient loadings at a regional scale can halt or reduce eutrophication, and should be a priority to maintain ecosystem services and protect habitat for species at risk in Cultus Lake and other regional lake ecosystems.

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Appendix A.

Study site description

Cultus Lake is located in southwestern British Columbia, 10 km south of the city of Chilliwack, within the Pacific Northwest (PNW) coastal mountains (Figure 2-1). The lake has a surface area of 6.3 km^2, with a mean depth of 31 m and a maximum recorded depth of 44 m (Shortreed 2007). The total area of the drainage basin is 69 km^2, 18% (12.2 km^2) of which lies in the United States (Binder L, University of the Fraser Valley, September 2013, pers. comm.). The watershed is located in the coastal western hemlock biogeoclimatic zone and has a temperate maritime climate (Meidinger and Pojar 1991). Forests contain both broadleaf and coniferous species, including western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn.), Douglas-fir (*Pseudotsuga mensiesii* (Mirb.) Franco), western white pine (*Pinus monticola* Dougl.), bigleaf maple (*Acer macrophyllum* Pursh), and red alder (*Alnus rubra* Bong.; found primarily in disturbed areas; Meidinger and Pojar 1991). Daily average temperatures for the Chilliwack station (1981-2010) range from a high of 18.8 C in August to a low of 3.3 C in December and January (Environment Canada 2013a). Total annual precipitation for Chilliwack averages 1,582 mm, most of which falls between the months of October and April (averaged from 1981-2010; Environment Canada 2013a).

The Cultus Lake watershed was logged throughout the early 1900's; however, by the 1940's and 1950's logging activity decreased and the lake's popularity as a recreational destination began to grow (Schubert et al. 2002). In 1932, a municipal park (244 ha) was created by the City of Chilliwack on the northern shore of the lake. Originally maintained jointly by the City and Township of Chilliwack, park operations were later handed over to the privately-run Cultus Lake Parks Board. In 1948, 385 ha on the eastern side of the watershed were designated as provincial park land through the creation of Cultus Lake Provincial Park. The park area was nearly doubled in 1969, and the area upslope was subsequently designated as the International Ridge Recreational Area. While no formal record exists of the annual number of visitors to the Cultus Lake watershed, traffic counts from the Fraser Valley Regional District (FVRD) indicate the total number of visits per year is as high as 3 million and is likely to increase if the Fraser Valley population grows as projected (Delcan 2012).

Subwatersheds of the Cultus Lake watershed

There are 11 major tributaries in the Cultus Lake watershed, the catchment areas of which combine to drain ~60% of the total watershed area (Table 2-1; Binder L, University of the Fraser Valley, September 2013, pers. comm.). The lake is located in a valley bounded by the Vedder Mountain ridge to the west, the International Ridge to the east, and the Columbia Valley to the south. The two ridges and the valley bottom have very different geological and hydrological properties, and these differences, combined with the chemical properties of Cultus Lake tributaries, were used to partition the watershed into subwatershed groupings and summarize watershed data on a broader scale. Subwatersheds were delineated using watershed characteristics supported by a hierarchical agglomerative cluster analysis (Ward 1963, Güler et al. 2002) performed using the logarithms of biweekly dissolved organic matter (DOM) and conductivity data from each of the streams. These two stream water quality constituents are related to differences in watershed geology and soil characteristics, and can be used to characterize and group drainage basins accordingly. Ward's linkage algorithm (Ward 1963) was used to cluster the streams into subwatershed groupings based on Euclidean distances of the chemical variables (R-package Pvclust: Ryota and Hidetoshi 2011). Because DOM and conductivity can be seasonally variable, hierarchical groupings were examined for each of the 2 study years as well as for calendar seasons. Based on the cluster analysis and geographic and land use considerations, the Cultus Lake watershed was divided into 4 subwatersheds: Vedder Mountain, International Ridge, Smith Falls, and Columbia Valley (Figure A1). A fifth subwatershed, Sweltzer Creek, was located at the northern extent of the watershed and included the lake's outflow (Sweltzer Creek) and a small portion of the northern watershed.

Vedder Mountain

The Vedder Mountain subwatershed includes catchment areas for 3 small creeks that drain into Cultus Lake: Ascaphus Creek, Fin Creek, and Reservoir Creek. These 3 streams were clustered together according to their low conductivities and similar DOM concentrations. The geology of the area is primarily metasedimentary sandstone, conglomerate, shale and other sedimentary bedrock overlain with shallow glacial gravel tills and organic soils (Holding and Allen 2012, MapPlace 2014). A portion of the flow in all 3 creeks runs subsurface in alluvial gravel fans near the lake shore, and there is likely direct subsurface discharge into Cultus Lake along the shoreline. Vedder Mountain has a mean slope of 16 degrees and is composed of a series of terraces separated by steep slopes and rock outcrops along the southern portion of the subwatershed. A substantial portion (53%) of the total area is not drained by the 3 tributaries but is instead drained by overland flow and subsurface interflows not channelized into permanent streams.

The subwatershed was logged until the 1930s, and the secondary forest is dominated by broadleaf species that cover >50% of the subwatershed area (Government of Canada 2009, Binder L, University of the Fraser Valley, September 2013, pers. comm.). Broadleaf forests in the watershed include bigleaf maple and red alder, a species commonly found in primary succession forests in the Pacific Northwest (Meidinger and Pojar 1991). The prominence of red alder and other broadleaf species is likely successional due to historic logging activity, which makes the Vedder Mountain forests the youngest in the watershed. In addition to broadleaf cover, the remaining subwatershed areas are primarily categorized as open coniferous and shrub cover types. Recreational use is present within the subwatershed, with mountain biking and dirt bike trails throughout the eastern portion, and the Cultus Lake Provincial Park group campsite located on the shoreline near Ascaphus Creek.

International Ridge

There are 4 major tributaries located in the International Ridge subwatershed: Windfall Creek, Clear Creek, Teapot Creek, and Watt Creek. Teapot Creek is a combination of 2 small creeks located near each other with similar chemical and physical characteristics. This subwatershed is a combination of 2 stream clusters with similar DOM values but different conductivities. One of the clusters contained Teapot Creek, while the other cluster contained the remaining three creeks. Teapot Creek is primarily groundwater-fed and flows subsurface for a substantial period before discharging into the lake. This subsurface movement results in high and seasonally constant conductivities in Teapot Creek relative to other creeks in the area; however, due to the close geographic proximity and similar land cover classes of the 2 clusters, Teapot Creek was included in the International Ridge subwatershed.

The geology of International Ridge is composed of argillite and shale, with bedrock overlain by glacial till and shallow organic soils similar to Vedder Mountain (Comar et al. 1962, Holding and Allen 2012). The streams have large colluvial and alluvial deposits of weathered rock and gravels near their outflows along the shoreline. Shallow subsurface discharges along the shore of the lake are likely occurring in this zone due to the permeable till and colluvial deposits and steep average slope of the subwatershed (24 degrees). Monitored tributaries account for 81% of the total drainage on International Ridge, with the remaining 20% of the subwatershed being drained by ungauged overland flow and interflow (Binder L, University of the Fraser Valley, September 2013, pers. comm.). The main land covers on the ridge are dense and open coniferous forest, which account for over 80% of the forest cover in subwatershed areas (Government of Canada 2009, Binder L, University of the Fraser Valley, September 2013, pers. comm.). The remaining area is dominated by dense broadleaf forest. Most of the subwatershed lies within Cultus Lake Provincial Park, which experiences intensive seasonal use. Campgrounds and day use areas are located along the shoreline, and forested land and hiking trails extend into the upper slopes of the ridge.

Smith Falls

The Smith Falls subwatershed contains only one tributary, Smith Falls Creek, whose drainage accounts for 100% of the total subwatershed area. The cluster analysis placed Smith Falls Creek in its own cluster due to high conductivity values and above-average DOM values. Saunders (1985) identified that a portion of the Smith Falls subwatershed was once the site of an ancient ice-margin lake, formed by stagnant ice left from receding glaciers at the Pleistocene-Holocene transition. The historic presence of this lake may explain the flat topography of the subwatershed, and the high-conductivity likely reflects the glacio-lacustrine clays from the ancient lake sediments underlying watershed soils.

A portion of the catchment lies in Cultus Lake Provincial Park, and the forest cover and geology are similar to the International Ridge subwatershed. Smith Falls is primarily open coniferous forest (>70% of the total area), although the watershed also has areas of herb, developed, and shrub cover types (Government of Canada 2009, Binder L, University of the Fraser Valley, September 2013, pers. comm.). A more north-eastern portion of the watershed is sparsely covered and contains a number of meadows and holding ponds created by beaver activity, which interrupt the flow of Smith Falls Creek.

Columbia Valley

The Columbia Valley subwatershed includes Frosst Creek, the largest tributary to Cultus Lake. A second creek, Spring Creek, is located in the watershed, and is almost entirely groundwater-fed. As it is not considered a surface waterbody, Spring Creek was not included in the cluster analysis. Frosst Creek was generally clustered with the Vedder Mountain streams, likely due to low conductivity in the creek. A portion of the Frosst Creek drainage is located on the same ridge as Vedder Mountain, which may also have contributed to similar water chemistry properties. Frosst Creek was placed in a separate subwatershed due to its unique slope, elevation, and land use categories.

The predominant topographical feature in the Columbia Valley is a raised terrace 500 m south of the Cultus Lake shoreline that abruptly drops ~100 m and then slopes towards the lake at a shallow gradient of 0.05 degrees (Holding and Allen 2012). The community of Lindell Beach and two golf courses are located below this terrace along the southern shoreline of Cultus Lake. The surficial geology in the Columbia Valley is characterized by glaciofluvial outwash sediments (primarily sand and gravel) that are >120 m deep in some areas and overlie unconsolidated glacial sediments and sedimentary bedrock (Zubel 2000, MapPlace 2014). These sediments are part of a large glacial deposit located in the Lower Fraser Region, collectively known as the Sumas Drift (Holding and Allen 2012). Above these outwash sediments is a 30 to 40 cm layer of sandy eolian loam, a fertile and rapidly-drained soil (Zubel 2000). Below the sandy eolian loam lies an unsaturated outwash sediment layer of 30 to 50 m in depth, located above the water table and the unconfined Columbia Valley aquifer. The aquifer is thought to be approximately 1,000 m wide in some areas and at least 50 m deep below the water table (Zubel 2000), extending from the lake boundary into the United States to the south. Groundwater discharges at depth directly from the aquifer into Cultus Lake and Frosst Creek (which bisects the valley) due to the northward gradient of groundwater movement in the Cultus Lake watershed (Holding and Allen 2012).

The eastern and western slopes bounding the Columbia Valley are predominantly forested, while agriculture and other development occur along the central valley floor. Non-forest covers in the watershed (including development, cropland, bare land, and herb cover) account for 18% of the total subwatershed area, while open broadleaf and dense coniferous make up the majority of the remaining cover types (Government of Canada 2009, Binder L, University of the Fraser Valley, September 2013, pers. comm.). Broadleaf forest dominates the western ridge, while the eastern ridge is primarily coniferous. The 2 ridges are continuations of International Ridge and Vedder Mountain, resulting in forest covers that are similar in composition to those subwatersheds.

Sweltzer Creek

The Sweltzer Creek subwatershed is located in the northern portion of the Cultus Lake watershed, and encompasses the small community of Cultus Lake (population ~1,000). The single outlet of the lake, Sweltzer Creek, is located in this area and flows from Cultus Lake 3 km northward into the Chilliwack River along a shallow gradient of 0.005 degrees. The surficial geology of this area is similar to that of the Columbia Valley watershed: primarily highly-permeable glaciofluvial outwash sediments, and land cover is dominated by open coniferous cover (66.2%) and developed land (27.8%). Due to the northward sloping groundwater gradient and the permeable nature of soils in the area, non-channelized flows arising from precipitation on this portion of the watershed likely flow north as groundwater towards the Chilliwack River and do not contribute significant runoff to Cultus Lake (Holding and Allen 2012).

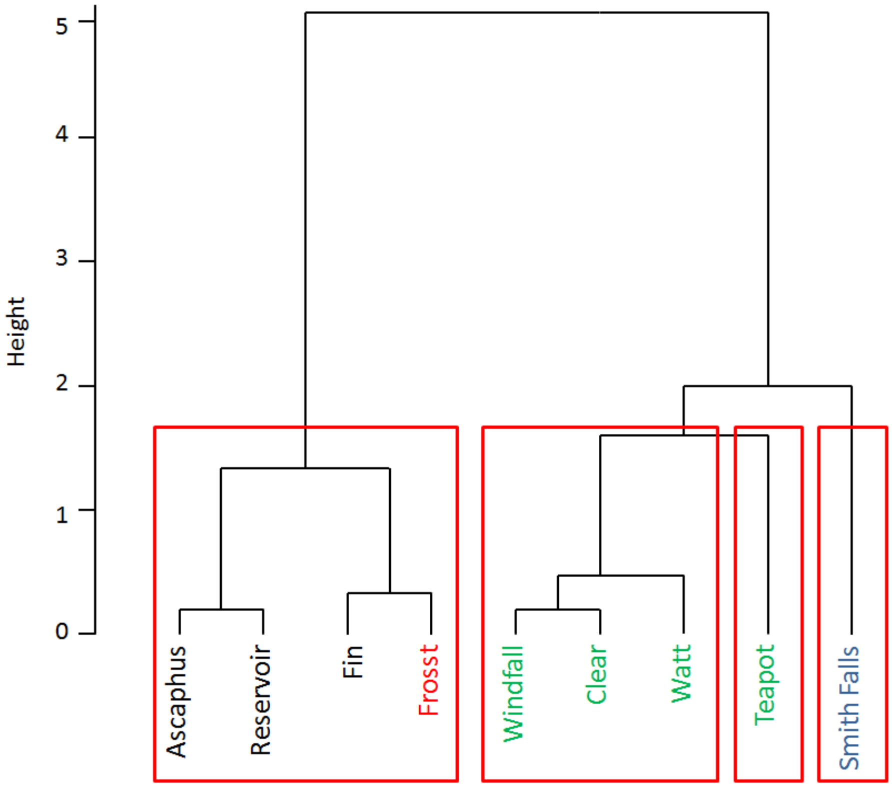

Figure A1. ***Hierarchical agglomerative cluster analysis results for Cultus Lake tributaries based on DOM and conductivity. Red squares represent raw clustering results, while font colours represent final subwatershed clusters. Although Frosst clusters with the Vedder Mountain subwatershed streams, it was assigned to its own subwatershed. Spring Creek was not included in this analysis as it is not considered to be a surface stream.***

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Appendix B.

Field sampling methods

Water chemistry was sampled near the outflow of each tributary and at the lake outflow (Sweltzer Creek) on a biweekly basis from May 2011 to May 2013. In Frosst Creek, the main drainage of the Columbia Valley, 3 stations were located on a transect along the stream reach to determine nutrient levels and water quality parameters as the creek flowed through different land use types (Frosst Creek stations 1 through 3 in Figure 2-2). Replicate water samples were syringe-filtered in the field through sample-washed, glass-fibre filters (Pall Acrodisc, 1.0 µm) for analysis of dissolved organic matter (DOM), dissolved organic nitrogen (DON), nitrate (NO_3^--N), ammonium (NH_4^+-N), dissolved inorganic phosphorus (DIP, PO_4^{3-}-P) and total dissolved phosphorus (TDP, PO_4^{3-}-P). Separate 250-mL whole water samples were collected for analysis of particulate phosphorous (PP) and particulate nitrogen (PN). Water chemistry analyses were performed at the Fisheries and Oceans Canada low-level water chemistry lab at Cultus Lake. *In situ* measurements of temperature, dissolved oxygen, and conductivity were also taken at each sampling event.

Water chemistry samples were stored in the dark at 4 C and stabilized by freezing within 8 hours of collection, except DOM samples, which were analyzed within 48 hours (not frozen), and TDP, which was collected directly into digestion tubes. Nitrate (including nitrite) was analyzed colorimetrically as the azo dye after cadmium reduction (detection limit 1.0 µg-N L-1), while DON was estimated by differences of NO_3^- and NH_4^+ concentrations from total nitrogen values converted to nitrate after wet ultraviolet/persulfate digestion. Ammonium was determined as indophenol blue using the nitroprusside-catalyzed phenolhypochlorite reaction (detection limit 1.0 µg-N L-1). DIP was analyzed as molybdenum-blue after stannous chloride reduction (detection limit 0.1 µg-P L-1) and TDP was analyzed as DIP after wet persulfate digestion. Segmented-flow autoanalyzer techniques were used for all analyses except DOM (Stephens and Brandstaetter 1983). DOM was measured as absorbance of ultraviolet light (UVA) at 254 nm wavelength in 1 cm quartz cuvettes using a spectrophotometer and reported as cm-1. Particulate phosphorus samples (PP) were filtered onto 25-mm ashed borosilicate microfiber filters (equivalent to a Whatman GFF), frozen in a clean vial, and analyzed using the method of Stephens and Brandstaetter (1983). Particulate nitrogen samples (PN) were similarly filtered onto 25-mm ashed borosilicate microfiber filters and stored frozen, however the PN analyses were not completed in time for inclusion in this report. Dissolved organic phosphorous (DOP) was calculated as the difference between TDP and DIP, dissolved inorganic nitrogen (DIN) was calculated as the sum of nitrate and ammonium, and total phosphorous (TP) was the sum of TDP and PP.

Three methods were used to approximate groundwater chemistry for the Columbia Valley subwatershed. Spring Creek, a primarily groundwater-fed creek located in the Lindell Beach community, was used as a direct estimate of groundwater chemistry. Although a part of the Spring Creek reach is above-ground, water chemistry data were characteristic of a groundwater-dominated creek with small seasonal variations in temperature and water chemistry characteristics, and were assumed to be representative of the underlying aquifer. For comparison to Spring Creek data, groundwater chemistry was also estimated using Frosst Creek data. Soils in the Columbia Valley are unsaturated and highly permeable, with negligible overland flows to Frosst Creek (Zubel 2000). Because Frosst Creek flows are supplied largely by groundwater during low-precipitation periods, discharge in Frosst Creek 2 could be partitioned into 2 source components: soil interflow water and groundwater. This was accomplished using a 2 end-member mixing model using conductivity and DOM, and predicted water chemistry data were obtained for each of the source components. Groundwater chemistry was also sampled directly on 20 August

2012 in 3 wells located in the Lindell Beach area (British Columbia well tag numbers 18149, 37208, and 92975).

A meteorological station located at the Cultus Lake Laboratory recorded daily temperatures (C), rainfall (mm), and relative humidity (ϕ) during the study. The station was composed of a Unidata 6003B data logger and 6501D weather sensor coupled with a Jarek 4000 tipping bucket rain gauge (20 cm diameter, 0.25 mm resolution). The logger was programmed to take a reading every 5 s and record 15 min averages of temperature and humidity, while totalling rainfall. Precipitation samples were collected with 25 cm funnels in light-excluded vessels for water chemistry analyses beginning in year 2 of the study. Weekly precipitation samples were pooled and analyzed at the Cultus Lake Laboratory for DIP, TDP, nitrate, and ammonium using the same methods as for stream samples.

Daily temperature and precipitation data collected at the Cultus Lake meteorological station (2011 to 2013) were compared to historic climate normals obtained from Environment Canada (Cultus Lake Station 1102220; 1971-2000; Environment Canada 2013a; Figure B1). Both study years were characterized by average precipitation levels, with total rainfalls of 1,272 mm (May 2011 to April 2012) and 1,476 mm (May 2012 to April 2013). Minimum and maximum monthly temperatures were slightly higher than historic values in year 1 of this study and substantially higher in year 2. The average monthly temperature in year 2 was approximately 3 C greater than the monthly climate normal, largely due to warmer than average temperatures in the late summer and early fall of 2012. Daily weather data were not available from Environment Canada for the Cultus Lake weather station during the study period. To verify measurements taken at the Cultus Lake meteorological station, data were compared to values from Environment Canada's station in Chilliwack (Environment Canada 2013a). A strong linear relationship was found between the two stations throughout the study period (average temperature: $R^2 = 0.89$, $p < 2e\text{-}16$, $n = 805$; daily rainfall: $R^2 = 0.66$, $p < 0.001$, $n = 805$).

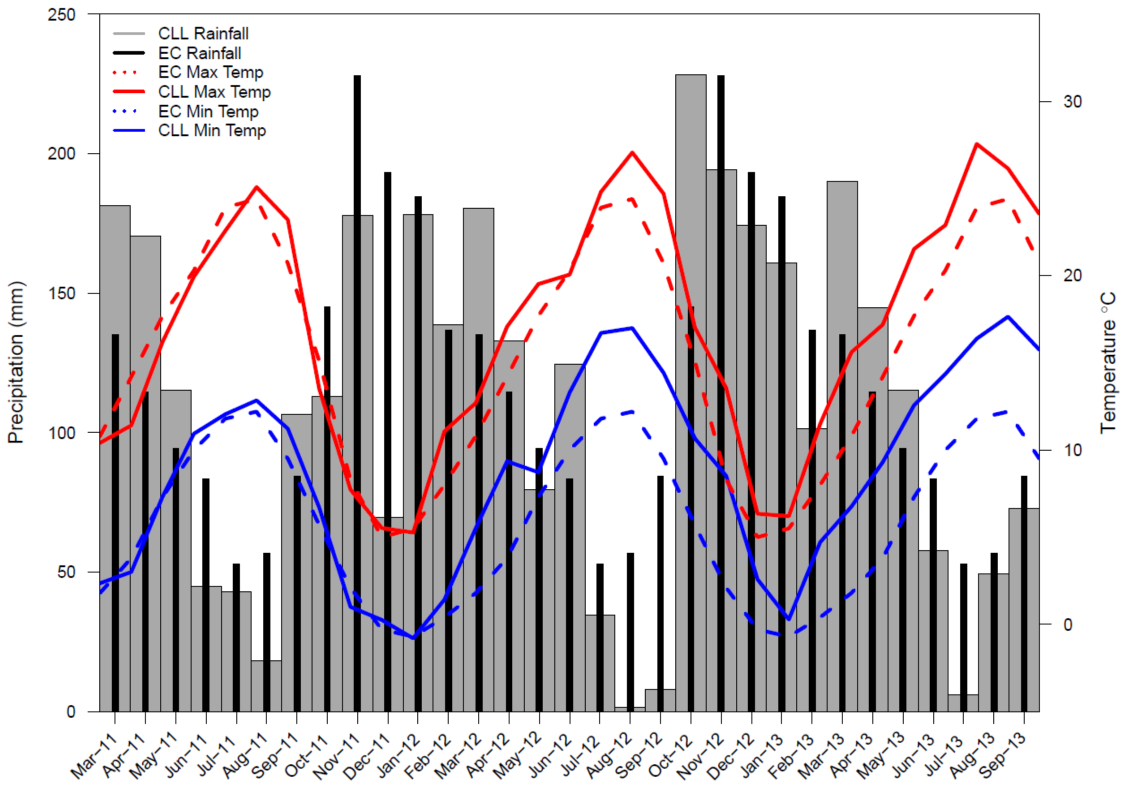

Figure B1. ***Total daily rainfall and average maximum and minimum temperatures from March 2011 to September 2013 from the Cultus Lake Laboratory (CLL) meteorological station, and historic climate normals from the Environment Canada Cultus Lake station (EC).***

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Appendix C.

Cultus Lake water balance

Methods

Direct precipitation contributions to Cultus Lake were measured at the Cultus Lake Laboratory meteorological station and verified using data collected at the Environment Canada station located in Chilliwack (2011-2013; Environment Canada 2013a) and historical averages for Cultus Lake (1971-1994; Environment Canada 2013b). Direct evaporation from the lake was estimated using evaporation data from the nearby Agriculture and Agri-Foods Canada station in Agassiz, Canada and scaled to the area of Cultus Lake (Zubel 2000). Groundwater outflow from Cultus Lake was obtained from a numerical groundwater flow model compiled by Holding and Allen (2012) using streamflow data from this study and soil hydraulic conductivity estimates from the neighbouring Abbotsford-Sumas aquifer.

Stream discharges were calculated using continuous stages recorded using Unidata 6004C data loggers and 6508B depth sensors installed in 4 tributaries (Frosst Creek, Ascaphus Creek, Smith Falls Creek, and Watt Creek) and the outflow (Sweltzer Creek), which provided average hourly measurements of stage height and temperature. Instantaneous stream discharges were also measured biweekly in each stream from May 2011 to August 2011, then monthly for the remainder of the study duration (up to May 2013). A Marsh McBirney Flowmate 2001D flow meter and a staff rod were used to measure a cross section of discharge at 60% of the creek depth, and discharge was calculated using the velocity-area method (consisting of an integration of stream velocities; Rantz 1982). Logpower stage-discharge rating curves were used to calculate continuous discharges for monitored streams (Baty and Delignette-Muller 2012), and whenever possible, instantaneous discharges for streams that were not monitored continuously were approximated using linear regressions of instantaneous discharges with a neighbouring stream. Discharges in 2 creeks, Spring Creek and Windfall Creek, were not correlated well with discharges from a monitored stream (all $R^2 < 0.4$), and average discharges between measurements were used to estimate daily discharges. The volume of overland flows (i.e. sheet flow not draining to a monitored stream) was also quantified in each subwatershed as the area-weighted average of monitored stream volumes during each day of the 2-yr study period.

Rating Frosst Creek during high flow periods was not possible because high water levels and velocities made it unsafe to wade the stream. During 2 high flow events, the flowmeter was attached to a torpedo weight and the stream rating was performed by lowering the flowmeter over a footbridge adjacent to the rating site. Three repetitions were performed when using this method, and verification measurements were made during a low-flow period to compare the torpedo and wading methods. Even with the addition of these high flow measurements, the upper ~25% of stage heights recorded by the data logger were outside of the rating curve range and extrapolation was required. Extrapolated discharges from the rating curve were compared to other streams in the watershed and to historic data for Frosst Creek from the Water Survey of Canada (WSC) and we concluded that high discharges were overestimated for Frosst Creek. As a result, Frosst Creek discharges >5.5 m^3/s were estimated using a linear regression between Frosst and Watt creeks. High water levels also prevented the rating of Sweltzer Creek in the spring of 2012, and the rating site was moved ~20 m upstream to a footbridge until water levels had subsided. Ratings performed at the upstream site did not deviate from the established rating curve pattern, and no corrections were made to the data.

For areal calculations, areas for gauged and ungauged catchments in each of the subwatersheds were determined using pour point models in ArcGIS as summarized by Binder (2013; Binder L, University of the Fraser Valley, September 2013, pers. comm.). The mean annual areal runoff of the gauged tributaries was used to estimate the surface and groundwater discharges for the ungauged portions of the same subwatersheds. Total annual areal runoff for the land portion of the Cultus Lake watershed was calculated from the sum of all annual outflows from the lake (including evaporation from the lake surface and direct groundwater discharge) minus direct precipitation on the lake, averaged over the land portion of the Cultus Lake watershed area (equation 1, where Q is discharge and A is area). The Sweltzer Creek area was excluded because it likely drains northward into the Chilliwack River catchment, rather than into Cultus Lake (Holding and Allen 2012).

$$Total\ Areal\ Runoff = \frac{Q_{Sweltzer}+Q_{groundwater}+Q_{evaporation}-Q_{lake\ precipitation}}{A_{total\ watershed}-A_{lake}-A_{Sweltzer}} \quad (1)$$

$$Subsurface\ Flow = Total\ Areal\ Runoff - Subwatershed\ Areal\ Runoff \quad (2)$$

The difference between the total annual areal runoff for the Cultus Lake land watershed and the total annual areal stream and overland runoff for each subwatershed was attributed to subsurface flows (groundwater flows and interflows; equation 2). For Vedder Mountain and International Ridge, subsurface flows were likely dominated by shallow interflows in unsaturated tills and soils above the bedrock, while groundwater was the predominant subsurface flow in the unconfined Columbia Valley aquifer.

Results

Average annual runoff into Cultus Lake from watershed sources and direct precipitation was estimated to be approximately 110.4 hm^3/yr (Table C1). Discharge from surface streams accounted for 55% of the total inflow, while ungauged surface flow and precipitation accounted for 7.0% and 7.8%, respectively. Subsurface flow was also an important source of discharge in the Cultus Lake watershed, contributing 30.3% of the total inflow. Groundwater and shallow subsurface interflow from Vedder Mountain, International Ridge, and Smith Falls Creek accounted for 20.8%, and aquifer discharge from the Columbia Valley was 9.5%. The main outflow from Cultus Lake, Sweltzer Creek, accounted for 97% of water leaving the watershed. Evaporation from the surface of the lake accounted for ~3% of the total outflow, while direct groundwater outflow from the lake was minimal (<1%).

There were differences between the water balances in the 2 years of this study, although the relative contributions of the different sources were the same. Despite higher precipitation in the second year of the study, discharges from streams were higher in year 1 compared to year 2. This discrepancy was a result of the study years beginning in May, at which point there was still snow storage from the previous year's precipitation present at high elevations. Snow water equivalent (SWE) levels in 2010-2011 (the winter before the first study year) were higher than average (Chilliwack River station; Government of British Columbia 2013), which would have resulted in higher snowmelt runoff in the spring of 2011. Precipitation that contributed to the snowmelt was not included in the total calculation because it fell as snow before the start of the monitored water year, and snowmelt precipitation could explain the anomalies in water balance calculations between years 1 and 2 of this study.

The Columbia Valley subwatershed was the largest contributor of average annual runoff to Cultus Lake (accounting for 47% of the total), followed by International Ridge (24%), Vedder Mountain (11%), Smith Falls (10%), and direct precipitation (8%) (Table C1). Seasonal discharge patterns followed those of wet and dry seasons typical of the Pacific Northwest (PNW), with maxima occurring October through May, and minima occurring July through September (Figure C1). Low flows were higher in the Columbia Valley compared to the other subwatersheds, consistent with a later freshet and higher groundwater baseflow contribution which supplemented subwatershed discharge during low-flow periods. Freshet occurred in the Columbia Valley nearly a month later than in the rest of the Cultus Lake subwatersheds, resulting in maximum discharges during the summer. The total volume of Cultus Lake remained relatively stable throughout the study period, with the exception of August through October, when outflow was ~0.5 m^3/s lower than inflow (Figure C2). This discrepancy was due to the annual partial damming of Sweltzer Creek, undertaken by the Cultus Lake Parks Board to maintain lake levels during the peak tourist season (late spring to early fall).

All creeks in the Vedder Mountain sub-watershed had similar seasonal hydrographs and no creek reached zero surface flow during late summer minima. In contrast, substantial variations were observed among stream hydrographs on International Ridge (Figure C3). Clear Creek and Teapot Creek had low and steady seasonal discharges that were indicative of predominately groundwater-fed creeks, while Watt Creek had the highest and most temporally variable discharges observed outside of the Columbia Valley, with no surface flows in the late summer of both study years. Windfall Creek and Clear Creek lost surface flows during the late summer, making International Ridge the only subwatershed with creeks that consistently ran dry in summer. Smith Falls Creek had much less seasonal variability in discharges relative to the rest of the Cultus Lake watershed, likely due to water storage in wetlands and marshes within the upper subwatershed.

The Columbia Valley subwatershed was the largest source of runoff to Cultus Lake, and Frosst Creek was the largest contributing tributary to the lake throughout the study period, with maximum discharges of ~5 m^3/s (Figure C1). Groundwater accounted for 20% of total runoff from the Columbia Valley, and contributed 9.5% of the total Cultus Lake water inflows. Seasonal groundwater discharge was not measured directly in the Columbia Valley; however, Spring Creek had very constant discharge, temperature, and conductivity throughout the study, suggesting groundwater discharge does not vary substantially by season.

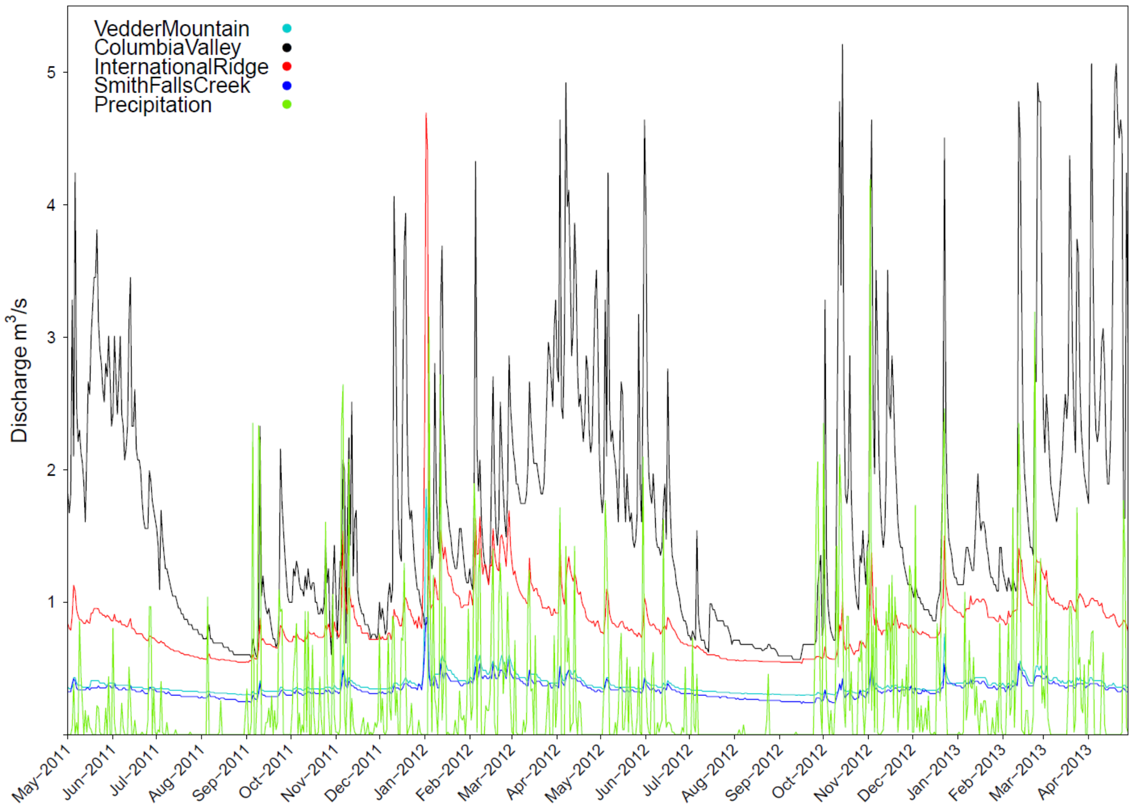

Figure C1. ***Hydrographs of calculated total subwatershed runoff (streams, ungauged runoff, and subsurface flows) and direct precipitation from May 2011 to May 2014. Lines for the Smith Falls and Vedder Mountain subwatersheds overlap in the figure.***

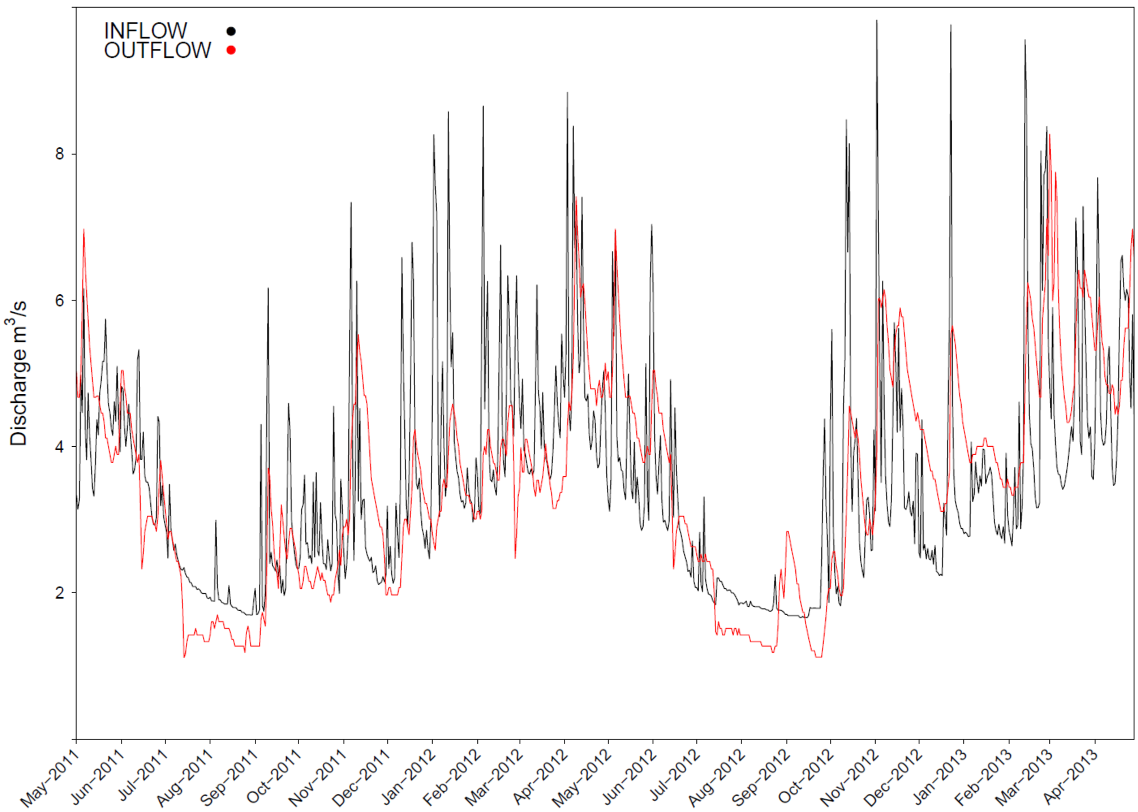

Figure C2. ***Time series of Cultus Lake calculated total inflows (summed subwatershed runoff and direct precipitation; black) and outflows (summed Sweltzer Creek discharge and direct evaporation; red) from May 2011 to May 2013.***

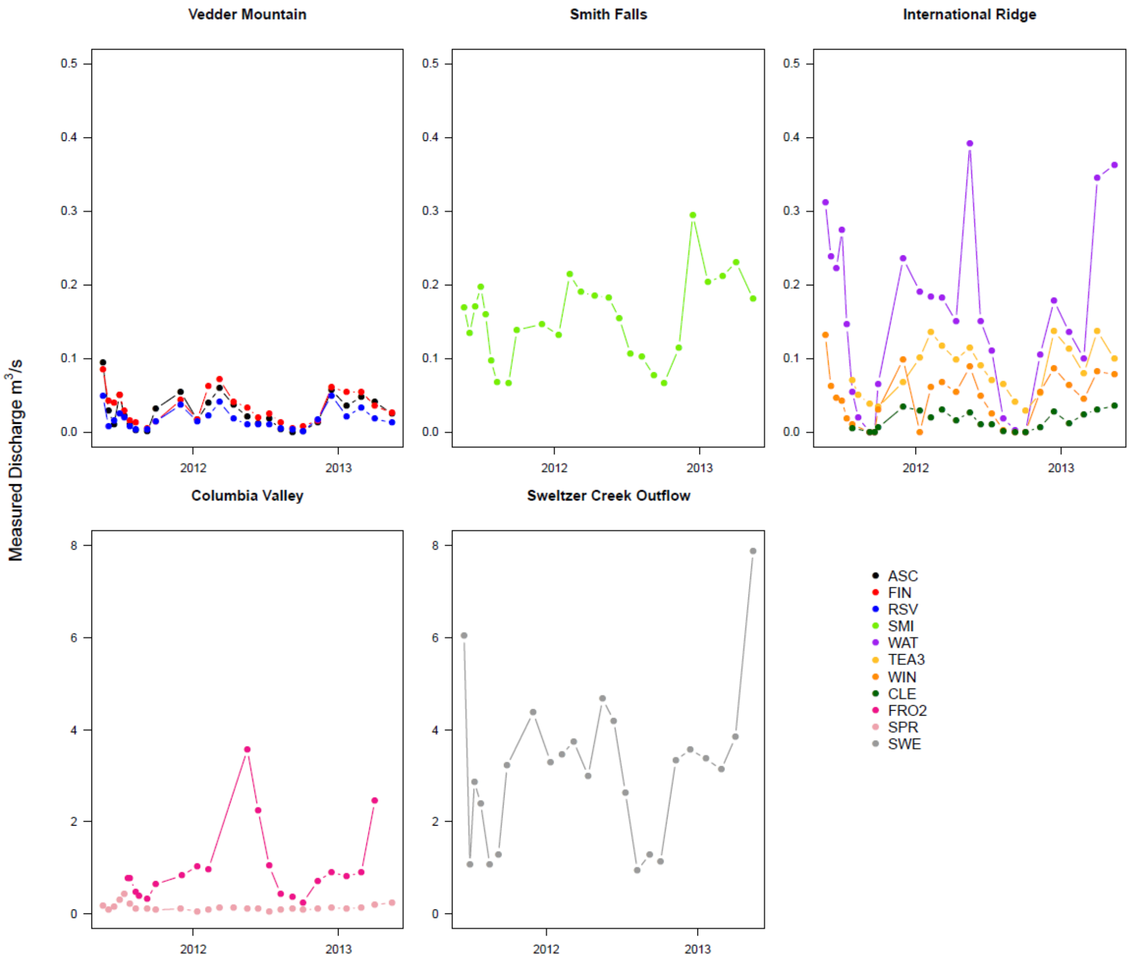

Figure C3. ***Measured stream discharges in m^3/s from May 2011 to May 2013 separated into subwatersheds and Sweltzer Creek outflow. Note different y-axis scales.***

Table C1. ***Average annual water balance in m^3/yr (inflow, outflow, and totals) for the Cultus Lake watershed (May 2011 to May 2013). Subwatershed totals are in bold and subwatershed sources are separated into streams, groundwater, and ungauged surface runoff.***

	m^3/yr	% Total
INFLOW		
Vedder Mountain	**11,9117,100**	**10.8**
Ascaphus	1,193,755	1.1
Fin	1,046,465	0.9
Reservoir	519,097	0.5
Vedder Mountain Groundwater	5,515,794	5.0
Vedder Mountain Ungauged Surface	3,641,990	3.3
Smith Falls	**10,765,499**	**9.7**
Smith Falls Creek	5,264,991	4.8
Smith Falls Groundwater	5,500,508	5.0
Smith Falls Ungauged Surface	0	0.0
International Ridge	**26,804,813**	**24.3**
Windfall	1,487,333	1.3
Clear	870,947	0.8
Teapot	2,793,320	2.5
Watt	5,644,275	5.1
International Ridge Groundwater	11,954,062	10.8
International Ridge Ungauged Surface	4,054,876	3.7
Columbia Valley	**52,374,432**	**47.4**
Frosst	41,823,995	37.9
Columbia Valley Groundwater	10,482,789	9.5
Columbia Valley Ungauged Surface	67,648	0.1
Direct Precipitation (Wetted lake area only)	**8,564,850**	**7.8**
OUTFLOW		
Sweltzer	106,788,407	96.7
Evaporation	3,629,755	3.3
Groundwater Outflow	39,366	0.0
TOTALS		
Total Inflow	110,426,694	
Total Outflow	110,457,528	
Outflow-Inflow	30,834	
% Discrepancy	0	

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Appendix D.

Columbia Valley groundwater sampling and modelling

Nutrient concentrations in Spring Creek were used to approximate groundwater chemistry from the Columbia Valley aquifer. Spring Creek temperatures showed little seasonal variation throughout the study period. Conductivity was elevated compared to Frosst Creek (Figure D1), and there was virtually no seasonal variation in total dissolved nitrogen (TDN) concentrations during the study (Figure 4-1). Discharge also showed little seasonal change throughout the year in Spring Creek compared to neighbouring streams, which allowed us to assume constant groundwater discharge from the aquifer.

Groundwater chemistry was directly measured in three wells on 20 August 2012 (Table D1). Mean dissolved inorganic nitrogen (DIN) concentration in the wells was 458 µg-N/L (SD 295 µg-N/L), while DIP averaged 5.7 µg-P/L (SD 1.4 µg/L). Historic groundwater nitrate data from the Lindell Beach area (2005-2011) were obtained from Fraser Health, which undertakes periodic well sampling for health and safety purposes (Sivia B, Fraser Health, September 2012, pers. comm.). Nitrates in Fraser Health groundwater samples were highly variable among wells and years (mean 543 µg-N/L, SD 678 µg-N/L), and nitrate concentrations in wells sampled by both Fisheries and Oceans Canada (DFO) and Fraser Health were similar but not equivalent. The variable nature of groundwater concentrations agrees with observations by Zubel (2000), who identified hotspots of nitrate contamination in wells upstream of those sampled in this study. High spatial and temporal variability was also found in nitrate concentrations in wells sampled in the Abbotsford-Sumas aquifer (Carey 2013), an aquifer with similar hydrologic properties to the Columbia Valley aquifer.

The end-member mixing analysis for Frosst Creek provided an estimated groundwater proportion in streamflow at each sampling event. The highest concentrations of TDN were observed when groundwater proportions approached 100%, corresponding with low-flow periods in the late summer (Figure D2). Concentrations of TDN were highly correlated with the estimated groundwater proportion ($R^2 = 0.74$, $p < 0.001$, $n = 48$), indicating that nitrogen in Frosst Creek was elevated when flows were predominantly groundwater.

The mixing model was used to calculate TDN concentrations in groundwater and surface partitions in Frosst Creek 2 (Figure D2). Model predictions indicated that high TDN concentrations in Frosst Creek during the summer were a result of nutrient-rich groundwater discharging to the creek. The results of the mixing model were supported by detailed transect sampling completed in Frosst Creek on 27 August 2012, during which water quality was measured at 5 locations along the stream reach (Figure D3). The Frosst Creek transect sampling revealed significant groundwater seepage directly from the creek banks between the upstream and downstream Frosst Creek sampling stations. Water chemistry shifted in Frosst Creek at this area of groundwater seepage: stations upstream of the lowest point of groundwater seepage had low concentrations of nitrate-nitrite (<50 µg/L; similar in magnitude to the upstream Frosst Creek station), while downstream stations had elevated nitrate-nitrate concentrations (>800 µg/L).

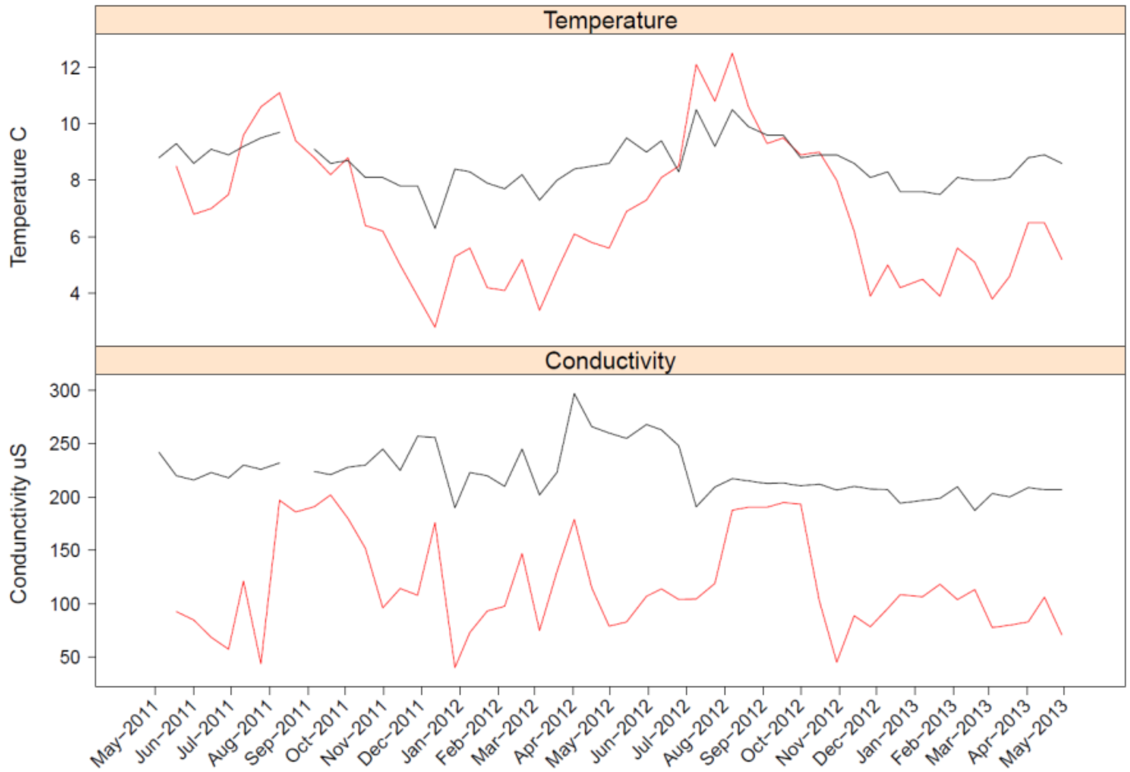

Figure D1. ***Temperature (C) and conductivity (µS) of Spring Creek (black) and Frosst Creek 2 (bridge site; red) from May 2011 to May 2013.***

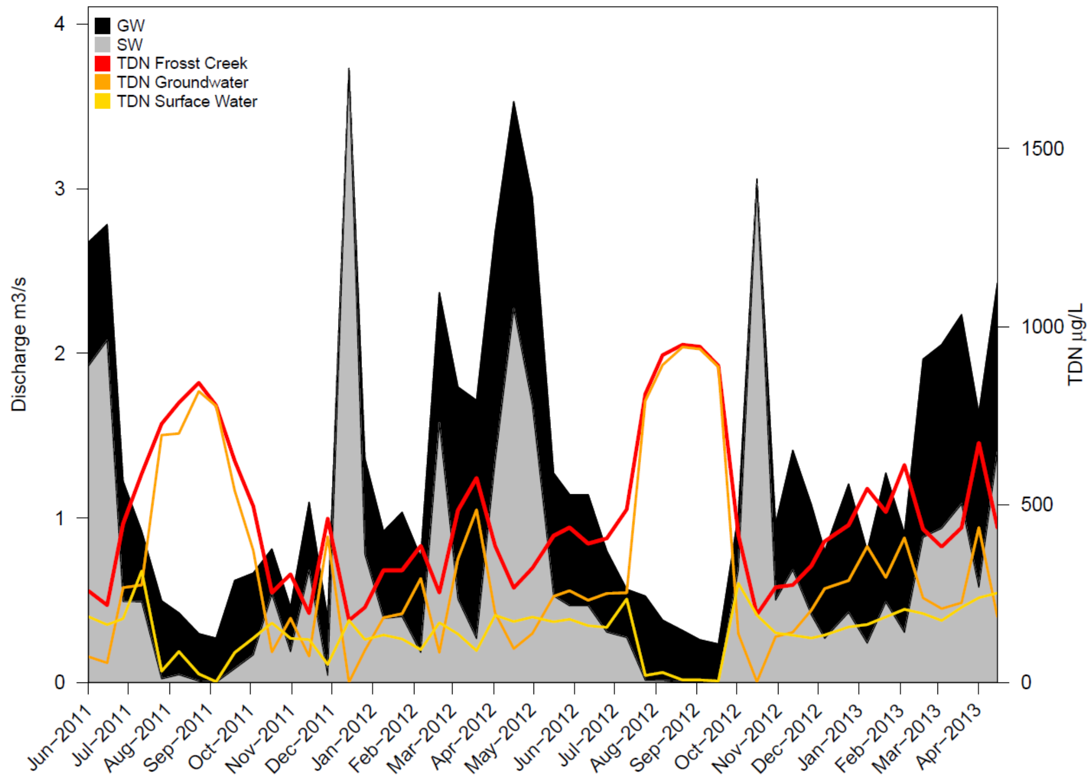

Figure D2. ***Modeled groundwater (GW) and surface water (SW) volumes (grey and black polygons) for Frosst Creek 2, overlain with Frosst Creek TDN concentrations (red). TDN concentrations are further separated into groundwater (orange) and surface water (yellow) partitions.***

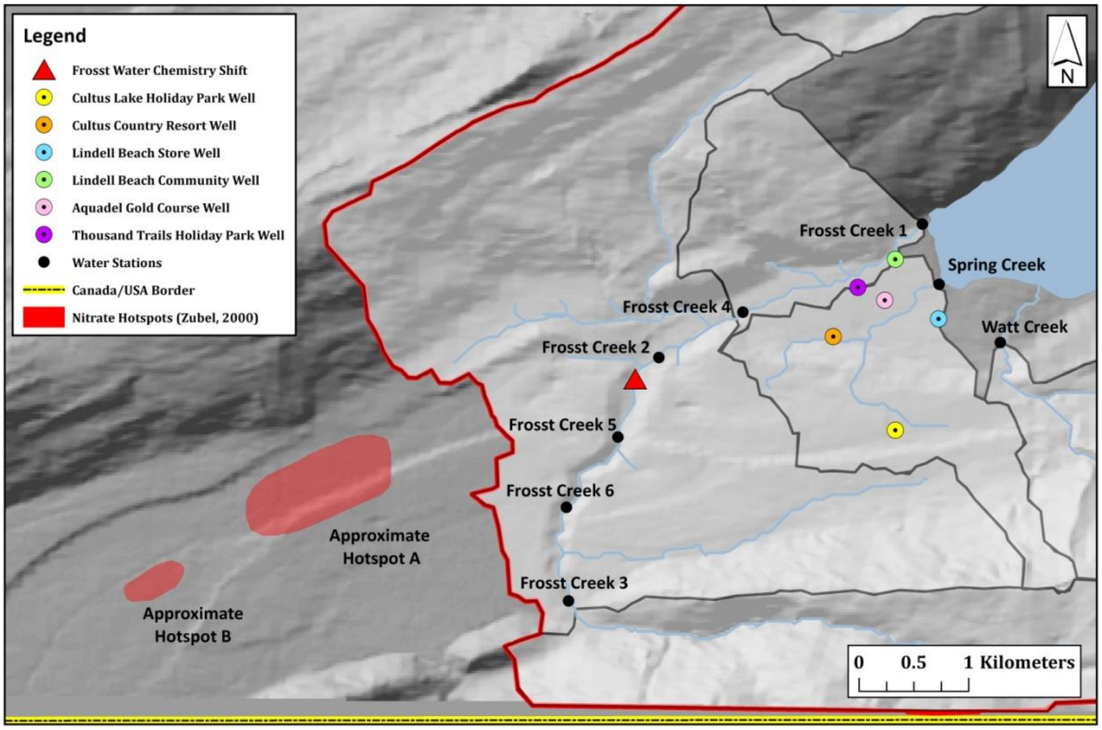

Figure D3. ***Map of the southern Cultus Lake watershed, including tributary sampling stations, groundwater well locations, and the approximate locations of nitrate hotspots in the southern Columbia Valley.***

Table D1. ***Columbia Valley groundwater well data from Fraser Health (FH; 2005 to 2011) and Fisheries and Oceans Canada (DFO; 2012).***

Source	Well ID	Location	Date	Depth (m)	Concentration (ug/L)		
					DIN	DIP	NO_3
FH	-	Cultus Lake Holiday Park	Apr-2005				10.0
FH	77444	Thousand Trails Holiday Park	Nov-2006				1,890.0
FH	92975	Lindell Beach Community Well	Jul-2009	22.0			460.0
FH	-	Cultus Country Resort	May-2010				200.0
FH	37208	Lindell Beach Store	Aug-2010	12.8			400.0
FH	18149	Aquadel Golf Course	Aug-2011	13.7			300.0
DFO	18149	Aquadel Golf Course	Aug-2012	13.7	234.5	7.4	231.9
DFO	37208	Lindell Beach Store	Aug-2012	12.8	350.4	4.9	349.8
DFO	92975	Lindell Beach Community Well	Aug-2012	22.0	793.4	4.9	792.5

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Zubel M. 2000. Groundwater Conditions of the Columbia Valley Aquifer Cultus Lake, British Columbia. Water Management (p. 98). Surrey (BC).

Appendix E.

Cultus Lake nutrient budget

Methods

Annual and seasonal nutrient loads for all major inputs to Cultus Lake were calculated, including gauged tributaries (L_T), ungauged flows (L_U), groundwater flows and interflows (L_{GR}), precipitation (L_P), gull guano (L_G), septic leachate (L_S), and sockeye salmon carcasses (L_{SC}):

$$L_{\mathrm{CL}} = L_T + L_U + L_{GR} + L_P + L_G + L_S + L_{SC} \qquad (1)$$

Six nutrient groupings were examined: dissolved inorganic and organic phosphorous (DIP and DOP), dissolved inorganic and organic nitrogen (DIN and DON), and total phosphorous and nitrogen (TP and TN).

Subwatershed runoff and atmospheric deposition

Nutrient loads for streams and direct precipitation were calculated using the weighted sample mean averaging method of Walling and Webb (1981):

$$L_A = \frac{\sum_{n=1}^{N} C_n Q_n}{\sum_{n=1}^{N} Q_n} \bar{Q} \qquad (2)$$

Where L_A was the estimated average load; N was the number of paired concentration (C) and discharge (Q) measurements; n was an index of N; and $\bar{Q}$ was the average of all discharge measurements. Loads were calculated seasonally and as an annual average over the 2-yr study. Two methods of stratification were used to examine seasonal loading in the watershed: calendar seasons and wet and dry seasons. To calculate average loading by calendar season, data from the 2 study years were separated into 4 seasonal bins according to month of collection (seasonal bins were based on 4-month calendar seasons: spring, summer, fall, and winter). Wet and dry periods were calculated jointly for the 2 study years to obtain an average, with the wet season being defined as 1 October through 31 March. In addition to total loading from each source, areal export coefficients (nutrient export per hectare) were calculated for all of the subwatersheds and for direct precipitation on the lake surface.

Tributary loads were also calculated using a number of alternative averaging methods commonly found in the literature (see Beale 1962, Quilbé et al. 2006, Zamyadi et al. 2007), and estimated loads were consistent between averaging methods. Another common estimation technique is the rating curve method, where daily chemistry values are obtained via linear regression with discharges, and the total load is the sum of the product of continuous discharge and chemistry. Nutrient loads calculated using this method differed greatly from those produced by various averaging methods due to low correlations between water chemistry and discharge in most creeks (R^2 values ranged from 0 to 0.4, with most values <0.2).

Nutrients loads were calculated using observed or estimated concentration and discharge values for watershed sources and direct precipitation on the lake surface using equation 2. Direct measurements of water chemistry and discharge were used to calculate loads for gauged tributaries, while subwatershed averages were used to approximate nutrient loads from ungauged areas. Precipitation volume directly onto Cultus Lake was calculated using data from the Cultus Lake meteorological station, while nutrient concentrations were obtained from the pooled samples collected biweekly at the station. Because precipitation chemistry sampling did not begin until the second year of the study, seasonal and average annual precipitation loads represent only data from year 1.

Although dry deposition was not measured directly at the Cultus Lake Laboratory meteorological station, data collected in other studies in the Lower Mainland allowed for the approximation of dry deposition to the watershed. Vingarzan et al. (2000) estimated wet and dry deposition for the Elk Creek watershed near Chilliwack, while Belzer et al. (1997) measured deposition in the Fraser Valley. The Elk Creek watershed is located close to Cultus Lake, and dry to wet ratios in total atmospheric deposition are likely similar between the 2 sites. In a study of nutrient concentrations in lichen (used as a proxy for atmospheric deposition), the Elk Creek and Cultus Lake watersheds had similar lichen nutrient concentrations, providing further evidence that atmospheric deposition patterns in the Elk Creek watershed can be used to approximate deposition in the Cultus Lake area (Raymond et al. 2010). In the Elk Creek watershed, dry deposition accounted for 18% of total nitrate-nitrite deposition, 68% of ammonia-ammonium deposition (for a total contribution of DIN to atmospheric loading of 62%), and 50% of total inorganic phosphorus deposition. Dry deposition loads were calculated for both DIN and DIP using these ratios and added to wet deposition to obtain total atmospheric deposition in the watershed.

Nutrient loads from subsurface groundwater flow and interflow were calculated for each of the subwatersheds using equation 2. Nutrient concentrations for ungauged areas in the Vedder Mountain, International Ridge, and Smith Falls subwatersheds were approximated using mean concentrations of monitored tributaries in the subwatershed. This resulted in identical chemistry values for ungauged flow, groundwater flow, and soil interflow, an approximation that is acceptable given the likely nature of water exchange between surface flows and subsurface flows in the shallow till and organic soils. In addition, using the same chemistry values for the 2 unknown sources resulted in loading estimates that were unaffected by errors from partitioning gauged and ungauged discharges in water balance calculations.

Groundwater in the Columbia Valley could not be approximated in this manner because the majority of groundwater discharge was from the underlying aquifer, which had different chemical and physical properties than Frosst Creek. Groundwater loads in the Columbia Valley were calculated using discharges obtained from the water balance model and nutrient concentrations in Spring Creek, a groundwater-fed creek located close to the Cultus Lake shoreline that was assumed to be representative of groundwater in the valley. There was very little seasonal variation in Spring Creek discharge or chemistry, and nutrient concentrations in the groundwater wells were very similar to Spring Creek levels. In addition, results of the 2 end-member mixing model indicated that Frosst Creek was almost entirely composed of groundwater flow in the late summer periods.

Migratory bird guano

The scope of this study did not allow for extensive gull enumeration or sampling; however, preliminary loading estimates were obtained using equations 3 and 4:

$$L_G = H_G * r \quad (3)$$

$$H_G = D * H * G \quad (4)$$

Where L_G was the total estimated load in kg/yr of nutrients from migratory gulls, H_G was the total gull hours in hours/yr, r was the production rate of migratory gull guano in kg/hour, D was the number of days of occupation, H was the hours of occupation each day, and G was the population size of migratory gulls estimated for Cultus Lake (gulls/yr). Glaucous-winged gulls (*Larus glaucescens*) are the primary gulls species found at Cultus Lake; however, literature values for guano production were not available. As such, published nutrient (nitrogen and phosphorous) excretion rates for herring gulls (*Larus argentatus*) were used (Gould and Fletcher 1978, Portnoy 1990, Marion et al. 1994, Hahn et al. 2007). Literature values for herring gull nutrient production rates vary widely: daily rates range from 0.44 to 1.82 g/gull for total Kjelidahl nitrogen (TKN), and

0.12 to 0.76 g/gull for total phosphorus (TP). None of the literature values for guano production rates partitioned nutrients into organic and inorganic fractions; however, nitrogenous contributions to gull guano are known to be primarily composed of organic nitrogen compounds (i.e., uric acid).

Population estimates for Cultus Lake gulls were obtained using visual surveys (tallies and photograph counts) and assumed to be constant over the total occupation period (Selbie DT, DFO, unpublished). Population estimates were obtained between 2013 and 2014 ranging from 9,500 to 12,500 gulls/yr. Gull loading was estimated using the mean gull population estimate and each of the literature values for gull nitrogen and phosphorus production, and median nutrient loading estimates from this approach were used in the nutrient balance calculations. Gull occupation of the Cultus Lake watershed was approximated as the 6-month period from October through to the end of March, based upon local observation and confirmed with migratory patterns obtained from the global eBird database (eBird 2012). Although residence times may vary with photoperiod and climatic factors, the daily duration of occupation for loading calculations was assumed to be an 8-hour overnight period, which provides an approximation of average diurnal watershed residency.

Septic leachate

Septic leachate was estimated for 2 subwatersheds that contain the majority of septic systems located near Cultus Lake: the Columbia Valley and International Ridge. Vedder Mountain and Smith Falls subwatersheds have minimal septic systems, and septic leaching is likely minor. Also, we assumed that any septic leaching from the Sweltzer Creek subwatershed would flow away from the lake due to the northward gradient of groundwater in the subwatershed. Loads from septic systems were calculated using equations 5 and 6:

$$L_S = L_{SPT} * (1 - r) \tag{5}$$

$$L_{SPT} = N * Q_{pc} * C \tag{6}$$

Where L_S was the nutrient load to Cultus Lake (kg/yr); r was a soil nutrient retention coefficient; L_{SPT} was the estimated nutrient load into septic systems (kg/yr); N was the total number of person days in the year (one person staying in the watershed for 20 days in the year would be equivalent to 20 person days); Q_{pc} was the per capita average daily sewage flow rate; and C was the nutrient concentration in sewage effluent. Septic loading can also be estimated using per capita export coefficients (i.e., kg/cap/yr), as in Reckhow et al. (1980). Septic loads calculated using equation 5 were verified with export coefficient calculations using mean export rates reported by Reckhow et al. (1980), and the resulting loads were similar between the 2 estimation methods. Septic loading and delivery to receiving bodies is known to be highly site-specific, and a lack of available site-specific substrate composition data made it difficult to estimate loading from septics to Cultus Lake. Parameters used in this study represent the best available data, and provide a conservative estimate of septic influence in the watershed that can be used as a starting point for future analyses.

Per capita average daily flow rates for residential and recreational areas were obtained from the Government of British Columbia's sewerage systems standards manual (BC Ministry of Health 2006), while residential sewage nutrient concentrations were obtained from a study of sewage effluent in the Okanagan Valley of British Columbia (Kennedy and Oldham 1972, Kennedy 1982). Soil retention coefficients were selected based on soil properties in the watershed (Comar et al. 1962) and coefficients used in a study of the Spokane Valley-Rathdrum Prairie Aquifer (HDR Consulting 2006). The unconfined Spokane Valley-Rathdrum Prairie Aquifer is located in northeastern Washington and is characterized by glacio-fluvial soils with high permeability, low organic matter content, and low clay and iron contents (Dobratz et al. 1986, HDR Consulting 2006). These soil characteristics are similar to those in the Cultus Lake area, suggesting that phosphorous retention in soils may be comparable. Due to large uncertainties in soil retention, total loading was estimated using soil retention coefficients ranging from 5% to 25% for TN and

50% to 70% for TP. Soil retention coefficients of 15% for TN and 60% for TP were used as primary model input parameters, and high and low coefficients were examined in a separate sensitivity analysis to determine the effect of uncertainty in soil retention on total watershed loading.

Person days for septics in the Columbia Valley were calculated using population estimates from a recent report by Urban Systems Ltd (2012) examining sewerage options in the Columbia Valley. Urban Systems Ltd (2012) estimated the total number of residential units to be 958 in the Columbia Valley, with seasonal occupancy based on residential occupancy rates and estimated household size. Occupancy in July and August was estimated as 90% with 3 people per unit; occupancy in May-June and September-October was 50% with 2 people per unit; and November through April occupancy was 10% with 2 people per unit (Urban Systems Ltd 2012). Per capita average daily flow rates for the Columbia Valley were set to 175 L/cap/day (BC Ministry of Health 2006) and TN and TP concentrations in septic leachate were 32 mg/L for TN and 7.8 mg/L for TP (Kennedy and Oldham 1972, Kennedy 1982).

Person days for day users and campers in the Cultus Lake Provincial Park (International Ridge subwatershed) were obtained from the BC Parks 2011-2012 statistics report (BC Parks 2012), which were separated into seasonal fractions using park opening dates and occupancy rates estimated for the Columbia Valley (Urban Systems Ltd 2012). Per capita average daily flow rates were 90 L/cap/day for campers and 20 L/cap/day for day users (BC Ministry of Health 2006). Nitrogen and phosphorous effluent concentrations were set 25% higher than values used for residential areas in the Columbia Valley based on the assumption that dilution in campground systems was lower than residential systems. Residential wastewaters are generally more diluted due to the presence of showers, laundry facilities, and flush toilets. Although there is limited research available on nutrient concentrations in campground effluent, Matassa et al. (2003) found peak effluent concentrations in the final effluent tanks of marinas and campgrounds to be several times that of residential effluent. Nutrient concentrations in Cultus Lake Provincial Park effluent are likely lower than dry pump-out systems observed by Matassa et al. (2003) due to dilution from the use of toilets and shower blocks.

Sockeye salmon carcasses

Historic and current annual nitrogen and phosphorus loading was estimated for sockeye salmon carcasses in Cultus Lake. Salmon spawn in the littoral areas of Cultus Lake during late November and December and subsequently die, resulting in nutrient rich carcasses decomposing in the lake. Using equation 7, nutrient loading from carcasses was calculated using Cultus Lake escapement estimates from Fisheries and Oceans Canada (DFO) from 1953 to 2013:

$$L_{SC} = w_{SC} * E * p \qquad (7)$$

Where L_{SC} was the nutrient load from sockeye salmon carcasses in kg/yr, w_{SC} was the weight of one spawner in kg, E was the estimated escapement in number of sockeye salmon, and p was the percent nutrient per wet weight of spawners. The average weight of an adult Cultus Lake sockeye salmon carcass was calculated using 2010 Cultus Lake sockeye field data (Patterson D, DFO, January 2014, pers. comm.). Male and female data were pooled, and average spawner weight minus gonad weight was found to be 1.55 kg for 2010 (SD = 0.29 kg, n = 17). Nutrient ratios were obtained from Larkin and Slaney (1995), with the percentages of TN and TP per weight being 3.04% and 0.36%, respectively.

Results

The estimated annual load of TN to Cultus Lake was 46,866 kg-N (Table 4-2). Subwatershed total nitrogen loads used TDN concentrations due to the unavailability of particulate nitrogen data, resulting in these sources likely being underestimated in the nutrient budget. Annual TN outflow in Sweltzer Creek was 18,467 kg-N, resulting in 61% of TN retained within Cultus Lake. The largest source of TN was the Columbia Valley, which contributed 43% of the annual load, followed by direct precipitation on the wetted lake area (19%), and International Ridge (15%) (Table 4-2; Figure E1). The total annual areal export of TN from watershed sources was 5.76 kg-N/ha/yr (Table 4-3). The largest source of TN areal export from watershed sources was direct precipitation on the lake area (13.7 kg-N/ha/yr), the Vedder Mountain subwatershed (7.92 kg-N/ha/yr), and the Columbia Valley (6.35 kg-N/ha/yr).

The average annual TP load to Cultus Lake was 2,199 kg-P, while the average annual outflow in Sweltzer Creek was 781 kg-P (43% TP retained in the lake; Table 4-2, Figure E-1). The largest sources of TP were the Columbia Valley (33% of the total load) and gull guano (16%), followed by International Ridge (14%) and septic leaching (11%). Total annual areal export of TP from the subwatersheds was 0.24 kg-P/ha/yr (Table 4-3). The largest single areal exporter of TP to the lake from watershed sources was the Smith Falls subwatershed (0.32 kg-P/ha/yr), followed by Vedder Mountain (0.31 kg-P/ha/yr), the Columbia Valley (0.23 kg-P/ha/yr), and direct precipitation (0.20 kg-P/ha/yr).

Subwatershed runoff and atmospheric deposition

Concentrations of DIP and DOP in precipitation were similar to those observed in the subwatershed streams; however, variations in concentration were more extreme in the precipitation data. Maximum concentrations of TDP in rainfall were >50 µg-P/L, almost double that of the maxima observed in stream samples (Figure 4-2), while TDN concentration maxima in rainfall and streams were similar (~1,200 µg-N/L; Figure 4-1). DON concentrations in atmospheric samples were slightly below subwatershed average values, while DIN was higher due to high concentrations of ammonium in rainfall (>50 µg-N/L). Nutrient concentrations in precipitation samples peaked in the spring and fall of both years. High nutrient concentrations in the spring corresponded with the timing of spring-early summer fertilizer application in the Fraser Valley, and nutrients observed in spring rainfall samples were likely a result of volatilization and wind erosion from agricultural fields. Maximum fall nutrient concentrations in atmospheric deposition corresponded to seasonal manure spreading in September in the Fraser Valley (Belzer et al. 1997).

Direct atmospheric deposition on Cultus Lake was a large source of nutrient loading in the watershed. The annual average nutrient loads in wet precipitation directly onto the lake were 3,573 kg-N/yr for TN (8% of the total load from all sources) and 82.7 kg-P/yr for TP (4% of the total load). Dry TN deposition was high due to elevated deposition estimates for ammonium in the Fraser Valley area; TN in dry deposition was 5,100 kg-N/yr, which accounted for 11% of the total TN load in the watershed. TP loads were more evenly split between wet and dry deposition, and both wet and dry deposition accounted for <5% of the total watershed load. Seasonal atmospheric loadings of both TN and TP (wet and dry) were highest in the spring, but remained fairly constant throughout the remainder of the year (Figure E2; Figure E3).

Concentrations of TDN and TDP were not strongly linearly correlated with discharge in the Cultus Lake watershed (Figure E4, Figure E5). All streams demonstrated a weak negative correlation between TDP concentrations and discharge ($R^2 < 0.2$). For most streams, there was no relationship or a weak positive correlation between TDN and discharge ($R^2 < 0.3$); however, Frosst Creek discharge was weakly negatively correlated with TDN concentration ($R^2 = 0.38$, $p < 0.001$, $n = 53$).

TDN concentrations were seasonally variable amongst the subwatersheds throughout the study duration. Vedder Mountain streams had the highest concentrations of TDN, with maximum concentrations greater than 1,000 µg-N/L observed shortly after the onset of the wet season (i.e., November and December; Figure 4-1). TDN concentrations on International Ridge and Smith Falls also peaked in November and December, whereas TDN in the Columbia Valley reached maximum concentrations in August and September, approximately 4 months earlier.

Individual streams within subwatersheds exhibited differences in seasonal TDN concentrations that reflected the influence of groundwater and land use in their catchments. Streams on International Ridge and in the Columbia Valley are diverse in the relative contributions of groundwater to their flows and land uses in their catchments, which was reflected in the differences in water chemistry between neighbouring streams; Figure 4-1). On International Ridge, Teapot Creek and Clear Creek had high groundwater contributions and exhibited less variation in temperature, conductivity, and TDN than other streams in the subwatershed. Spring Creek in the Columbia Valley is also a groundwater-fed creek, and TDN concentrations showed little seasonal variation compared to Frosst Creek. These within-watershed variations contrast with the consistent nature of water quality parameters among streams on Vedder Mountain, which likely reflects the homogeneity of geology and land cover of the Vedder Mountain subwatershed.

Two stations on Frosst Creek (one upstream of the agricultural area and one on the valley floor) had markedly different seasonal patterns in TDN concentration. The Frosst Creek station upstream of agricultural areas had TDN concentrations similar to International Ridge in magnitude and temporal variation, which peaked in November through January. In contrast, the downstream Frosst Creek station reached peak TDN concentrations during August and September, indicating that the creek gains a significant amount of dissolved nitrogen as it flows through the Columbia Valley and into Cultus Lake.

With the exception of the Columbia Valley, all subwatersheds displayed higher nitrogen export during the wet season (October through March), and the largest exports occurred in the winter (Figure E6). In contrast, TN loads in the Columbia Valley were almost identical in both dry and wet seasons, with the highest exports occurring during the spring. Throughout the year, Vedder Mountain displayed very high TN areal export, and was the largest source of TN per hectare in fall and winter (Figure E6). In the spring and summer, however, the Columbia Valley was the largest source of TN per hectare to Cultus Lake.

Seasonal patterns in DIN and DON loadings were the same as for TN, with maximums occurring during the wet season for all subwatersheds with the exception of the Columbia Valley, in which maximums occurred during the dry season. TDN loads were dominated by DIN in all of the subwatersheds, with approximately 80% of TDN present as DIN. DON was higher in the Smith Falls subwatershed, where only 60% of TDN occurred as DIN. Seasonal patterns in DIN and DON were the same as for TDN, with maximum loadings occurring in the winter for all subwatersheds except the Columbia Valley, where the largest loads corresponded with the timing of spring fertilizer application.

Compared to nitrogen, seasonal patterns in TDP concentrations and TP loads were less pronounced in the Cultus Lake subwatersheds. TDP was elevated from July through November, with slight maxima occurring September through November. Maximum concentrations corresponded with the onset of winter precipitation and increased discharges throughout the watershed (Figure 4-2). Vedder Mountain and Smith Falls had the highest concentrations of TDP throughout the study duration, with maximum concentrations of >20 µg-P/L in October and November. Seasonal patterns in TDP concentration were the same in the Columbia Valley as in the other subwatersheds, and there was little difference between TDP concentrations in Frosst Creek stations upstream and downstream of the Columbia Valley agricultural area (Figure 4-2).

Despite relatively low TDP concentrations in Frosst Creek compared to the other subwatershed streams, the Columbia Valley had the highest TP loads throughout the study due to high discharge volumes. In the spring, TP loads from the Columbia Valley were more than twice those of International Ridge, the second largest subwatershed source. TP loads were highest in all subwatersheds during the wet season, with loads 20% to 60% higher than the dry season. There was very little seasonal variation in TP loads in the Vedder Mountain, International Ridge, and Smith Falls subwatersheds, displaying only slightly higher spring and winter loadings. In the Columbia Valley, spring loads were ~50% greater than calculated for other seasons. Average areal exports of TP from Vedder Mountain and Smith Falls were higher than International Ridge and the Columbia Valley, suggesting mineral weathering sources, decreased phosphorous retention, or other phosphorous sources (Figure E7).

TDP loads from stream sources were evenly split between DIP and DOP. The Smith Falls subwatershed had a slightly lower proportion of DIP relative to the other subwatershed; DIP accounted for approximately 38% of total phosphorous loads, compared to 42% to 50% in the other subwatersheds. Seasonal patterns in DIP and DOP loadings mirrored those of TP.

Migratory bird guano

Direct loading from gull guano was calculated using 4 different literature estimates for gull nutrient production. The median annual TN loading for a gull population of 11,000 gulls/yr was 585 kg/yr, while annual TP was 355 kg/yr. TN loads from migratory gulls accounted for only 1% of the yearly total load to the lake, whereas migratory gulls contributed 16% of the yearly TP load. Seasonal nutrient loads for migratory gulls were greatest during seasons with the longest occupation periods (fall and winter), and no gull loading occurred during the summer. Literature values for gull guano production rates were highly variable, leading to uncertainty in calculated loads. The maximum calculated load from gulls using the highest guano production rate reported in the literature was 1,811 kg/yr for TN (Gould and Fletcher 1978), and 760 kg/yr for TP (Portnoy 1990).

Septic leaching

The annual load of TN from septic sources to Cultus Lake was 2,070 kg-N/yr, with 1,485 kg-N/yr originating in the Columbia Valley and 586 kg-N/yr originating from International Ridge. Septic loads for TN accounted for 4% of the total nitrogen load to Cultus Lake. The TP load from septic systems was 238 kg-P/yr (170 kg-P/yr from the Columbia Valley and 67 kg-P/yr from International Ridge), accounting for 11% of the total annual phosphorous load to the lake.

Inputs to septic systems were highest during the summer tourist season, when occupancy in both subwatersheds was at a maximum. Despite low precipitation and soil percolation in the summer, the highest nitrogen and phosphorous loadings from septics occurred during this season due to high rates of septic use in the Columbia Valley, particularly in Lindell Beach and nearby resort areas. The exact timing of loading from septic sources into Cultus Lake could not be verified due to a lack of site-specific seasonal data on precipitation infiltration in the subwatersheds. However, high precipitation levels and high water use rates during the summer likely resulted in year-round septic-sourced loading into Cultus Lake.

We examined the effect of varying soil retention coefficients on the magnitude of loads from septic systems to Cultus Lake, but found that a 10% change in the soil retention coefficient did not have a substantial effect on the contribution of septics to Cultus Lake nutrient loads (Table E1). At a low level of retention (a worst case scenario), loads of TN and TP to Cultus Lake rose to 2,313 kg-N/yr and 297 kg-P/yr, respectively. These values would account for 5% of annual TN loads and 14% of TP loads in the watershed. The high, or most conservative retention coefficients, resulted in TN loads of 1,827 kg-N/yr (4% of the total) and TP loads of 178 kg-P/yr (8% of the total).

Sockeye salmon carcasses

Sockeye salmon escapements to Cultus Lake were almost an order of magnitude different between the two study years. Total escapement of sockeye to Cultus Lake was 7,211 in 2011 and 892 in 2012, resulting in loads of 340 kg/yr (2011) and 42.0 kg/yr (2012) for TN and 40.2 kg/yr (2011) and 5.0 kg/yr (2012) for TP (Figure E8). Average annual TN and TP loads were 191 kg (<1% of total loading) and 23 kg (1% of total loading), respectively. Maximum escapement recorded for Cultus Lake sockeye salmon occurred in 1959, with a total escapement of 48,461 spawners. If an escapement of this size had occurred during the present study, TN from sockeye carcasses would have accounted for 5% of the total load, while sockeye TP would have been 12% of total loadings.

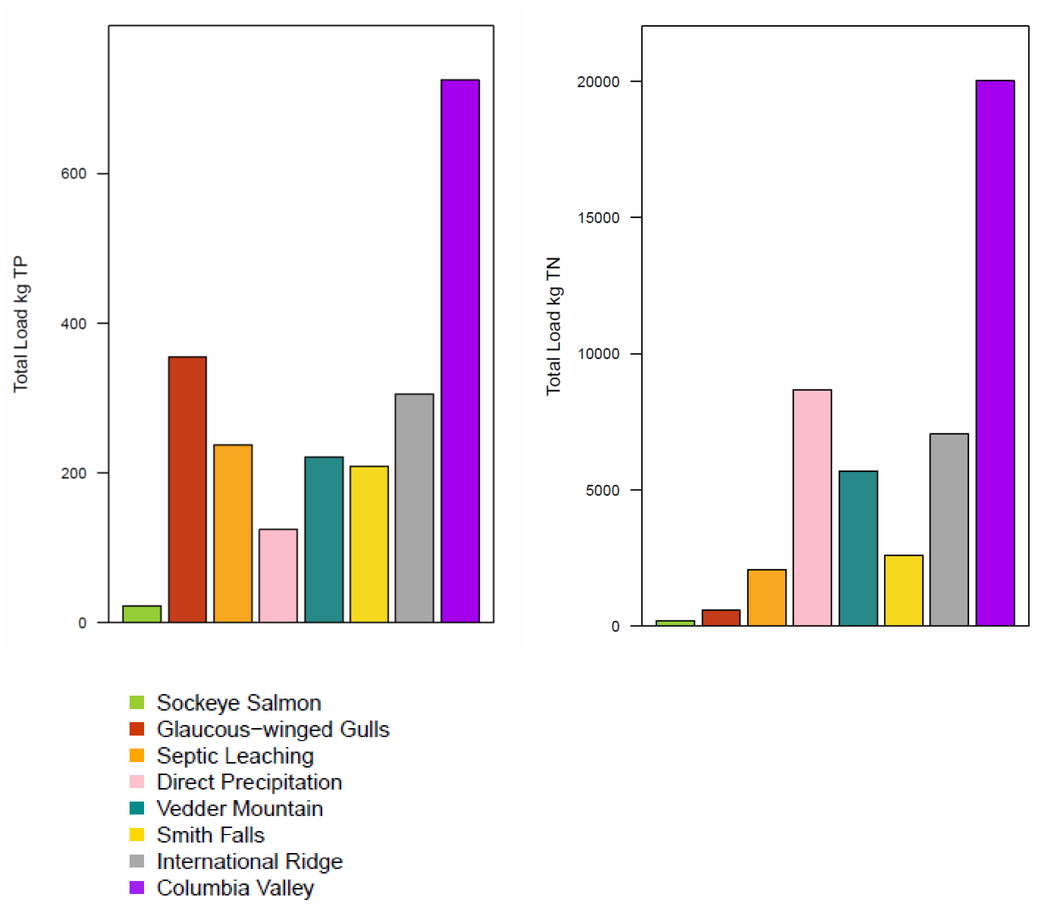

Figure E1. ***Average yearly loads (kg/yr) of TP and TN to Cultus Lake for all measured and estimated sources including watershed and direct sources. Nitrogen loads from subwatershed sources are TDN because particulate nitrogen data were not available for the analysis.***

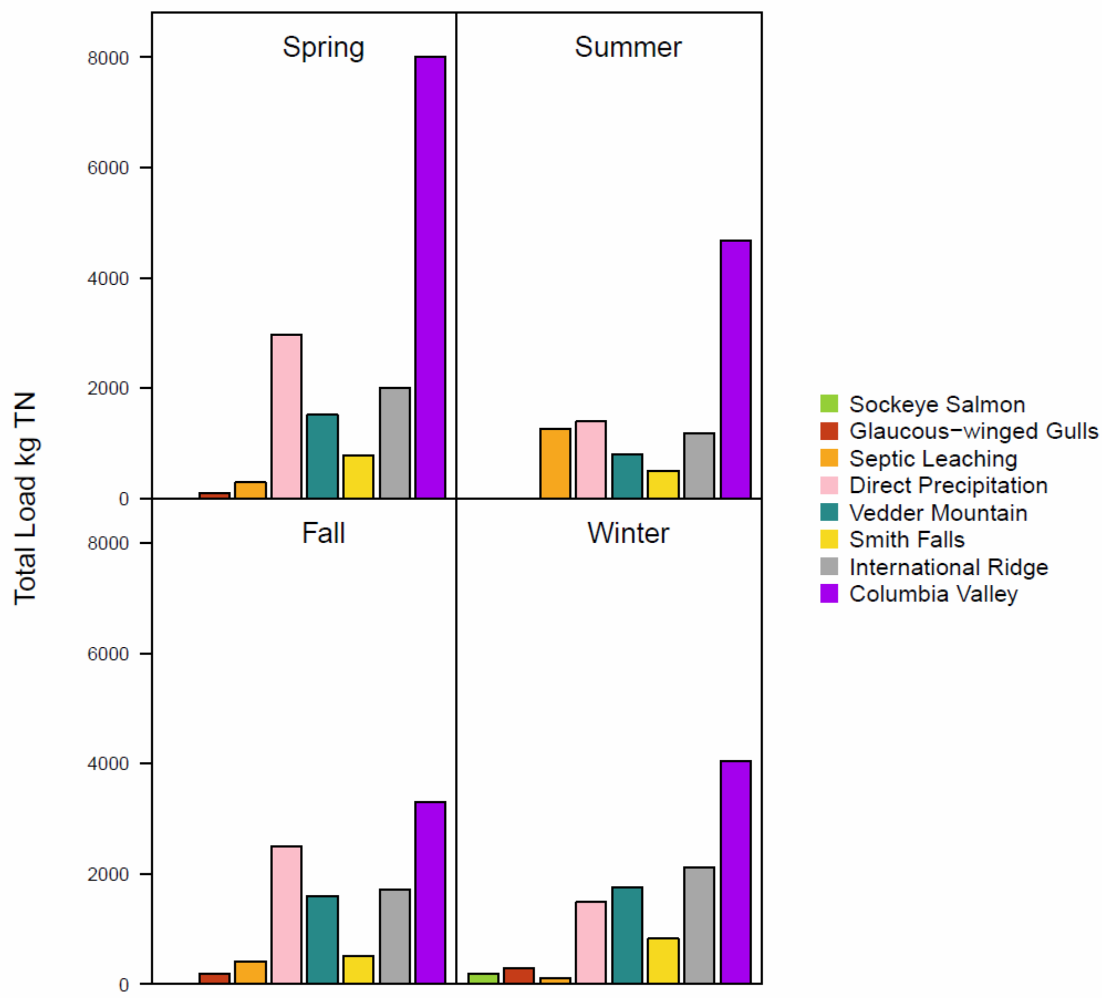

Figure E2. ***Average seasonal loads of TN (kg-N) to Cultus Lake from all measured and estimated sources including watershed and direct sources. Nitrogen loads from subwatershed sources are TDN because particulate nitrogen data were not available for this analysis.***

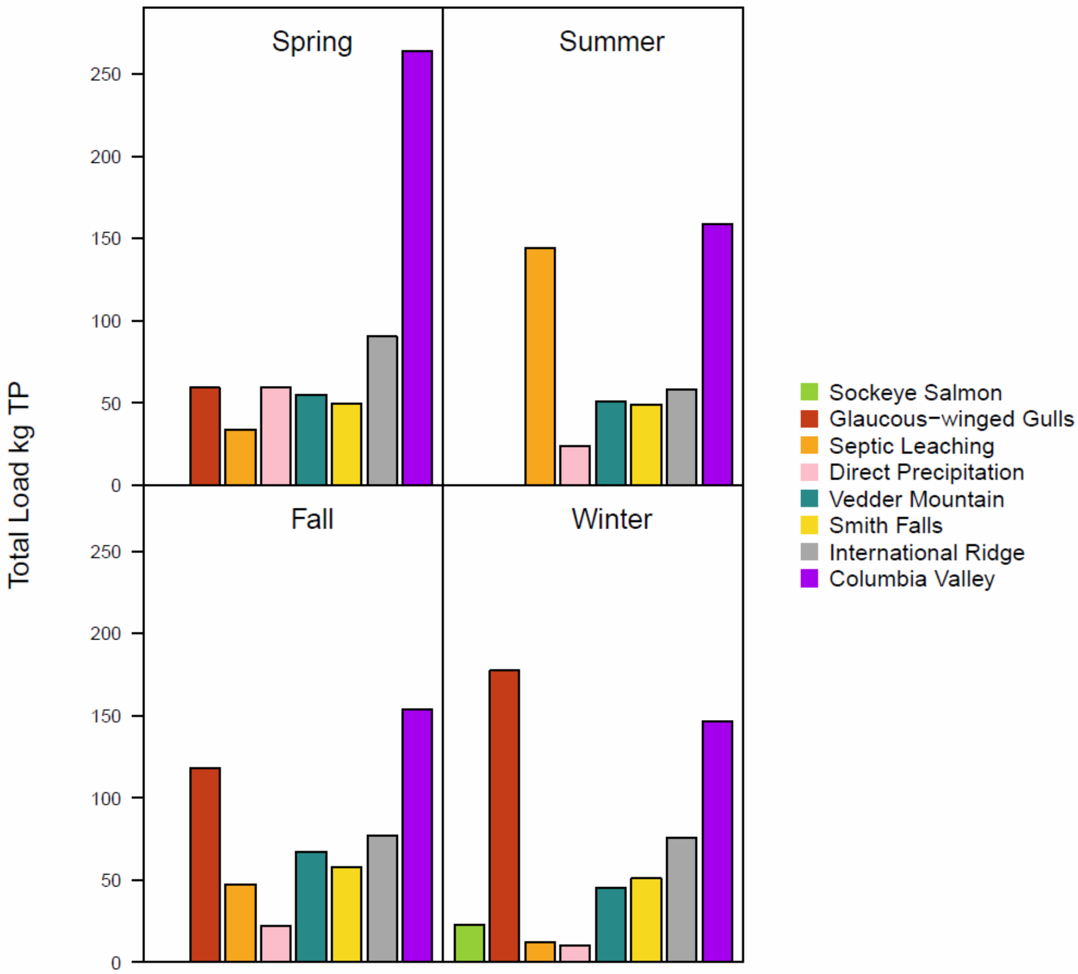

Figure E3. ***Average seasonal loads of TP (kg-P) to Cultus Lake from all measured and estimated sources including watershed and direct sources.***

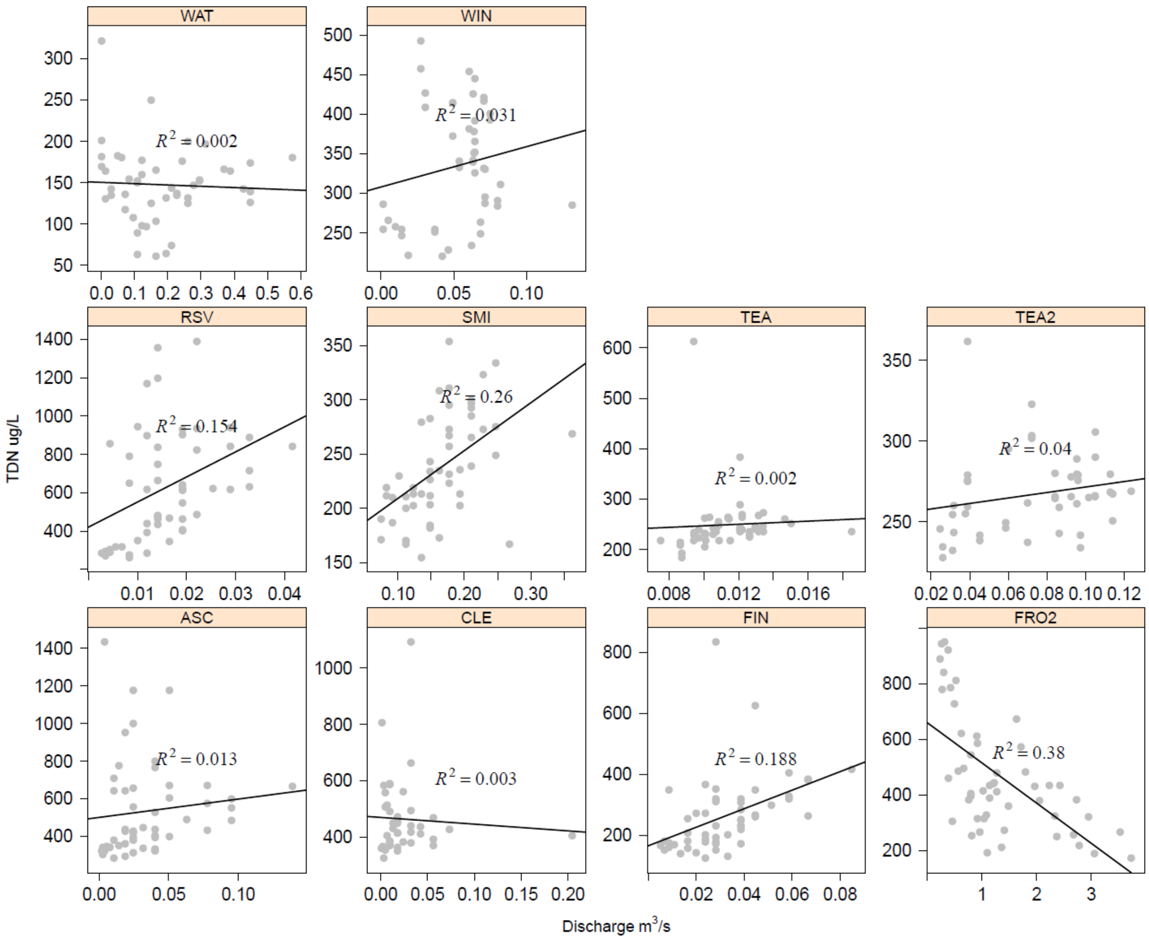

Figure E4. ***Correlations between TDN (µg/L) concentration and discharge (m^3/s) in Cultus Lake tributaries on twice-monthly sampling dates between May 2011 and May 2013. Teapot Creek has been separated into its two original streams: TEA and TEA2.***

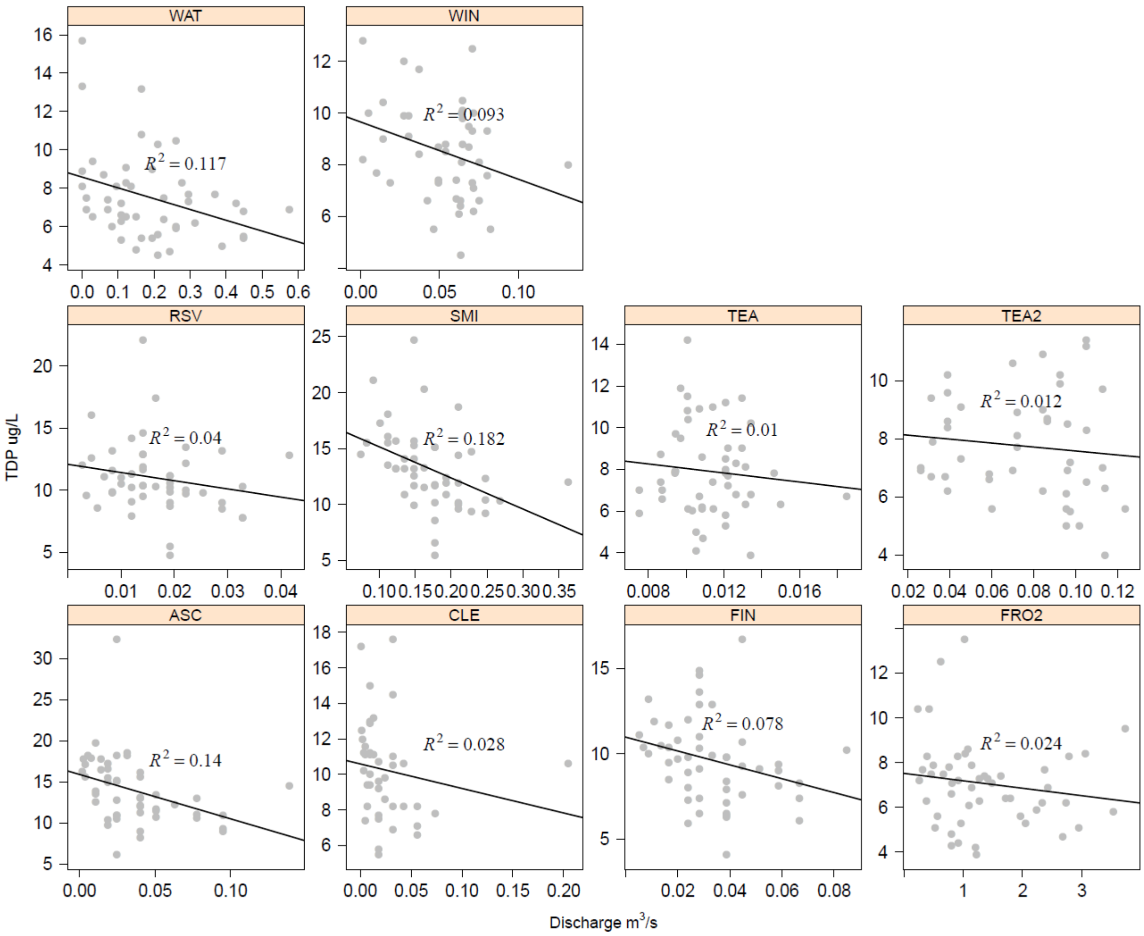

Figure E5. ***Correlations between TDP (µg/L) concentration and discharge (m^3/s) in Cultus Lake tributaries on twice-monthly sampling dates between May 2011 and May 2013. Teapot Creek has been separated into its two original streams: TEA and TEA2.***

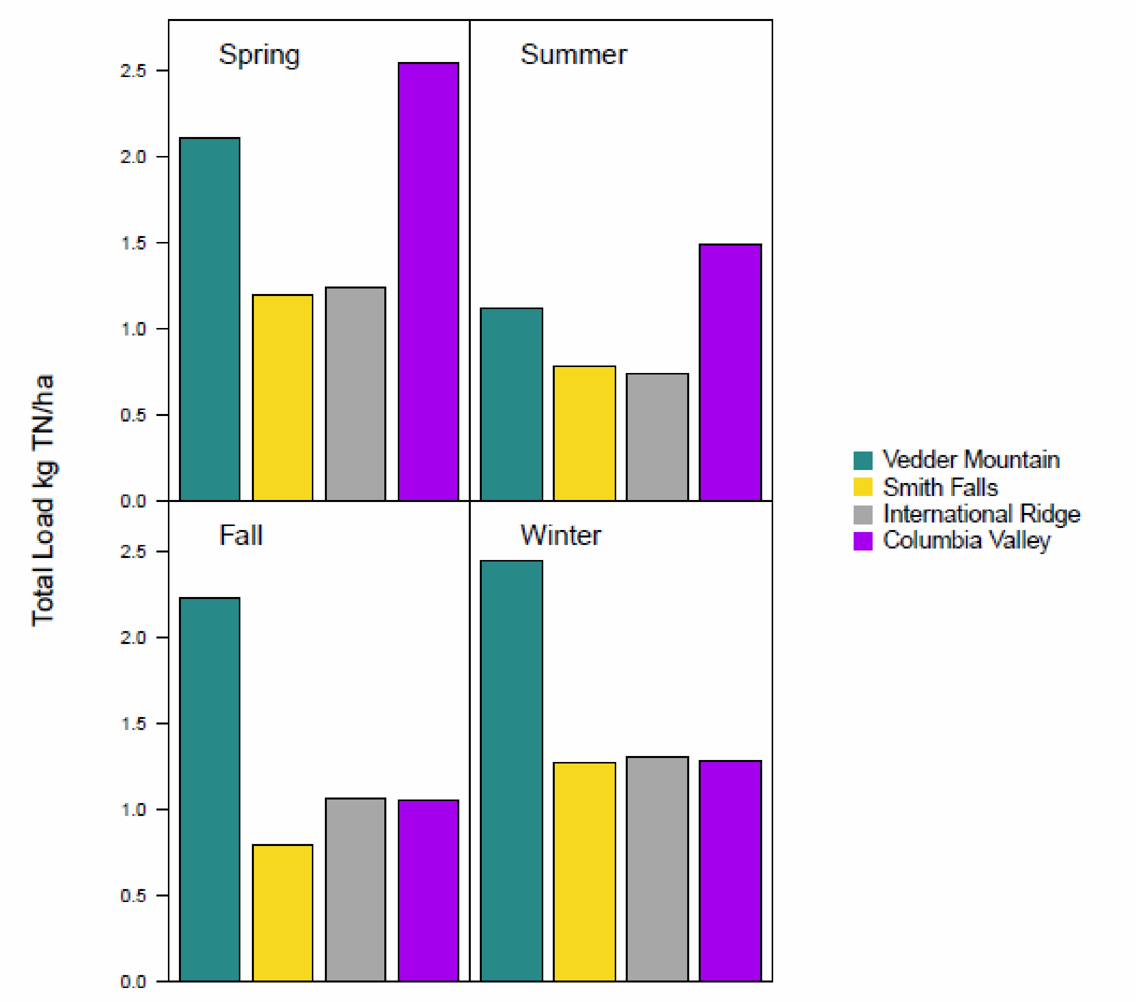

Figure E6. ***Average seasonal areal export (kg-N/ha) of TN to Cultus Lake from subwatershed sources. Export of TN from subwatersheds is TDN because particulate nitrogen data were not available for this analysis.***

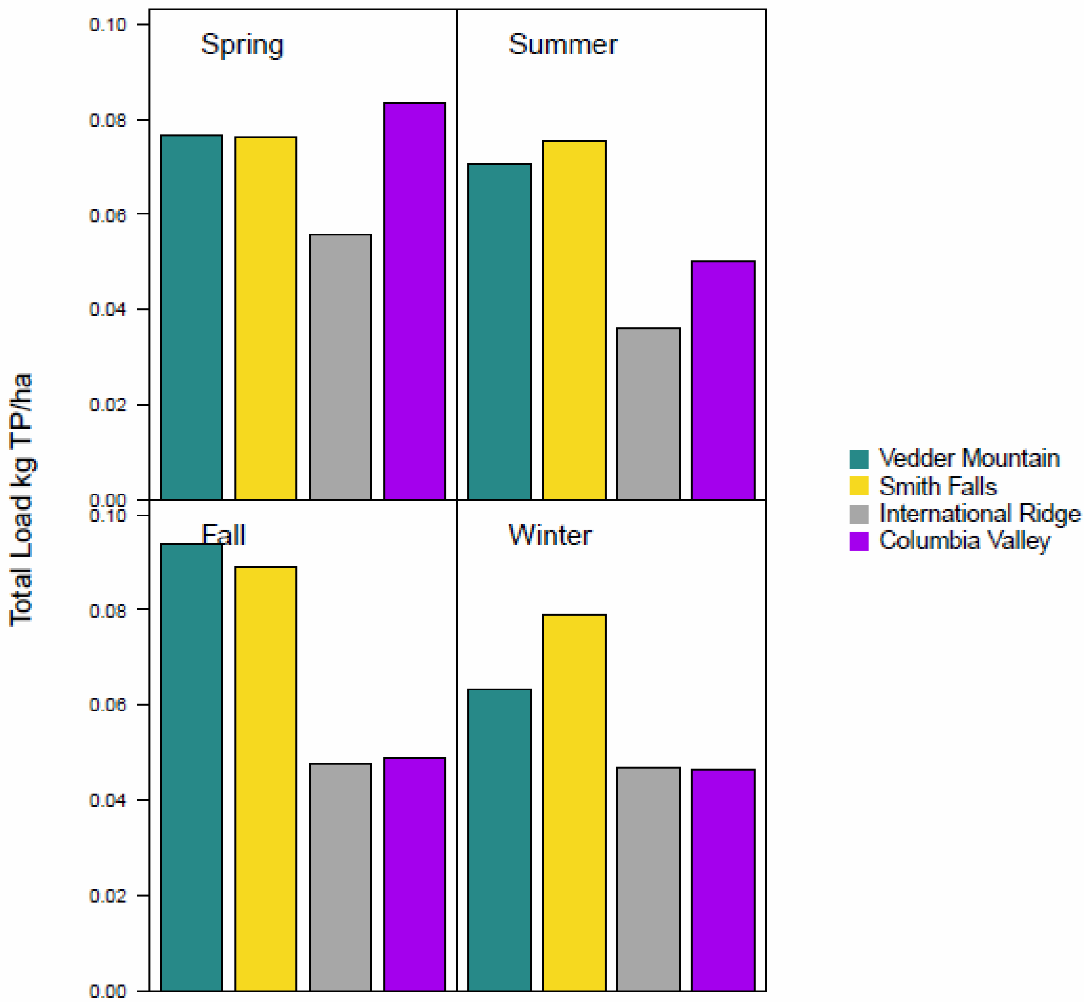

Figure E7. ***Average seasonal areal export (kg-P/ha) of TP to Cultus Lake from all watershed sources.***

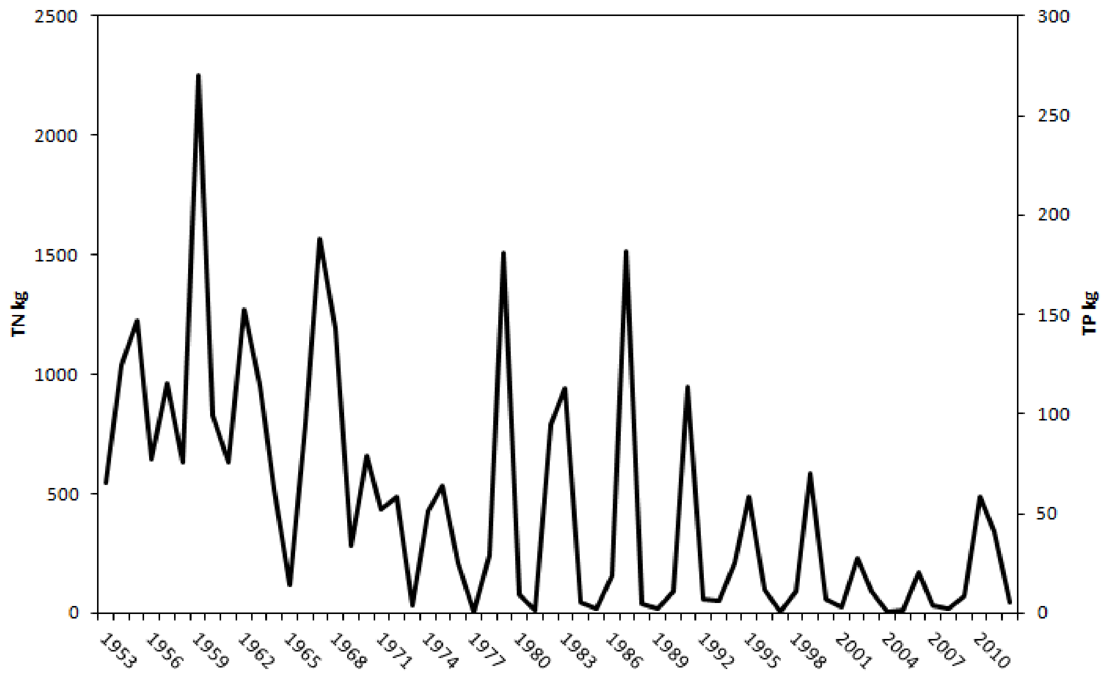

Figure E8. ***Estimated historic loads of TN (kg-N) and TP (kg-P) from sockeye salmon carcasses to Cultus Lake from 1953 to 2011.***

Table E1. ***Table of sensitivity analysis for retention coefficients used to calculate septic effluent nutrient loads to Cultus Lake***

	Nitrogen Loading (kg-N/yr)		Phosphorus Loading (kg-P/yr)	
Retention Level	**Col. Valley**	**Int. Ridge**	**Col. Valley**	**Int. Ridge**
Low[a]	1,659	654	213	84
Medium[b]	1,485	586	170	67
High[c]	1,310	517	128	50

a. Coefficients: TP: 0.50, TN: 0.05

b. Coefficients: TP: 0.60, TN: 0.15

c. Coefficients: TP: 0.7, TN:0.25

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