TEMPORAL COHERENCE OF NUTRIENTS AND IMPLICATIONS FOR UNDERSTANDING BRITISH COLUMBIA LAKE WATER QUALITY VARIATION

by

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ABSTRACT

Temporal coherence, or the degree to which lakes behave similarly through time, provides new insights into the relationship between extrinsic drivers such as climate, and synchronous variation in lake variables at scales beyond the individual lake and catchment. A review of relevant literature suggests coherence of nutrients is highest among proximate pairs of short water residence time lakes within a common drainage path. High connectivity and short water residence times reduce the potential for catchment and lake specific alteration of the discharge signal. Few studies to date have explored coherence of total nitrogen and total phosphorus among lakes. To evaluate nutrient coherence among British Columbia (BC) lakes, I assembled spring estimates of total nitrogen and total phosphorus values over the period 1977 to 2007 for twenty-six lakes. To optimize coherence, I utilized a depth composite mean from a single deep site on lakes with at least 10 years of spring data. All lakes occur in catchments with varying degrees of anthropogenic disturbance and reflect a broad range of lake morphology and climatic conditions in both coastal and interior areas of BC. I explored the potential for climate to cause nutrient coherence by determining whether discharge was synchronous among nearby drainages, and whether lake nutrient variability was dependent on antecedent catchment discharge. Subsequently, I tested whether nutrient coherence was dependent on lake-pair proximity, similarity in lake water residence time, or lake fertility. Temporal coherence was calculated as the average Pearson Product Moment Correlation (r). Discharge was found to be highly coherent, particularly among streams in southern BC, over distances of several hundred kilometers. Temporal coherence of total nitrogen among lakes at all spatial scales was very weak but positive. Coherence was greater and positive for total phosphorus. Phosphorus coherence was not dependent on lake pair proximity, and dependence on water residence time was limited to coastal lakes. Temporal coherence of phosphorus was significantly greater for oligo-mesotrophic lakes than eutrophic lakes across significant spatial scales. These findings should be considered when interpreting lake response to local stressors and setting lake management targets.

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BC	British Columbia
ELA	Experimental Lakes Area
ENSO	El Nino Southern Oscillation
LTER	Long term ecological research
Km	kilometres
µg/L	microgram per litre
mdc	minimum detectable concentration
NAO	North Atlantic Oscillation
NH3-N	ammonia nitrogen
NO3-N	nitrate nitrogen
SD	standard deviation
SE	standard error
SO^4	sulphate
TKN	total kjeldhal nitrogen
TN	total nitrogen
TP	total phosphorus
TDP	total dissolved phosphorus
WRT	water residence time

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CHAPTER 1

TEMPORAL COHERENCE OF NUTRIENTS: A REVIEW OF
RECENT FINDINGS AND IMPLICATIONS FOR UNDERSTANDING
BC LAKE WATER QUALITY VARIATION

INTRODUCTION

Fundamental to the management of freshwater resources is an understanding of lake
nutrient dynamics through time, and the ability to apportion the influence of extrinsic
forces such as climate variability on lake water quality, relative to that which may be
intrinsic to the lake and catchment or be driven locally due to land-use or environmental
pollution (Scarsbrook, 2003). Without this broad long-term view of lake dynamics, our
understanding of individual lake ecosystems can be constrained. Magnuson *et al.*,
(2004) refers to this metaphorically as being in the "invisible present" and "invisible
place"; in other words being unaware of broader processes and longer term dynamics
and antecedent conditions affecting short term observations on individual lakes and
variables of interest. This concern is particularly acute for resource management
agencies engaged in lake monitoring and management programs which typically lack
long-term reference lakes within integrated monitoring networks. Lacking this broader
perspective, each lake is considered largely unique in terms of catchment and climate
interaction, and resulting water quality variability.

Climate is a strong driver of lake dynamics on interannual time scales, and climate
variation and change are expected to profoundly affect lake ecosystems through altered
hydrologic flowpaths, biogeochemical fluxes, and water residence times of surface
waters (Carpenter *et al.,* 1992; Melack *et al.,* 1997; Schindler, 2001). Although much of
our understanding of lake ecosystems arises from studies occurring at the lake and
catchment scale, it is reasonable to expect that lakes and their catchments within a
region should experience similar interannual variation in climate forces, and
limnological variables strongly affected by climate might co-vary similarly through time
in neighbouring lakes. In contrast, as the interannual variation of a variable is

increasingly governed by intrinsic factors such as internal nutrient recycling or complex biotic interactions, or local disturbance and inputs, the climate signal would be modified or attenuated (Magnuson *et al*., 1990). The degree to which lakes within a region behave similarly through time has recently been described as temporal coherence, or lake synchrony (Magnuson *et al*., 1990). Temporal coherence of parameters among diverse lakes, and across various spatial scales, offers a new means of assessing the role of extrinsic drivers such as climate or other regional drivers such as acid rain, on lake dynamics. Moreover, temporal coherence has practical importance, as it potentially enables extrapolation of results from a few well studied lakes to other lakes, and aid prediction of lake dynamics in the future (Magnuson *et al*., 2006).

Research on lake coherence in general, and nutrient coherence in particular, is still exploratory. While physical variables such as surface temperature, are shown to be highly coherent within a region (Baines *et al*., 2000), chemical variables, especially nutrients, appear to be only weakly to moderately coherent among nearby lakes. Coherence of reactive ions and nutrients among lakes, is attributed to a variety of factors including variability in material processing within catchments as a function of flow path complexity (Kratz *et al*., 1998; Webster *et al*., 2000) and proximity of lake pairs (Baron & Caine, 2000; Kling *et al*., 2000), or material processing as a function of lake water residence time (Sorrano *et al*., 1999). Coherence of nutrients among lakes also occurs where simultaneous anthropogenic nutrient load changes are common among catchments (Anneville *et al*., 2005; George *et al*., 2000; Kratz *et al*., 1998). Regardless of cause, temporal coherence of nutrients among lakes continues to be of much interest as it provides a pattern of response which establishes the importance of external drivers to lake ecosystems across larger spatial scales.

At the present time it is not known to what extent long term nutrient variation in BC lakes might be governed by climatic forces acting over larger spatial and temporal scales. I suggest that without this understanding, interpretation of long term trends in limnological variables related to eutrophication control, catchment protection initiatives, or fisheries and hydrologic manipulation in BC lakes, could be incomplete and

compromise water management decisions. Nutrients are important water quality measures linked to trophic classification (Carlson, 1977), trend assessment and water quality protection initiatives in BC (Nordin, 2005) and elsewhere (Anderson *et al.*, 2005). Moreover, nitrogen and phosphorus concentrations are considered important sentinels of climate warming on freshwater ecosystems (Schindler, 2009). Surprisingly, these nutrients, in particular total nitrogen and total phosphorus, are poorly incorporated in coherence studies to date.

In this chapter, I further introduce analysis of temporal coherence as a measure of patterned variation among lakes. Given the limited number of North American and European studies which have explored coherence of nutrients, it is reasonable to first briefly chronicle this work. My intention is not to provide an exhaustive review of temporal coherence across all variables and landscapes, but rather to explain the basic organizing concepts, and review recent work describing coherence of nutrients. I will first however, review and illustrate temporal coherence using physical parameters and a general conceptual model put forward by Magnuson *et al.* (1990), that of climate acting as a signal and the catchment and lake serving as a receptor. I then consider ion reactivity and material processing, within catchment and lake environs, as the second conceptual model to organize a synthetic understanding of the coherence work to date for nutrients. Finally, I describe the relevance of these findings to lake management in BC, and establish the rationale to examine the extent to which nitrogen and phosphorous may vary synchronously among BC lakes. Based on previous work, and the BC context, I propose a number of hypotheses to guide further analysis, and discuss the significance of any observed coherence.

TEMPORAL COHERENCE ANALYSIS

Temporal coherence for a parameter of interest is typically reported as the average statistical correlation among all possible pairs of lakes across the spatial scale of interest (Magnuson *et al.*, 2006). Studies to date often report variable coherence as the average Pearson product-moment correlation (*r*) among lakes within a drainage or region (Baron & Caine, 2000; George *et al.*, 2000; Kling *et al.*, 2000; Soranno *et al.*, 1999; Webster *et*

al., 2000). Correlation coefficients are typically calculated using annual or seasonal mean values for the same parameter from a lake-by-year matrix. Concerns and assumptions over use of time series data for coherence analysis (null hypothesis equal to zero for all lake pairs; equal variances; influence of autocorrelation in the time series; effect of maximum values; seasonal or long term trends) have been explored and generally not found to seriously affect assessment of coherence using correlations (Kling *et al.*, 2000; Kratz *et al.*, 1998; Magnuson *et al.*, 1990). As temporal coherence aggregates multiple lake-pair correlations, and coherence estimates are not statistically independent, some studies employ a Bonferroni, or similar correction, to determine what proportion of the correlation coefficients are significantly different from zero (Anneville *et al.*, 2005; Baron & Caine, 2000). The Bonferroni correction is a safeguard against multiple tests of statistical significance on the same data falsely giving the appearance of significance, as 1 out of every 20 hypothesis-tests is expected to be significant at the $\alpha = 0.05$ level purely by chance.

LIMITED PREVIOUS STUDY OF NUTRIENT COHERENCE

Only six North American studies and one European study, have directly examined and reported interannual coherence of nutrients among lakes for 11 lake districts. The seminal work of Magnuson *et al.,* (1990) examined a 7 year data set for 7 groundwater dominated lakes in the Wisconsin Long Term Ecological Research (LTER) lake district. This work is expanded by Kratz *et al.,* (1998) to include 4 additional lakes connected by surface drainage in southern Wisconsin over a 13 year period. Subsequent studies include a 7 year study of a chain of 9 lakes in the Alaska Arctic LTER area (Kling *et al.*, 2000), and a 10 year data set for 3 lakes in the Loch Vale and 4 lakes in the Green Valley lake chains of the Rocky Mountain front range in Colorado (Baron & Caine, 2000). A synthesis of the studies, along with new data for Adirondack and Qu'appelle lake systems and Tennessee reservoirs, is provided by Soranno *et al.* (1999). Shortly thereafter temporal coherence of chemical variables over a 14 year period was also examined for 4 lake districts in the upper Great Lakes region (Webster *et al.*, 2000) and

among lakes within the English Lake District (George *et al*., 2000). Average nutrient coherence values reported in these studies are summarized in Table 1.1.

Table 1.1 Lake characteristics and average nutrient coherence for various lake groups.

Lake district	No. Lakes	Years	Trophic Status	Average Coherence (r)				
				NO3-N	NH4-N	SRP/TDP	TP	TN
Northern Wisconsin LTER	7	1982-88	Meso-Eutro-Dystrophic			0.39[a]		
Northern Wisconsin LTER	5	1982-95	Meso-Eutro-Dystrophic	0.077	0.585		0.139	0.573
Southern Wisconsin	4	1982-94	Eutrophic	0.12	0.331		0.674	0.311
Northern and Southern lakes	11	1982-94				0.22[b]	0.15[b]	0.08[b]
Arctic LTER	8	1991-97	Ultra-oligotrophic	0.691	0.863	0.7[c]		
Adriondacks A	4	1983-93	Oligotrophic	0.926	0.492			
Adriondacks B	3	1983-94	Oligotrophic	0.902	0.325			
Vale LTER	3	1984-96	Oligotrophic	0.881	0.447			
Green Valley LTER	4	1984-97	Oligotrophic	0.28				
ELA	10	1982-95	Oligotrophic				0.267	0.491
Red Lake	6	1982-96	Oligotrophic				0.467	0.426
Dorset	9	1982-97	Oligotrophic				0.385	0.689
English Lake District	6	1950-90	Eutrophic	0.73[d]		0.65[d]		

NO3-N, nitrate nitrogen; NH4-N, ammonia nitrogen; SRP/TDP, soluble reactive/total dissolved phosphorus; TP, total phosphorus; TN, total nitrogen ELA, Red Lake and Dorset from Webster *et al*., (2000); otherwise data from Sorrano *et al*., (1999) or as indicated: a -Magnuson *et al*., (1990); b -Kratz *et al*., (1998); c-Kling *et al*., (2000); d - George *et al*., (2000). See citations for lake membership

THE CLIMATE SIGNAL AND COHERENCE

Climate variation on an interannual scale can be considered conceptually as a signal that is modified in complex ways by lake and catchment attributes to attenuate, transform, or delay the climate signal (Magnuson *et al.*, 2006). Coherence is expected to be most evident when the climate signal has sufficient interannual variation and limited spatial variation, so as to cause easily measured variation, in a variable of interest (George *et al*., 2000; Kling *et al*., 2000). Perfect coherence is only conceivable among identical lakes for a variable which responds directly and faithfully to external drivers such as climate. In reality, various aspects of catchment local weather, soils, vegetation or lake morphometrics, trophic status, and hydrology can combine to alter and degrade the climate signal and reduce coherence among lakes. Thus the potential for high coherence should be greater for variables such as water temperature with direct mechanistic links to meteorological forcing, than chemical or biotic measures which are more often the product of complex interactions (Magnuson *et al*., 2006). Indeed, coherence of surface

water temperatures, resulting from direct signal transmission of solar radiant energy to the lake surface, is high among proximate lakes in North America (Benson *et al*., 2000; Magnuson *et al*., 2004) and Europe (Livingstone, 2008). For example, epilimnetic water temperatures, are highly coherent (r>0.8) within and among lakes spanning tens of kilometres to a few hundred kilometres in the upper Great Lakes Region of North America (Benson *et al*., 2000). Similarly, ice-off dates are highly coherent among lakes across significant spatial scales in both North America (Kratz *et al*., 1998; Magnuson *et al*., 2004) and northern Europe (Livingston *et al*., 2008).

However, as lake specific exposure to the thermal signal is altered by variation in lake morphology or other factors governing the vertical transfer of heat (e.g. surface area to mean depth ratios, fetch, wind speed), the climate signal is modified or attenuated, and temporal coherence diminishes. For example, coherence of thermocline depth, is moderate ($r \sim 0.5$) within lake districts, and low ($r < 0.26$) between lake districts in the upper Great Lakes Region of North America (Benson *et al*., 2000). Thus solar radiation with low spatial variation enables high coherence of a physical variable, when lake specific modification of the climate signal is low.

Although precipitation and run-off are more spatially variable than temperature, these same concepts of the catchment and lake functioning in various ways to attenuate and modify the climate signal, also apply to coherence of variables affected by precipitation and consequent hydrologic variability.

HYDROLOGIC VARIABILITY AS A CLIMATE SIGNAL

Hydrology is an important climate driver governing the dynamics of freshwater ecosystems (Poff & Allen, 1995; Schindler *et al*., 1996). Similar to the examples given above for temperature, temporal coherence should be high among neighbouring lakes for variables linked mechanistically to variation in precipitation and run-off. Furthermore, it is reasonable to expect neighbouring lakes to experience similar year to year variation in precipitation including anomalous periods of multiple year drought, or wetter years with greater annual precipitation. These interannual patterns in

precipitation should potentially produce corresponding variation in run-off and coherence of catchment discharge among neighbouring lakes.

Although few lake studies to date have examined physical limnological measures with direct mechanistic links to discharge variation, in one case, lake water levels are shown to be highly coherent (r=0.87-0.94) among a set of groundwater fed lakes in the Northern Wisconsin Long Term Ecological Research (LTER) area (Magnuson *et al*., 1990). However, when the analysis also included data for surface drainage lakes of the southern Wisconsin area, coherence of lake levels was reduced (r=0.55) (Kratz *et al*., 1998). Thus as diversity and complexity of water flow path increases, and catchments differ in the ratio of infiltration to run-off and evaporative losses, the climate signal is increasingly modified or filtered, and coherence diminishes among nearby lakes.

Hydrology is a strong determinant of lake water chemistry. Within catchments, periods of higher flow contribute to greater export of sediments, solutes and nutrients, to downstream waters (Schindler *et al*., 1996). Conversely, during periods of drought and lower flow, water movement and flux of materials from catchments to lakes diminishes, and evapoconcentration of conservative ions, and in-lake scavenging of reactive solutes increase (Schindler *et al*., 1996; Webster *et al*., 2000). Conservative ions in lakes vary largely as a function of mechanistic processes of soil weathering, hydrologic transport along surface and groundwater flow paths, and evapoconcentration. Moreover, because biological and chemical reactions within lakes are relatively minor for conservative ions, outputs from a lake closely follow inputs (Soranno *et al*, 1999). Conversely, lakes retain or process a significant portion of their nutrient load as a function of loading and water residence time, and as water residence time increases, lake specific reactions are increasingly important to nutrient variability. Thus, contrasts in hydrology among catchments and among lakes may provide insights into the coherent tendencies of chemical variables.

CONTRASTS IN COHERENCE OF CONSERVATIVE AND REACTIVE IONS

Studies of individual lake districts, in almost all cases, show greater coherence for conservative ions and measures, than for nutrients and reactive variables (George *et al*., 2000; Kratz *et al*., 1998; Soranno *et al*., 1999; Webster *et al.*, 2000). For example, calcium, a conservative ion largely unaffected by chemical or biotic reactions along ground or surface water flow paths is highly synchronous ($r=0.81$) among groundwater fed lakes in the Northern Wisconsin LTER lake district, as well as in Southern Wisconsin surface water dominated lake district ($r=0.76$) (Soranno *et al*., 1999). In strong contrast, the average overall synchrony of total nitrogen and total phosphorus, is uniformly lower among both the Northern ($r=0.36$) and Southern ($r=0.49$) Wisconsin lake districts (Soranno *et al*., 1999). Similar to calcium, chloride is another conservative ion and among lakes within 3 surface water dominated lake districts on Canadian Shield bedrock, chloride is consistently more coherent ($r=0.62-0.92$) than nutrient variables such as total phosphorus ($r=0.27-0.48$) or total nitrogen ($r=0.49-0.69$) (Webster *et al*., 2000). And finally, within the English Lake District, alkalinity coherence among five lakes is high ($r=0.94$) relative to nitrate nitrogen ($r=0.73$) or dissolved reactive phosphorus ($r=0.65$). Thus in these diverse hydrogeological settings, coherence of nutrient variables is consistently lower relative to conservative ions.

It seems logical then, that among lakes where contrasts in flow path complexity (e.g. groundwater versus surface water; position within a series of lakes) and water residence time (WRT) are evident, coherence of nutrients should be reduced over landscapes and lakes which are similar in these processes. Clearly, mass balance steady state models, which incorporate water residence time, have been useful in developing a predictive understanding of the concentrations of various chemicals in waterbodies, most notably that of phosphorus (Dillon & Molot, 1996), nitrogen (Windolf et al., 1996), and dissolved organic carbon (Curtis, 1998). Conceptually, longer water residence times enable longer flow path and longer water contact with catchment soils as well as longer within lake processing. Combined these should contribute to greater individuality of chemical signals in downstream waters and thus lower coherence.

FLOW PATH AND COHERENCE

Hydrologic flow path and lake pair proximity are important to coherence expression. Contrasts in flow path are most pronounced between surface-water fed lakes and seepage lakes fed largely by groundwater. Groundwater flow is orders of magnitude slower than that of surface water. Where lake districts are largely dominated by groundwater flow paths, or incorporate both seepage and drainage lakes, coherence is reduced, particularly for TP. For example, among Northern Wisconsin LTER seepage lakes governed by groundwater flow paths, coherence is moderate for TN (r=0.573) but very low for TP (r=0.139) (Webster et al., 2000).

Direct surface water flow paths between catchment and lake, and from lake to lake, also contribute to higher coherence, and proximate lakes are generally more coherent than distant pairs. For example, among Arctic LTER lakes, where flow path dynamics are governed by permafrost melt-water flow along surface water drainages and shallow soil horizons, coherence is high (NO3-N r=0.691; SRP r=0.7) but diminishes with distance between lakes (Kling et al., 2000). In this setting, Kling et al. (2000) conclude coherence is primarily related to proximity through the consistent ion processing along the drainage, and secondarily to water residence time. Similarly among Colorado lakes, coherence of NO3-N is higher among proximate pairs of lakes within the drainage, than distant pairs within or between the Vale Loch and Green Lake drainages (Baron & Caine, 2000). Finally, in a much different setting, that of the Ontario ELA, Dorset and Red Lake areas, moderate coherence of both total nitrogen (r=0.416-0.689) and total phosphorus (r=0.267-0.467) occurs among lakes at high and low positions along the hydrologic flow path (Webster et al., 2000). The Ontario lakes (ELA, Red Lake and Dorset) lie on bed rock with thin soils, and surface drainage flow paths enable annual changes in precipitation, particularly multiple years of drought, to be conveyed synchronously to downstream lakes.

WATER RESIDENCE TIME AND COHERENCE OF NUTRIENTS

Support for water residence time (WRT) as an organizing concept, comes from a synthesis of data from a number of lake district studies (Sorrano *et al*., 1999). Using aggregated data for lake chains in Wisconsin, Arctic, Colorado Front Range, and Adirondack lake districts, Sorrano *et al*. (1999) shows the collective coherence of dissolved reactive variables (sulphate, dissolved silica, nitrate, ammonia) decrease with increasing lake district median WRT (r^2=0.31, P=0.003). Colorado and North Wisconsin lakes serve as end members in this relationship. Snowmelt over thin soils of the Colorado Front Range, result in very short water residence times (0.02-0.08 yr). In these drainages, water moves quickly from catchment to lake and from lake to lake, and average coherence of dissolved reactive ions are high (r=0.79) (Sorrano *et al*., 1999). Conversely, average coherence of dissolved reactive variables is low (r=0.234) among the Northern Wisconsin LTER groundwater lakes with relatively long residence times (median ~9 yrs) (Sorrano *et al.,* 1999). Interestingly, the average WRT of the Ontario Lakes reported by Webster *et al*., (2000) is greater than that of the Northern Wisconsin lakes. Thus low nutrient coherence among lakes with long water residence times is not universal. Webster *et al*. (2000) suggest the low coherence of Wisconsin groundwater lakes is related more to hydrologic setting, than to differences in water residence time among lakes.

TROPHIC STATUS AND COHERENCE

Trophic status as defined by nutrient concentration ranges, notably that of phosphorus, is a common descriptor of lake dynamics, and enables categorization of lakes based on similarities and differences in productivity (Carlson, 1977). Coherence studies reported to date are largely of oligo-mesotrophic systems (Arctic, Colorado, Adirondack, and Ontario lake districts). Only Wisconsin and the English lake districts provide lakes of higher and diverse trophic status. Nonetheless, three patterns are suggested from these limited data. First, coherence of nitrogen species is often greater than that of phosphorus. This occurs among Arctic LTER, all three Ontario lake districts, the English Lake district, and the Northern Wisconsin LTER lakes (Table 1.1).

Second, coherence of phosphorus tends to be greater when lake groupings incorporate lakes of lower and similar trophic status. For example Arctic LTER lakes are ultra-oligotrophic (e.g. SRP 3.8 µg/L; NO3-N 2 µg/L), and coherence of SRP (r=0.7) is high. Similarly, for Ontario lake districts average nutrient concentrations are low for TP (ELA 8.3 µg/L; Dorset 6µg/L; Red Lake 9.5 µg/L), and TN (ELA 350 µg/L; Dorset 237µg/L; Red Lake 329 µg/L), and coherence is moderate for TP (r=0.267-0.467) among lakes of each district (Webster *et al*., 2000). Finally among the combined Wisconsin lakes of higher TP status (47 µg/L) coherence of TP is low (r=0.15) (Kratz *et al*., 1998). In this study lowest coherence occurs among lake pairs including a dystrophic lake.

And finally, simultaneous changes in lake productivity related to land use can serve as a common driver within catchments. For example, among Southern Wisconsin lakes, higher coherence (TN r=0.311; TP r=0.674) is attributed to agriculture and urban landuse common along the drainage path (Sorrano *et al*., 1999). High coherence is driven by strong hydrologic connections among the three lower lakes where internal loads may not vary much year to year (consistently high), but large and similar interannual differences in external loads are common among the lakes (Sorrano, pers. comm.). Similar to the Southern Wisconsin lakes, high coherence of NO3-N (r=0.73) and SRP (r=0.65) occurs among productive English Lake District lakes where changes in fertilizer application and land-use are simultaneous and common among the catchments (George *et al*., 2000). Thus, in disturbed catchments, simultaneous landuse or nutrient load can contribute to higher coherence of both nitrogen and phosphorus.

SUMMARY

In summary, coherence of nutrients is higher among proximate lakes with direct surface water flow paths connecting lakes to catchments, and lake to lake. However, in most cases studied to date, the catchments and drainages with direct flow paths also have short water residence times. From the work to date the dependence of nutrient coherence on water residence time is unclear.

Nitrogen is generally more coherent than phosphorus. However, phosphorus coherence is greater among lakes of low trophic status and high connectivity and short flow paths. In each study to date flow path complexity, water residence time and trophic status may act in concert to produce varying coherence among lakes. Although lake coherence is strongly dependent on external drivers, the importance of individual processes cannot be inferred from the current literature. Thus the limited work to date constrains establishing the fundamental processes governing patterns of nutrient coherence among neighbouring lakes. I suggest further study of nutrient coherence among lakes is warranted.

THE NEED FOR FURTHER STUDY

Further study, to more clearly define factors contributing to coherence of nutrient variables among lakes, should incorporate three important variables: spatial proximity, water residence time, and trophic status.

First, future studies of nutrient coherence should examine spatial scales beyond that of the individual district or drainage. Coherence studies cited above, are largely confined to that of lake pairs within drainages or districts of modest size. For example, the Arctic LTER lakes, Colorado Vale and Green Valley lakes, and Northern Wisconsin and Southern Wisconsin lakes occur within chains or districts of 15km or less. Similarly, for Dorset, ELA and Red Lake study areas of modest size, coherence estimates are constrained to among lakes within districts, rather than among districts.

Although limited regionalization of coherence findings is suggested (Kratz *et al*., 1998; Webster *et al*., 2000), the broader spatial application of these findings is unclear. Climate drivers such as snow accumulation and freshet, acting uniformly over large spatial scales, and beyond that of lake districts (Cayan *et al*., 1999), could contribute to coherence on spatial scales beyond that of the lake district. Similarly, multiple years of drought can act as a driver of lake ecosystems on significant spatial scales (Webster *et al*., 2000). Certainly, examining coherence among districts over large spatial scales has been beneficial to understanding coherence of physical variables such as surface water temperature (Livingstone, 2008). Thus, determining whether common dynamics of chemical variables occur among lakes across spatial scales beyond that of neighbouring lakes, could be beneficial to understanding the spatial extent of chemical coherence and sensitivity to climate variation.

Second, further coherence work should incorporate lakes with diverse water residence times. The limited coherence work to date has focused largely on short residence time systems. Five of the seven lakes districts have residence times less than 1 year; only two districts have residence times greater than 1 year (Arctic and Northern Wisconsin LTER), and these two might well be considered atypical of drainage waterbodies common to lake management districts in North America. In the Arctic case, the range of water residence times is uniformly low (mean 1.7 ± 0.4yrs), and coherence is attributed to consistent material processing along the lake chain flow path (Kling *et al*., 2000). In the Northern Wisconsin case, hydrologic setting and groundwater flow paths produce both longer soil water contact times as well as longer water residence times. Combined these contribute to individuality among lakes and lower coherence values for dissolved reactive ions. Whether groundwater lakes serve as a logical end member in the Sorrano *et al*. (1999) analysis for all reactive variables (both total and dissolved), including those such as TP, which is strongly associated with overland flow and erosion (Sorrano *et al*., 1996), is unclear.

Finally, future studies of coherence should include TN and TP and evaluate the potential role of lake trophic status in governing coherence. Much of the work to date

involves dissolved ions among lower productivity lakes (Arctic, Colorado, Ontario), and lake districts of relatively similar status, thus determining whether contrasts in coherence occur in relation to trophic status among nearby lakes is not possible. However, the Wisconsin lakes illustrate how catchment specific nutrient drivers and dissimilar trophic status can contribute to low coherence among lakes. In this case, coherence was low among dystrophic lakes, and lake pairs including a dystrophic lake (Kratz *et al*., 1998). Differences in trophic status can also arise from internal cycling of nutrients. For example, seasonal anoxia and return of phosphorus from sediments back into the water column is important to productive lake status (Nurnberg, 1984). It is conceivable that among lakes with varying degrees of within-lake cycling of nutrients, coherence would be reduced, over lakes where this intrinsic driver is absent. I suggest examination of additional lakes across the entire trophic gradient may provide useful insights into coherent tendencies of nutrients.

THE BC CONTEXT

Coherence is expected to be more readily detected among lakes where significant year to year variation occurs in a key driving variable (George *et al*., 2000; Magnuson *et al*., 1990). Climate variation across BC is strongly influenced by proximity to the Pacific Ocean. Strong westerly air flow from the Pacific collides and rises up and over coastal mountain ranges dropping rain and snow in an enhanced orographic effect. Hydrographs of coastal streams are dominated by winter rains. Leeward of the coastal mountains precipitation decreases markedly and continental climate enables storage of precipitation as snow with increasing latitude and elevation. Discharge on interior streams is therefore snow melt dominated. In addition to spatial variation in precipitation, interannual climate variation in the Pacific Northwest and BC is linked to Pacific Ocean circulation and climate anomalies associated with the El Nino-Southern Oscillation (ENSO) index (Melack *et al*., 1997). Similar to NAO, ENSO influences run-off during El Nino (dry) and La Nina (wet) phases over a large area of southern Canada from BC, through the prairies and into the Great Lakes region (Shabbar *et al*., 1997).

Southern British Columbia for example, tends to receive more snow during La Nina years and flows in the Columbia River system, are approximately 20% higher in La Nina years than El Nino and neutral years (Mote *et al*., 1999). Thus strong spatial and temporal variation in BC climate could combine to contribute to contrasts in coherence of variables among BC lakes.

In only a few cases has nutrient variation in BC lakes been considered as a function of varying climate (Nordin *et al*., 1985; Jensen and Epp, 2001; Regnier, 1998). Nevertheless, spring nutrient status and trend information is considered essential to development of lake specific management targets or objectives (Cavanagh *et al*., 1985; McKean *et al*., 1987; Nordin, 2005; Rieberger, 2007), guiding nutrient management programs (Allen & LeFloch, 2009; Nordin, 2005), and the enabling state of environment reporting for BC lakes.

Given the importance of nutrients to BC lake management, and the strong climate variation across this landscape, I propose to determine whether coherence occurs among representative hydrometric signals proximate to the study lakes. The degree of coherence among discharge sites could provide insights into the spatial nature and potential for interannual variation to contribute to coherent dynamics of nearby lakes. Subsequently, I propose to examine data from representative BC lakes for temporal coherence of nutrient variables. However, because, regional lake monitoring programs in BC do not stem from a unified network, I question whether aspects of sampling program variation over time, within and among regions, could impose significant data integration challenges and introduce data artefacts which could obscure coherence. Therefore, I propose to initially assemble nutrient data from a subset of representative lakes to examine whether data gaps, time series length, variations in the methods and timing of sampling, could individually or in combination compromise estimates of coherence of nitrogen and phosphorus. On the basis of those findings, I propose to assemble data from lakes across BC and assess nutrient coherence among lakes grouped at various spatial scales. To guide this work I propose a number of hypotheses.

HYPOTHESES

Rather than explore the coherent tendencies among lakes at the lake district scale, where some commonality in geomorphic and hydrometric factors is expected, I initially ask whether coherence occurs among lakes at a larger spatial scale. Thus, my first expectation is that both nitrogen and phosphorus nutrients would demonstrate low but positive synchronous interannual variation among BC lakes. This expectation is premised on the presence of strong climate drivers acting across the BC landscape, as well as limited observations elsewhere that nutrient coherence is generally positive but low.

Thus, my hypothesis is that both nitrogen and phosphorus nutrients will demonstrate low but positive synchronous interannual variation among BC lakes. Related to this is my expectation that a spatially structured response may also occur as a result of hydrologic differences between coastal and interior run-off regimes, or individual drainage groups, similar to that of a lake district. Thus, I will test whether coherence is dependent on distances among lakes grouped at provincial, coastal, interior, and drainage scales.

My second hypothesis is that parameter coherence among lakes will decrease with increasing water retention times (WRT). This follows on the work to date which suggests that longer and variable WRT's within a lake district, increase lake-specific material processing of nutrient inputs, and contribute to lower coherence among lakes.

Finally, I propose to explore whether the strength of the coherence might be related to lake fertility as estimated by long term average nutrient concentrations. Therefore, my hypothesis is that coherence of nutrients among lakes will be dependent on lake status as described by nutrient concentration.

SIGNIFICANCE

Lakes are important to ecology and economies at local and provincial scales in BC (Nordin, 2005) and considerable investment occurs to protect surface water quality and

monitor its status and trends through time (Allen & LeFloch, 2009). Predicting and recognizing trends and patterns in lake ecosystems is fundamental to water resource management. Because climate variation and change are expected to increasingly stress freshwater ecosystems (Schindler, 2009), and because water protection initiatives are costly, coherence could provide a broader understanding of lake quality variation and ensure protection measures are adequate and appropriate. For example, understanding when lake nutrient variation was largely attributable to climate variation would ensure protection measures were not applied prematurely. Conversely, reduced coherence or changes in coherence of a lake relative to some norm, would suggest lake specific behaviour linked to local drivers such as changing landuse and anthropogenic nutrient load change, or intrinsic processes such as internal loading.

Resource allocation to lake monitoring, and the design of lake monitoring programs are common challenges among lake management and research agencies (Schindler, 2001). Therefore, I suggest that identifying lakes which respond similarly to climate or other external drivers, will enable enhanced monitoring of climate variability, selection of appropriate indicator or reference ecosystems within synoptic surveys or networks, and aid lake managers to recognize lakes which deviate from the regional norm.

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CHAPTER 2

ESTABLISHING DATA SELECTION CRITERIA FOR TEMPORAL
COHERENCE ANALYSIS OF NUTRIENTS IN BC LAKES

INTRODUCTION

Recent analysis of long time series data for lakes, attribute temporal coherence, or
shared interannual variation of nutrients among lakes, to climate forces, or landuse
changes affecting neighbouring lakes similarly over time (Baron *& Caine*, 2000; Kling
et al., 2000; Kratz *et al.* 1998; Magnuson *et al.,* 1990; Sorrano *et al.,* 1999; Webster *et
al.,* 2000). Temporal coherence, estimated as the average correlation among all possible
lake pairs for a variable of interest, provides a means of understanding which variables
and drivers lead to coherent dynamics among lakes over various spatial scales
(Magnuson *et al.,* 2004).

To date, no studies of lake temporal coherence are reported west of the Rocky
Mountains. Given the importance of British Columbia (BC) freshwaters to the
economy and environment, it is useful to ask whether various long term water quality
data sets for BC lakes are suitable for analysis of temporal coherence. The majority of
BC lakes have been studied to address concerns related to eutrophication, sewage or
septic seepage inputs, influence of changing landuse patterns, or other non-point source
nutrient or contaminant loading concerns (e.g. Boyd *et al.,* 1985; Cavanagh *et al.,* 1994;
French & Booth, 2004; Holmes, 1996a,b,c,d; Jensen & Epp, 2001; McKean *et al*.,
1987; Nordin, 2005; Rieberger, 2007; Zirnhelt *et al.,* 1997). In all cases, nitrogen and
phosphorus provide important water quality status and trend indicators linked to
nutrient management efforts. Therefore, determining whether nutrient variation in BC
lakes exhibits temporal coherence has practical significance.

PURPOSE

To facilitate selecting lakes, sites, and variables, for temporal coherence analysis among BC lakes, I initially questioned how variation in laboratory detection limits, and changes in sampling frequencies and protocols used by the regional offices over this multi-decadal time span, might affect coherence estimates. For example, minimum detectable concentration (mdc) limits for total phosphorus and nitrate decreased over the data collection period, and non-detectable concentration records were evident in the time series. Data points below the detection limit present significant challenges to data analysis (Helsel, 2005). Therefore, I explored how left censored data records might affect coherence estimates.

Although temporal coherence studies elsewhere use seasonal or annual means of either discrete or composite epilimnetic samples (Kratz *et al.*, 1998; Sorrano *et al.,* 1999) or volume weighted averages (Magnuson *et al.,* 1990), seasonal data collection is uncommon for BC lakes, particularly for consecutive years. Spring data collection, when primary production is low and thermal stratification is absent or minimal, has been a common strategy among monitoring networks in BC over the period of 1977 to 2007. However, because for many BC lakes spring sampling dates can vary by weeks from one year to the next, and increasing solar radiation through the spring period could affect nutrient uptake and scavenging from surface waters (Barica, 1990), I questioned whether variation in spring sampling date could compromise coherence estimates. As well, given that coherence of a broad range of limnological variables is shown to be higher in decadal scale time series (Kratz *et al.,* 1998; Magnuson *et al.,* 1990; Webster *et al.,* 2000), I questioned whether the short (i.e. < 10yrs) or fragmented time series for many BC lakes could confound coherence analysis. Other factors such as lake morphometry could also be important to temporal coherence (Magnuson *et al.* 1990), thus I questioned whether spatial integration of data using concentrations averaged over multiple depths or multiple sites within a lake, could potentially improve estimation of spring nutrient concentrations and temporal coherence.

To evaluate these issues, I employed a sequential and iterative process, beginning with the data censor issue, and then progressing from smaller to larger temporal and spatial scales. I first evaluated the change in temporal coherence due to increasing proportions of non-detect values using both a hypothetical dataset, and a BC dataset. Next, I examined the seasonal effect of sampling date variation, and subsequently I examined the effect of time series length and fragmentation at the inter-annual level. Similarly for spatial considerations, I first examined the influence of sampling depth on temporal coherence, and then subsequently examined whether temporal coherence was improved by using data from multiple sites on a lake, versus using data from a single site. In each case I evaluated data sets which were expected to provide optimal coherence. From this work I established data selection criteria to optimize subsequent temporal coherence analysis of spring nutrients among BC lakes.

METHODS

Nutrient data

For temporal coherence analysis, I used total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen (TN), and nitrate nitrogen (NO3-N), as these are important and commonly reported nutrient variables in BC lake monitoring programs. Nutrients for all lakes were analyzed using standard analytical methods at a common series of laboratories (BC Environmental Laboratory 1977 to 1989; Zenon Laboratories 1989 to 1997; Environment Canada Pacific Environmental Science Centre 1997-2002; and Maxxam Analytical 2002-present). As such, at the provincial scale, the data are of high and comparable quality. Of note is that in 1997 and subsequent years, laboratory minimum detectable concentrations (mdc) decreased for TP, from 3 µg/L to 2µg/L, and for NO3-N from 20 µg/L to 2 µg/L. For some lakes, total Kjeldhal nitrogen (TKN) is reported in the provincial database rather than TN. Where necessary, I report TN as the sum of TKN and NO3-N values, otherwise all values were reported as TKN for the lake. The majority of the data reported in this work is archived in the provincial Environment Management System (EMS) or in files at the Ministry of Environment regional offices.

Data analysis

I assembled the data for each variable into a year by lake matrix. The influence of outliers and distributions were inspected using scatterplot matrices. Normal distributions were expected given the nature of the comparisons, and for all possible lake pairs, Spearman rank correlations were similar to Pearson product-moment correlations (e.g. for TP, Spearmans = 0.0417 + 0.884 Pearson, (Prob >F, <0.001; r^2=0.81). Therefore, to be consistent with the majority of previous studies, I report temporal coherence using the Pearson product-moment correlation (*r*) (Kratz *et al.*, 1998; Magnuson *et al.*, 2004; Webster *et al.*, 2000). I use an average of correlations among multiple lake pairs to estimate temporal coherence at the spatial scale of interest, either provincial, regional, or by drainage.

RESULTS

Influence of detection limit

I tested two hypothetical data series of 20 paired values to determine how three different treatments of non-detectable (i.e. < mdc) data values might affect coherence estimates. The treatments were: retention of the mdc value, substitution of half the mdc, and pair-wise deletion of records below the mdc. Values of one series were selected to initially provide high (*r*=0.84), medium (*r*=0.58) and low (*r*=0.24) correlation. Values of the second series were uniformly and progressively decreased so the proportion below the mdc increased from 0% to 50%. Substitution of either the mdc or half the mdc, gave very similar correlations, with no change in coherence up to 50% affect levels (Figure 2.1; Appendix 1a).
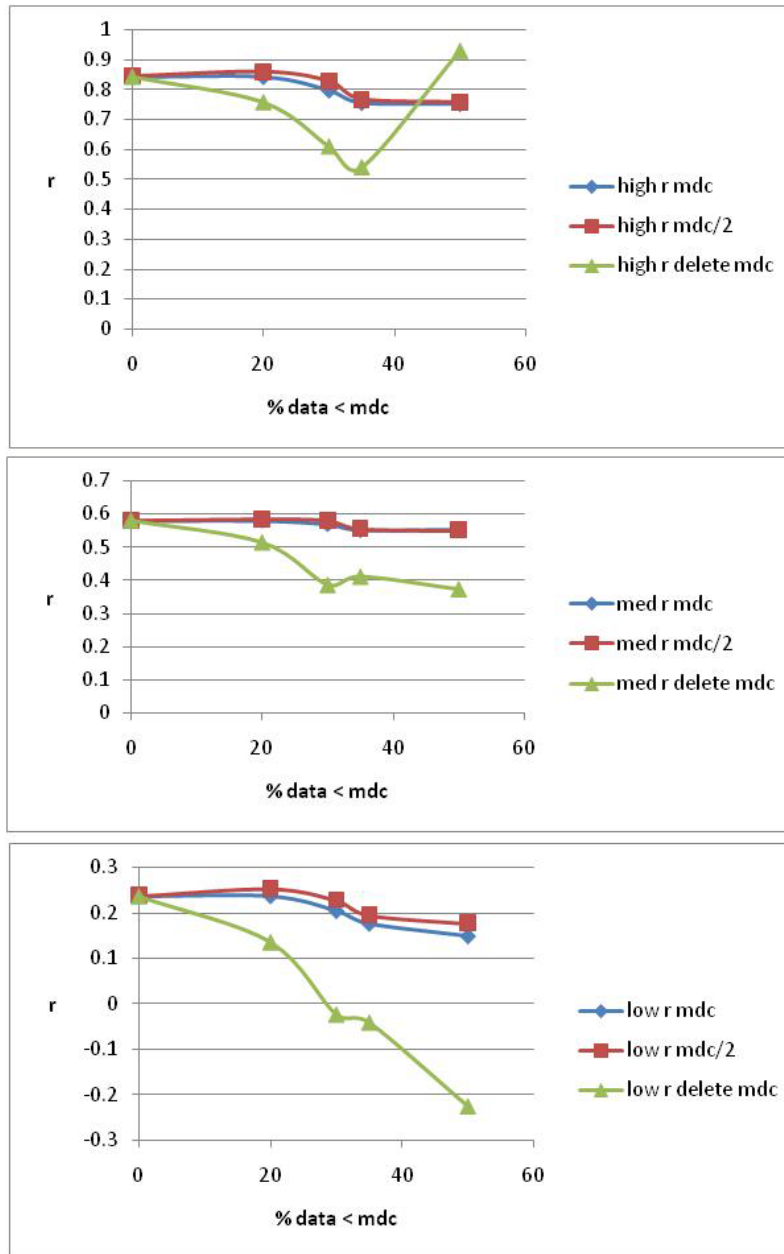
Figure 2.1 Variation in coherence of three hypothetical data sets (high coherence r=0.84; medium coherence r=0.58; low coherence r=0.24) following substitution of non-detect values with the minimum detectable concentration (mdc), substitution of half the mdc, or pairwise deletion.

Coherence estimates based on pair-wise deletion of non-detect values were significantly different between 20% and 30% affect level groups. Thus, for these hypothetical data, as the proportion of non-detect data increased beyond 20%,

coherence estimates based on pair-wise deletion were significantly different than those retaining the mdc or substituting half the mdc.

I examined this further using TDP data for Christina and Sugar lakes for which 22% and 32% of the records respectively, are below the mdc. In this case coherence using pair-wise deletion (r=0.327) was equivalent to retention of the mdc (r=0.337) whereas using half the mdc provides a similar but greater coherence (r=0.404) (Appendix 1b). On the basis of this, I concluded that retention of mdc values, or pair-wise deletion of the mdc value may make little difference to coherence estimates when non-detectable values make up to less than 20% of the data. However, as the proportion of non-detect data increased beyond 20%, pair-wise deletion could significantly decrease coherence estimates. Over estimation of coherence by substitution with the mdc however cannot be ruled out, as it may produce internally consistent sets of results. Nevertheless, as records below the mdc have informational value, I conclude that retention of the mdc value for the non-detect records is a reasonable compromise to a difficult data management issue. However, I recommend against inclusion of datasets where non-detect records exceed 20%.

Influence of sample date

I tested the effect of variation in spring sampling date on coherence using data from Skaha and Kalamalka lakes over the period 1985 to 2007. Over this period, these lakes have a high number of multiple spring sampling dates, and for individual years, significant relationships were evident between spring date and nutrient concentration for TDP in Kalamalka Lake and NO3-N in both lakes (Table 2.1). The difference in sampling date between lakes was also high, ranging from 1-29 days and averaged 12 days. Thus, the large range in spring sampling dates, and the observed seasonal variation in these nutrient forms, could confound coherence estimates.

Table 2.1 Relationship between spring sampling date and nutrient concentration in Skaha Lake in 1985, and Kalamalka Lake in 1988.

		r^2	p > F			r^2	p > F
Skaha*	TP	0.227	0.118	Kalamalka **	TP	0.071	0.358
	TDP	0.308	0.061		TDP	0.34	0.029
	NO3	0.861	<0.0001		NO3	0.726	0.015
	TN	0.247	0.101		TN	0.535	0.062

* 1985, five dates March 26- April 24   ** 1988, four dates January 21 and April 27

Coefficients of determination for first spring sampling date nutrient concentrations between Skaha and Kalamalka lakes ranged from r^2=0.258 for TP to r^2=0.111 for TDP (Table 2.2). Residuals were then regressed against the difference in annual sampling dates between the two lakes. I found that the difference in sampling date between these two lakes, over 21 years, had no significant additional explanatory power at the p=0.05 level (Table 2.2).

Table 2.2 Stepwise multiple regression for total phosphorus, total dissolved phosphorus, total nitrogen and nitrate nitrogen concentrations in Skaha and Kalamalka lakes.

Variable	Regression	r2	p >F
TP	Skaha x Kalamalka[1]	0.258	0.019
	residuals x days [2]	0.156	0.076
TDP	Skaha x Kalamalka	0.111	0.14
	residuals x days	0.005	0.759
TN	Skaha x Kalamalka	0.184	0.052
	residuals x days	0.046	0.348
NO3	Skaha x Kalamalka	0.183	0.053
	residuals x days	0.03	0.454

1 regression of spring nutrient concentration between lakes
2 regression of residuals from 1st regression against sampling date difference between lakes

I conclude, variation in sampling date between lakes within the period of February 1 and May 1, may not significantly confound temporal coherence estimates.

Influence of time series length

I examined the influence of time series length on coherence using data for Mabel and Mara lakes in the Shuswap drainage. Direct flow paths between short water residence time lakes in drainages with low spatial variation geomorphology are considered to be important determinants of coherence (Kling *et al*., 2000; Kratz, *et al.* 1998). Thus, higher coherence might be expected between Mabel and Mara lakes, given they are hydrologically connected and proximate, have similar landuse, and are exposed to the same climate. Data for all consecutive sets of years from 3 to 29 (e.g. 29 values for 3-year sets; 1 value for final 29 year set) were used to calculate correlations for each nutrient variable. For this lake pair, both total and total dissolved phosphorus coherence increased as the length of record increased from 3 years (TP: r=0.48; TDP: r=0.32) to 11 years (TP r=0.78; TDP r=0.76) then stabilized with little increase in correlation to 29 years (mean coherence: TP r=0.73; TDP r=0.66) (Figure 2.2). Much more consistent, but reduced temporal coherence, was apparent for nitrogen species (TN: r=0.4; NO3-N r=0.23), with little variation over the 29 year period. Thus, my initial concern that lower estimates of coherence might arise from concurrent data sets of less than a decade was supported, particularly for phosphorus variables. I conclude a minimum time series length of 10 years will optimize coherence estimates. However, time series longer than a decade may not necessarily yield appreciably greater coherence values.
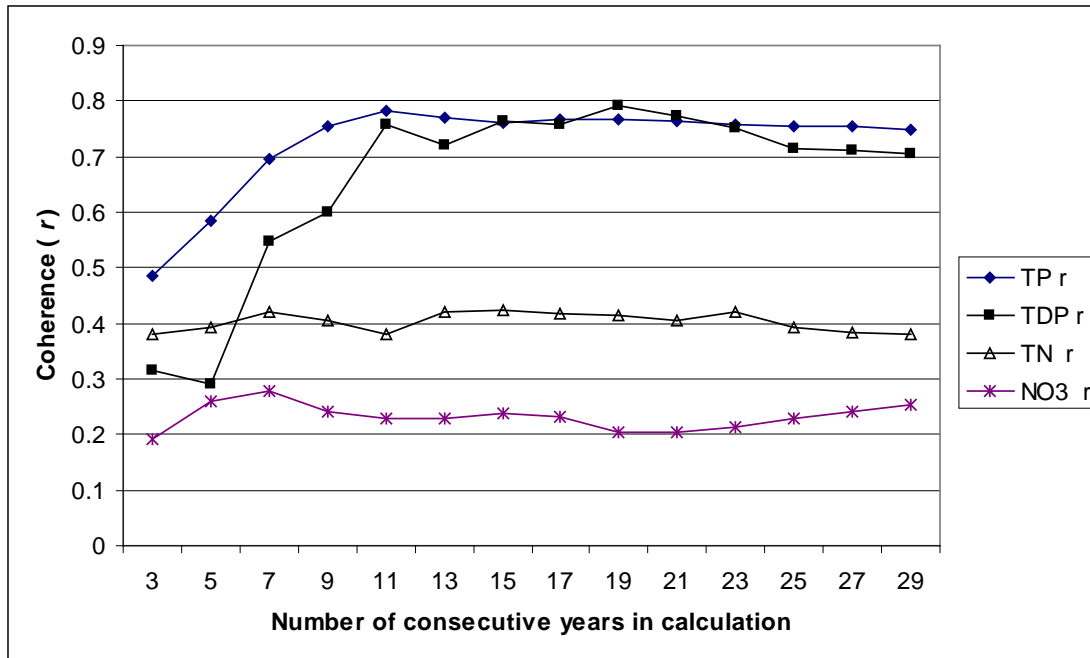
Figure 2.2 Sensitivity of temporal coherence estimates (r) to the number of years of record for nitrogen and phosphorus in Mabel and Mara lakes. All consecutive sets of years from 3 to 29 were used (e.g.: 29 values for 3-year sets; 1 value for final 29 year group).

Influence of time series fragmentation

Given the relationship between TP coherence and time series length, I further examined the Mabel and Mara data to determine the influence of discontinuity or fragmentation in the time series, on estimates of temporal coherence. Correlations remained high after removal of every 5th (r=0.790), 3rd (r=0.782) and 2nd (r=0.887) value in the time series. Random exclusion of years to achieve a sample size of 10, provided an estimate of coherence slightly lower (mean r=0.696, n=10), but similar to the entire data series (mean r=0.76, n=29). Random sub-sets of 7 years of TP data however, provided lower estimates of coherence (mean r=0.33, n=10) and were significantly different than groups of 10 (p<0.0001). Thus, I conclude time series of 10 years or more, whether contiguous or fragmented, should yield optimal estimates of temporal coherence of

phosphorus, whereas inclusion of lake pairs for which there are less than 10 years in common, contiguous or otherwise, is likely to yield lower estimates of coherence.

Influence of sampling depth

I tested whether temporal coherence estimates for total forms of nutrients at a central site on the first sampling date, were improved by inclusion of all water column nutrient analyses, as compared to estimates based on only a single surface value. Because southern interior lakes are sampled using surface (1-10m) and deep ($\geq$20m) composites, and coastal, central, and northern interior lakes have often been sampled with discrete depths, I evaluated the effect of sampling depth for both sampling method groups. I selected Shawnigan, St Mary, Prospect, and Lac La Hache lakes with discrete depth collection, and Skaha, Kalamalka, Mabel and Mara lakes with composite sample collection due to similar maximum time series length, and the range of trophic states these lakes provided. The average correlation or coherence among all possible lake pairs within the discrete depth group was marginally greater for composite depth data (TP r=0.292; TN r=0.157) than surface only (TP r=0.242; TN r=0.148). For the southern interior lakes however, combining surface and deep water composites provided higher correlations for TP (TP r=0.546 ; TN r=0.003) than using only the surface composite (TP r=0.387; TN r=-0.069), but little difference for TN. Given the consistently greater coherence obtained by depth composite data, particularly for TP, I conclude that temporal coherence estimates are improved through spatial averaging of all data for the water column.

Influence of numbers of sites

I questioned whether aggregation of data from multiple sites on a lake, would significantly improve temporal coherence estimates among pairs of lakes. Although many BC lakes had multiple sites with varying data records, in most cases one site for a lake has the longest record of collection. For smaller lakes of simple morphology, correlations in concurrent time series between sites were expected to be high. For example temporal coherence of TP and TN for proximate sites on lakes of simple basin

morphology, such as Wood Lake are high (TP r=0.929; TN r=0.860). However, for morphologically complex lakes, estimates of annual nutrient concentration may vary among sites due to spatial variation in nutrient inputs and incomplete mixing. I explored this concern using data for Okanagan Lake, a long narrow lake with previously noted spatial variation in spring TP (Nordin, 2005). In this case, average coherence of TP among the three basins of the lake is only moderate (r=0.548). Okanagan Lake spring TP data averaged across the three sites, provided only slightly greater estimates of average temporal coherence (r=0.487) with other oligotrophic lakes nearby (Christina, Mabel, Mara, Sugar lakes), than using data from just one central site on Okanagan Lake (r=0.467). However, correlations using an Okanagan Lake average value, were always significant (p < 0.05) with the other oligotrophic lakes, whereas individual Okanagan Lake site correlations were not significant in 54% of the comparisons. Similarly, for TN, temporal coherence estimates based on multiple sites (r=0.132) were similar to individual correlations with other southern interior oligotrophic lakes (r=0.138), however, few correlations in either case were significant. Thus, at least for TP, lake pair correlations based on an average Okanagan Lake spring concentration yielded greater coherence estimates. Amongst other lake pairs however, I conclude the slight improvement in temporal coherence estimates afforded by using data from all sites for a lake, are unlikely to justify the significant data collation effort.

CONCLUSIONS

Variation in analytical and sampling regimes over time, within and among sampling programs, are important concerns when broader spatial and temporal interests require pooling or merging of data sets. Based on my analysis of both hypothetical and representative nutrient data from BC lakes, I conclude that temporal coherence estimates for BC lakes may be optimized by implementing the following data selection criteria:

1. Restrict temporal coherence analysis to data series with fewer than 20% non-detect values in the data series. For data series with non-detect data records of 20% or less, I advocate retention of the mdc value, given that the temporal

coherence estimates based on substitution of half the mdc or pair-wise deletion are not significantly different.

2. To reduce the potential for variation in sampling date to influence temporal coherences estimates among BC lakes, restrict temporal coherence analysis to data collected on the first sampling date, between February 1 and May 1.

3. As continuous or fragmented time series of less than ten years are shown here to yield lower estimates of coherence particularly for phosphorus, restrict the analysis to those lake pairs with at least 10 years of concurrent data,

4. Use an average of all water column data to estimate the spring nutrient concentration. Temporal coherence estimates for phosphorus are incrementally greater among low nutrient lakes when all water column data are employed in the analysis as opposed to a single surface sample.

5. Use spring nutrient data from one central site. Spring nutrient estimates based on data from a number of sites are unlikely to provide higher estimates of temporal coherence unless significant spatial variability is apparent for the lake.

In summary the analyses employed here to screen and clean the data have been used to provide defensible and optimal estimates of temporal coherence of nutrients among BC lakes, and may serve as a guide for similar studies elsewhere. Further assessment of nutrient coherence at the provincial scale is clearly warranted. The greater temporal coherence of phosphorus relative to nitrogen in these exploratory analyses suggests a contrast in coherence may occur between phosphorus and nitrogen. Thus climate may more directly affect phosphorus variation in BC lakes, than nitrogen. Further analysis is warranted to determine the strength and spatial extent of this relationship, and from this, better inform lake nutrient status and trend interpretations by BC lake managers. These findings also suggest that lake phosphorus trend interpretation, using less than 10 years of data, may be compromised by variation related to climate. Thus 10 years may serve as a minimum lake data collection target for nutrients or other water quality measures, where the influence of climate variation is of interest.

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CHAPTER 3

TEMPORAL COHERENCE OF TOTAL NITROGEN AND TOTAL PHOSPHORUS AMONG BC LAKES

INTRODUCTION

Limnologists have recently been interested in understanding the degree to which variables demonstrate temporal coherence or vary synchronously through time in neighbouring lakes (Magnuson *et al.,* 2006). Climate is an important driver of lake dynamics (Carpenter *et al.,* 1992; Schindler, 2001) and is expected to be a primary contributor to synchronous variation or temporal coherence among lakes at various spatial scales (Kratz *et al.,* 1998; Magnuson *et al.,* 1990; Sorrano *et al.,* 1999; Webster *et al.,* 2000). Because neighbouring lakes are exposed to the same climate, the extent to which temporal coherence occurs provides useful in-sights into the sensitivity of parameters and lakes, to climate variation (Magnuson *et al.,* 1990) and furthers our understanding of the long term dynamics of important variables at the regional level (Webster *et al*., 2000; Zhang *et al*. 2010). Importantly, the predictability of variables to climate forcing governs extrapolation or regionalization of results and development of new conceptual models to explain lake dynamics (Livingstone, 2008; Magnuson *et al.,* 2004).

Indeed, for some physical properties such as surface water temperature, ice off dates, and lake level, which are directly and mechanistically linked to climate variation, coherence is high among lakes over significant spatial scales (Benson *et al.,* 2000; Magnuson *et al.,* 2004). However, as variation in a lake property is increasingly the product of interaction between local climate and intrinsic aspects of catchment and lake interaction, the climate signal is altered (attenuated, delayed, extended) and coherence among lakes diminishes (Magnuson *et al.,* 2006). Predicting nutrient variation and concentrations in lakes continues to be central to limnology and lake management (Reckhow and Chapra, 1983; Schindler *et al.,* 1996). Although nutrient concentrations

are the product of complex interactions between external drivers such as hydrology, and catchment and lake specific attributes (soils and land use, aquatic food webs), coherent interannual variation in reactive ions and nutrients have been reported among North American (Magnuson *et al.,* 1990; Kling *et al.,* 2000; Kratz *et al.,* 1998; Webster *et al.,* 2000) and European lakes (Anneville *et al*., 2005; Bleckner *et al*., 2007; George *et al*. 2000).

Among neighbouring lakes, in uniform hydrologic and climatic settings, coherence of reactive ions and nutrients is found to be positive. Proximity or high connectivity, and short water residence times promote coherence of reactive variables among lakes with streams linking catchment to lake, and lake to lake (Magnuson *et al*., 2006). Conversely, long catchment flow paths and long lake water residence times may lead to increasing contrasts among lakes within a drainage, and thus lower overall coherence of reactive variables (Sorrano *et al.,* 1999). Other factors such as simultaneous changes in nutrient loading (George *et al*., 2000) or landuse (Kratz *et al*., 1998) also contribute to coherence of nutrients among lakes. In the few landscapes studied to date, some, or all of these factors may simultaneously influence nutrient coherence among lakes (Kling *et al*., 2000; Kratz *et al*., 1998). While assessments of coherence among neighbouring lakes within catchments of relatively homogeneous geomorphology (i.e. a lake district), provides insights into spatial and temporal patterns of conservative ions, neither concentration (Quinlan *et al*., 2003) nor coherence of TN or TP are clearly associated with lake order or location along hydrologic flow paths within the landscape (Sorrano *et al*., 1999; Webster *et al*., 2000). Thus, establishing fundamental patterns, and clarifying the importance of flow path, water residence time or trophic state, to TN and TP coherence among lakes, requires further study. No coherence studies have focused on nutrients and fewer still have incorporated total nitrogen (TN) and total phosphorus (TP) data. Thus, the spatial extent of TN and TP coherence, as well as the explanatory power of lake pair proximity and catchment flow path, lake water residence time (WRT), or lake trophic state, to these important lake status indicators, is unclear. Examination of large scale regional data sets to assess the response of lakes to climate variation is a worthy challenge (Quinlan *et al*., 2003).

Temporal coherence has not been reported for lakes in the Pacific Northwest. Here, I assembled hydrometric, and spring nutrient data provided by BC regional lake monitoring programs over multi-decadal time scales. I expect there is a continuum of coherence across various spatial scales. Therefore, I considered the following questions: (1) Over what spatial scale are interannual patterns in catchment discharge hydrographs coherent and potentially acting as synchronous drivers of lake dynamics? (2) Do lake nutrient concentrations vary with regional hydrology, thus linking this climate driver to nutrient variation? (3) Is coherence of TN or TP observable among British Columbia (BC) lakes, and if so over what spatial scales? For example does coherence decrease with distance between lake pairs within and among drainages? (4) Does lake water residence time (WRT) influence coherence of either total nitrogen or total phosphorus? Based on the findings of previous work, I expected positive coherence for both TN and TP among lakes grouped at provincial and smaller spatial scales. However, differences in hydrologic regimes and timing of run-off between coastal lakes and interior lakes, could contribute to a spatially structured response. Given the importance of WRT to lake dynamics, I expected nutrient coherence should diminish among lakes with longer water residence times. However, as lake trophic status increases, the influence of climate variation on lake dynamics should be increasingly obscured by variation in nutrient loading and processing intrinsic to either catchment or lake. Therefore, (5) I also questioned whether nutrient coherence might demonstrate some dependence on trophic state. To the extent that temporal coherence occurs among BC lakes, this work should contribute to a broader understanding of the sensitivity of various forms of nutrients, and lakes in general, to climate variation and improve our ability to predict lake dynamics in the future.

METHODS

Lake selection

Lake selection was governed by data availability. Twenty-six lakes, with at least 10 years of nutrient data collection between 1977 and 2007, were chosen to reflect a broad range of lake and climatic conditions in both coastal and interior areas of BC (Table

3.1). These lakes express considerable morphologic and trophic diversity but are all drainage lakes within catchments of varying degrees of anthropogenic disturbance. Across this scale, precipitation and run-off vary considerably with latitude and proximity to the Pacific Ocean. I grouped lakes based on run-off regimes, as either Coastal with winter rain dominated hydrographs, or Interior with snow-melt dominated hydrographs. I used lake pair proximity to estimate spatial aspects of flow path. Proximate lakes are more likely to be within common surface water flow paths, and exposed to similar variation in hydrology, than would be the case for distant lake pairs. To further understand the importance of flow path and lake pair proximity to coherence, I also examined coherence among lakes grouped by major drainage membership (Columbia, Shuswap, Fraser, Skeena, Peace).

Nine of the lakes are from the Coastal zone of southern BC. Lizard, Shawnigan, Prospect, Quamichan, Glen, Fork and Stocking lakes occur on southern Vancouver Island, and St. Mary and Maxwell lakes are nearby on Saltspring Island. These relatively small and shallow lakes have relatively short water residence times (range 0.1-14 yr; av. 3yrs) and although these lakes are located within a 35 km radius of each other, none are interconnected by surface flows. Coastal lakes experience a mild maritime climate with limited incidence and duration of ice cover. Stream hydrographs, are dominated by winter precipitation, and little if any precipitation is stored as snow. An orographic effect of the Vancouver Island Range and Olympic Mountains produces a strong precipitation gradient across the Coastal area, with annual precipitation ranging from a high of 3612 mm at Lizard Lake on the west coast near Port Renfrew, to lows of 977 mm on Saltspring Island.

Fifteen lakes represent the Interior zone. Ellison, Wood, Kalamalka, Okanagan, Skaha, and Osoyoos, occur 300 km east of the coast, and form the Okanagan chain of lakes. Combined with Christina Lake 100 km to the east, these 7 lakes drain to the Columbia River. Sugar, Mabel and Mara lakes, 50 km northeast of the Okanagan basin are interconnected along the Shuswap drainage. Chimney, Horse, Lac La Hache and Williams lakes in the Cariboo area and Tabor Lake, farther north, occur some 400-

600km north of the Coastal zone, and flow to the Fraser River. Kathlyn Lake is located in the Skeena drainage and Charlie Lake, is located east of the continental divide in the Peace River drainage approximately 880km from the Coastal lakes. Annual precipitation ranges from 318 mm at Osoyoos in the south, to 600 mm at Prince George in central BC. In all cases a significant portion of the winter precipitation is stored at higher elevations as snow, and interior stream hydrographs are dominated by spring snow melt and freshet in late May and June. The majority of the interior lakes are considerably larger than the coastal lakes, and on average have longer water residence times (0.13-60 yrs; av. 20 yrs) (Table 3.1). Aspects of water quality status and trends for some but not all lakes have been previously reported (Boerger, 2001; Boyd *et al.* 1985; Cavanagh, *et al.* 1994; French & Petticrew, 2007; French & Carmichael, 1999; Bryan & Jensen, 1999; Jensen & Bryan, 2001; Jensen & Epp, 2001; Holmes, 1996a,b; McKean *et al.*, 1987; Nordin, 2005; Pommen, 1996; Rieberger, 2003; Zirnhelt *et al.* 1997).

Table 3.1 Lake metrics, and average nutrient values (µg/L) between 1977 and 2007. Number of years varies by lake and parameter from a minimum of 10 to a maximum of 31, and averages 23 years for total phosphorus (TP), and 19 for total nitrogen (TN).

Area	Drainage	Lake	TP	TDP	TN	NO3-N	WRT	SA	V	Zm	Zx	Latitude	Longitude
Interior	Columbia	Ellison	35	13	407	12	1.2	2.1	5	2.5	5	49.99074	119.40172
		Wood	47	35	433	92	22	9.3	200	22	34	50.0794	119.38997
		Kalamalka	10	5	287	132	51	25.9	1520	59	142	50.16681	119.34785
		Okanagan	9	5	200	73	53	351	24640	76	230	49.87724	119.51258
		Skaha	13	6	256	11	1.2	20.1	560	26	57	49.4116	19.58474
		Osoyoos	21	9	315	63	0.7	23	400	14	63	49.05694	119.48074
		Christina	7	6	104	2	4.5	25.1	930	37	54	49.05367	118.22703
	Shuswap	Sugar	6	4	181	103	0.6	20.8	730	35	83	50.39979	118.52247
		Mabel	6	4	145	89	2.8	59.9	7180	120	200	50.54064	118.73679
		Mara	11	6	189	104	0.13	19.4	357	18	46	50.78966	119.00611
	Fraser	Williams	65	42	717	114	0.62	7.2	88.2	12	24	52.11858	122.07287
		Lac le Hache	13	7	451	11	10	23	336	14.6	ND	51.83853	121.58548
		Horse	19	12	350	3	3.5	11.6	175	15.2	34	51.58925	121.11721
		Chimney	19	10	819	9	16.8	4.3	37.5	9.5	20.9	51.91556	121.96111
		Tabor	25	13	406	34	0.7	4.1	220	5.4	9.2	53.91701	122.54293
	Skeena	Kathlyn	23	13	314	52	1.2	**1.7**	8	4.6	9.5	54.82372	127.20611
	Peace	Charlie	43	26	630	107	5	19	127	7	15	56.31991	120.9757
Coastal		Shawnigan	7	4	230	105	1.2	5.4	64	12	52	48.63725	123.64064
		St Mary	23	9	423	65	14	1.82	15.9	8.8	16.7	48.8899	123.5427
		Prospect	14	9	366	74	0.8	0.7	4.1	6.9	13.5	48.51341	123.44248
		Stocking	6	4	136	9	1	0.23	2.1	9	19	48.96008	123.82704
		Fork	10	6	227	52	0.1	0.002	0.092	2.3	10	48.51941	123.48492
		Quamichan	19	10	403	33	1.3	0.313	13.7	4.7	8.2	48.79908	123.66489
		Glen	21	11	292	403	0.4	0.17	1.2	6.4	14	48.43752	123.52244
		Maxwell	10	5	249	20	7	0.3	2.3	7.7	19.2	48.82221	123.54146
		Lizard	6	3	81	ND	0.75	0.009	0.66	7.5	15.5	48.6062	124.22345

TP=total phosphorus (µg/L); TDP=total dissolved phosphorus (µg/L);TN=total nitrogen (µg/L); NO3-N=nitrate nitrogen as nitrogen (µg/L)
WRT= water residence time (yrs); SA=lake surface area (km2); V=lake volume in Mm3; Zm=mean depth (m); Zx=max depth (m); ND=no data

Water quality database

I focused my analyses on spring estimates for total nitrogen and total phosphorus. For these lakes, over the period of study, no records for TN were below the minimum detectable concentration (mdc). For the few TP records below the detection limits, I retained the mdc as the spring estimate. Spring is defined here as the first spring sampling date of the calendar year occurring between February 1 and May 1. During this period, thermal stratification is absent or minimal, and precedes spring freshet for interior lakes, and follows the winter storm period on the coast. Variation in sampling date among lakes, within this period has little or no affect on coherence estimates (see Chapter 2). As time series with 10 years of data, either contiguous or fragmented, are known to optimize coherence (see Chapter 2), I included only lake pairs with at least 10

years of concurrent data in coherence estimates. As well, because depth integrated averages can provide higher coherence estimates than surface samples (see Chapter 2), I used a depth integrated average concentration from a single main site on each lake, typically a central deep site, to represent spring nutrient conditions and accommodate variation in sampling protocols. All nutrient samples were analyzed using accepted standard analytical methods at a common series of laboratories.

Stream hydrograph data

To estimate hydrographic variation I used average annual discharge records for 12 drainages proximate to the lakes of interest, as regional climate proxies of discharge. My intention here was to develop a general understanding of the spatial nature of any synchronous interannual hydrologic variation within and among lake districts. To aid this spatial analysis, discharge records for 2 drainages of contrasting size, within each drainage area were obtained from Water Survey of Canada records for the period 1976 to 2005 (Table 3.2). Distances between hydrometric sites within and among lake drainage areas ranged from 15 to 100km and 141 to 861km respectively.

Table 3.2 Area, location and Water Survey Canada reference number for large and small drainages proximate to study lake areas.

Area	Drainage name	Area (km2)	Latitude	Longitude	WSC No.
Skeena	Goathorn Creek near Telkwa	126	54 38' 50"	127 07' 20"	08EE008
	Bulkley River at Quick	7350	54 37' 05"	126 53' 55"	08EE004
Fraser	San Jose River above Borland	1990	52 04' 37"	121 59' 27"	08MC040
	Chilcotin River below Big Creek	19300	51 50' 52"	122 39' 11"	08MB005
Shuswap	Criss Creek near Savona	490	50 53' 04"	120 57' 54"	08LF007
	South Thompson R at Chase	16200	50 45' 54"	119 44' 25"	08LE031
Columbia	Mission Creek near E Kelowna	811	49 52' 44"	119 24' 47"	08NM116
	Okanagan River at Penticton	6090	49 29' 44"	119 36' 55"	08NM050
Coastal	Shawnigan Creek near Mill Bay	92	49 39' 29"	123 34' 08"	08HA033
	Cowichan River near Duncan	826	48 46' 22"	123 42' 44"	08HA011
Peace	Alces River at 22nd Base Line	303	56 10' 01"	120 09' 17"	07FD004
	Beatton River near Ft. St. John	15600	56 16' 48"	120 42' 20"	07FC001

Temporal coherence analysis

I assembled annual stream discharge (not shown) and spring lake nutrient values (Appendix 3) into year-by-site matrices and used the average Pearson product-moment correlation coefficient (*r*) to estimate temporal coherence of stream discharge and spring nutrient concentrations within and among coastal and interior lake areas. Similar to the work of others, average correlations were considered as a measure of temporal coherence, not as an inferential statistic (Magnuson *et al.,* 1990). Temporal coherence aggregates multiple lake-pair correlations, therefore, coherence estimates are not statistically independent. I employed a Bonferroni correction, to determine what proportion of the correlation coefficients, were significantly different from zero. The Bonferroni correction is a safeguard against multiple tests of statistical significance on the same data falsely giving the appearance of significance, as 1 out of every 20 hypothesis-tests is expected to be significant at the $\alpha=0.05$ level purely due to chance.

Regressions linking nutrients to hydrology

I used linear regression to assess the dependence of temporal coherence of annual average discharge on proximity or distance between drainages. Similarly, I used linear regression to broadly determine whether lake nutrient concentrations were responding to local variation in mean annual discharge over the preceding year, or whether coherence among lake pairs could be explained by proximity or distance between lake pairs. To test whether nutrient coherence varied with lake water residence time (WRT) I estimated coherence of both TN and TP among multiple lake pairs grouped by WRT. For TN, equal number of lakes were assigned to WRT groups of < 1 year, 1-5 years, and > 5years. Because of the larger number of lake pair combinations available for TP, lake pair combinations were divided into approximate quartiles with 2 groups at or below WRT of approximately 1 year (<0.75 yr; 0.75-1.2 yrs) and 2 groups having water residence time greater than a year (1.2-5 yrs; >5 yrs).

Similarly, to test whether a relationship occurred between nutrient coherence and nutrient concentration, I calculated coherence among lakes grouped over three

concentration ranges for both TN (<200 µg/L; 200-400 µg/L; >400 µg/L) and TP (<10 µg/L; 10-20 µg/L; >20 µg/L). For TP, the concentration ranges reflect approximate boundaries between oligotrophic, mesotrophic and eutrophic states. Finally, I used analysis of variance to determine if differences among lake groups based on WRT or concentration groups were significant.

RESULTS

Interannual variation in stream discharge

Standardized average annual discharge plots show similar interannual patterns for the hydrograph pairs within each of the drainage areas (Figure 3.1). Moreover, cyclical interannual patterns of high and low discharge were visually evident in the standardized discharge plots, particularly for Coastal, Okanagan and Shuswap drainages. For these systems, multi-year periods of higher than average run-off were evident for years 1981-84, 1990-1991, and 1996-2000. Periods of lower discharge were common among these same districts 1985-1989, 1992-1995, and 2001-2007.
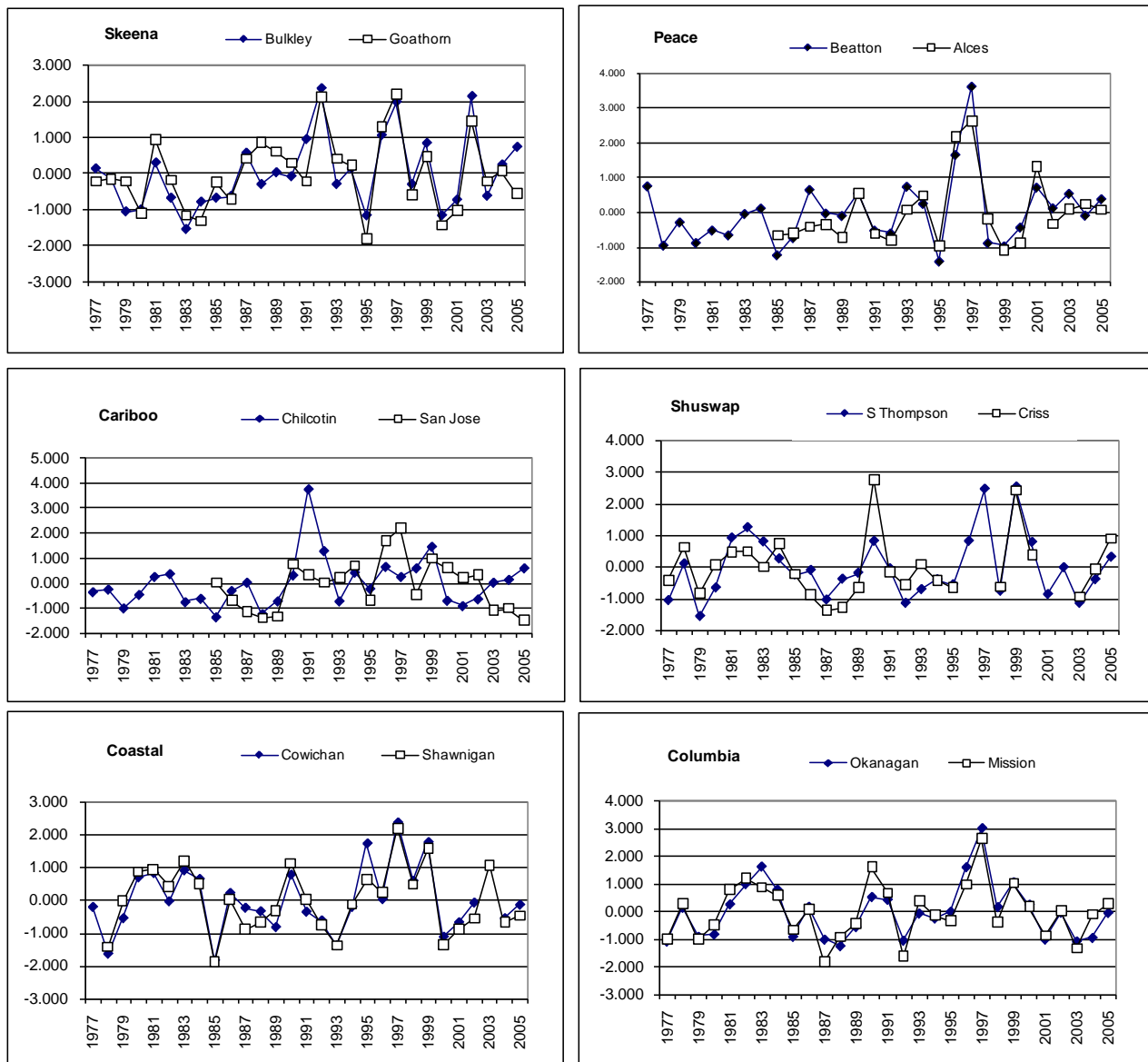
Figure 3.1 Standardized average annual discharge (Water Survey Canada data, 1977 to 2005) for large and small drainages in various districts: coastal (Shawnigan, Cowichan), Columbia (Okanagan River, Mission Creek), Shuswap (South Thompson River, Criss Creek), Fraser (Chilcotin River, San Jose River), Skeena (Bulkley River, Goathorn Creek), and Peace (Alces Creek, Beatton River).

Within each area, the hydrograph pairs were highly correlated: Coastal (r=0.933), Columbia (r=0.902), Peace (r=0.883), (Skeena (r=0.837), Shuswap (r=0.769), Cariboo (r=0.713). Hydrograph coherence was also moderately strong between Okanagan River and Cowichan River (r=0.556), Okanagan and Chilcotin (r=0.529) and Shuswap and Chilcotin (r=0.776) drainage areas. Coherence was weakest among pairs with the Bulkley River (r=0.226) and strongest among those matched with Okanagan River (r=0.493). Using all sites, a strong relationship was evident between hydrograph coherence and distance (r^2=0.748, p<0.0001) (Figure 3.2). Thus, to the degree that regional hydrology acts as a driver of lake dynamics, the potential for coherence to manifest itself among lake pairs should be greater among proximate lakes, particularly those in southern interior and coastal zones of BC, than those separated by more than a few hundred kilometers.
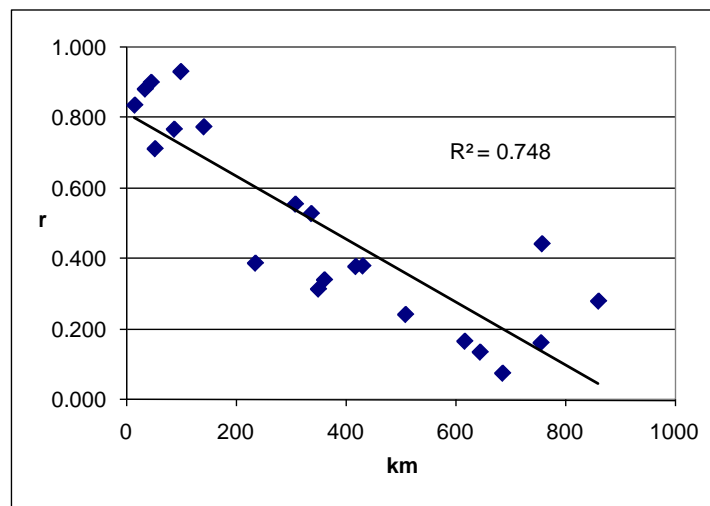
Figure 3.2 Dependence of correlations among standardized annual average discharge (Water Survey Canada data, 1977 to 2005) on the distance within and between drainages. Drainages are: Coastal (Shawnigan, Cowichan), Columbia (Okanagan River, Mission Creek), Shuswap (South Thompson River, Criss Creek), Fraser (Chilcotin River, San Jose River), Skeena (Bulkley River, Goathorn Creek), and Peace (Alces Creek, Beatton River).

Spatial aspects of nutrient concentrations and dependence on discharge

Spring total nitrogen and total phosphorus concentrations vary considerably among lakes at all spatial scales (Appendix 3A,B). However, both nitrogen and phosphorus were significantly greater in lakes of the Fraser, Skeena and Peace (TN, $p<0.0001$; TP $p< 0.05$) than Coastal, Columbia and Shuswap drainages, reflecting the prevalence of eutrophic and mesotrophic lakes sampled in those geographic areas (Appendix 4).

Correlation between lake spring TN concentration and antecedent (lag 1 year) annual average discharge (m3/s) at nearby hydrographic sites were negative for 6 of 9 Coastal lakes, 5 of 7 Columbia lakes, 1 of 3 Shuswap lakes, 3 of 5 Fraser lakes, and Kathryn Lake in the Skeena (Appendix 5A). None of the distributions (positive versus negative correlations) could be considered significantly different from zero at $\alpha=0.05$ level. However for Kathlyn Lake a significant ($r^2=0.725$, $p=0.03$) relationship (negative) occurred with antecedent Bulkley River discharge. In contrast, significant relationships (positive) occurred between TN in Charlie ($r^2=0.978$, $p=0.011$) and Chimney ($r^2=0.293$, $p=0.056$) lakes, and antecedent discharge on the Beatton and Chilcotin rivers respectively (Figure 3.3).

In contrast to the prevailing inverse relationship between TN concentration and discharge, correlations between lake spring TP concentration and antecedent discharge at proximate discharge sites were positive for 7 of 9 Coastal lakes, 4 of 7 Columbia lakes, all 3 Shuswap lakes, but only 2 of 5 Fraser lakes (Appendix 5B). However, none of the distributions were significantly different from zero at the $\alpha=0.05$ level, and significant (positive) relationships between TP concentration and antecedent discharge were only evident for Christina Lake ($r^2=0.311$, $p <0.0007$) and Okanagan Lake ($r^2=0.324$, $p <0.001$) with antecedent discharge on Okanagan River (Figure 3.3).
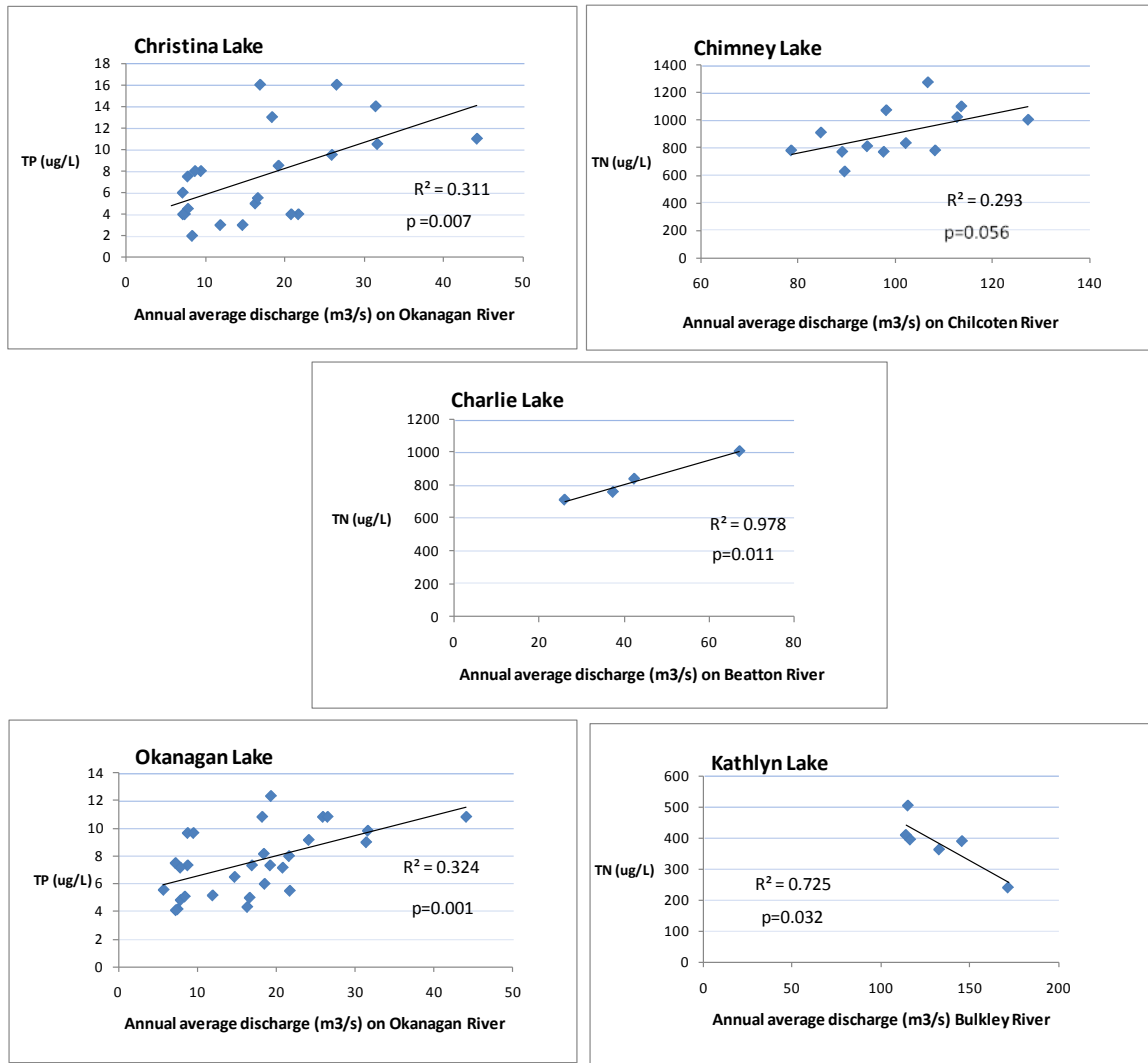
Figure 3.3 Significant relationships between lake nutrient concentration (µg/L) and regional average annual discharge (m³/s) in the antecedent year.

Temporal coherence of nutrients

Although a maximum of 322 pair-wise correlations are possible from 26 lakes, after screening for missing data (see Chapter 2) the number of lake pairs with 10 years of concurrent data was reduced to 192 for TN and 296 for TP. Correlations among lake pair combinations at the provincial scale, ranged considerably (TN r = -0.696 to 0.825;TP r = -0.996 to 0.980) (Appendix 6A,B). However the average of all

correlations, or temporal coherence for both TN and TP were positive (TN $r = 0.058$; TP $r = 0.284$) and statistically different from zero for both TN ($p<0.01$) and TP ($p<0.0001$) (Table 3.3; Appendix 7A,B). TN coherence however, was very low at the full study scale, and improved only modestly at smaller spatial scales (Shuswap lakes $r = 0.18$; Fraser lakes $r = 0.17$).

Importantly, temporal coherence was consistently greater for TP than TN at all spatial scales examined. Low to moderate TP coherence occurred among all lakes at the full study scale (TP $r = 0.284$), and among interior lakes grouped at various smaller spatial scales (all $r = 0.314$; Cariboo $r = 0.397$; Columbia $r = 0.380$; Shuswap $r = 0.645$) (Table 3.3). TP coherence was low however among Coastal lakes ($r = 0.166$). Interestingly, moderate TP coherence occurred between certain individual lakes from both interior and coastal areas, and all other lakes at the full study scale: Mara ($r = 0.501$), Fork ($r = 0.468$), Kalamalka ($r = 0.452$), Shawnigan ($r = 0.415$), and Lac La Hache ($r = 0.411$). Among all sites, and at coastal and interior drainage (Columbia, Shuswap, Fraser) scales, strong correlations (after Bonferroni correction) were absent. However, at the drainage scale, strong correlations were more frequently observed for TP within the Shuswap (100%), and the Columbia lakes (38%). Percent strong correlations were absent for TN at all scales.

Interestingly, two lakes demonstrated negative TP coherence tendencies with many other lakes. For example, TP correlations were negative in 55% of lake pairs involving Lizard Lake, and coherence was negative between Lizard Lake and other Coastal lakes ($r = -0.194$), and between Lizard Lake and all lakes ($r = -0.03$). Similarly, TP correlations were negative in 85% of lake pairs involving Charlie Lake. Temporal coherence was negative between Charlie Lake and other interior lakes ($r = -0.166$) and with all lakes at the full study scale ($r = -0.09$). Nonetheless, my expectation that nutrient coherence would be positive among all lakes, and at smaller drainage scales, was supported for both TN and TP.

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Table 3.3 Average temporal coherence (*r*) for total phosphorus (TP) and total nitrogen (TN) between all lake pairs at provincial, coastal and interior locations, and at sub-group scales.

Area	Drainage	TP		TN	
		no. lake pairs	*r*	no. lake pairs	*r*
Coastal	all	32	0.166	11	0.045
Interior	all	124	0.314	93	0.039
	Columbia	21	0.380	21	0.050
	Shuswap	3	0.645	3	0.180
	Fraser	11	0.416	5	0.170
Provincial	all lakes	296	0.284	192	0.058

Dependence of nutrient coherence on lake pair proximity

I examined whether nutrient coherence could be explained by distance between lake pairs. For all lakes, the relationship between lake pair TN coherence and lake pair distance was not significant (r^2=0.0008, p=0.689) (Figure 3.4). At smaller scales however, a significant (negative) relationship was only evident between TN coherence and lake proximity (r^2=0.463, p=0.09) within the Coastal area; in this case the relationship relied heavily on a relationship between TN coherence and distance for Fork and St. Mary lakes. A weak but significant (negative) relationship (r^2=0.09, p<0.0001) was also evident between TP coherence and distance among all sites at the provincial scale (Figure 3.4). Removal of distant Charlie Lake, which exhibited negative correlations with most other lakes, further reduced the dependence of TP coherence on proximity of lake pairs (r^2=0.01, p=0.1). Only for Coastal lakes was a significant relationship (negative) evident, with TP coherence diminishing with distance (r^2=0.266, p=0.003) largely due to negative correlations between Lizard Lake and other Coastal lakes. For Fraser drainage lakes, a relationship (positive) (r^2=0.187, p=0.2) was evident due to a high correlation between Horse Lake and distant Tabor Lake. No relationship was evident between TP coherence and distance for combined Columbia and Shuswap lake pairs (r^2=0.001, p=0.8). I concluded that TN appears to have low coherence, even when lakes are in close proximity. Similarly, TP coherence

among lakes is not strongly associated with proximity, particularly when Charlie Lake is removed from the data set.
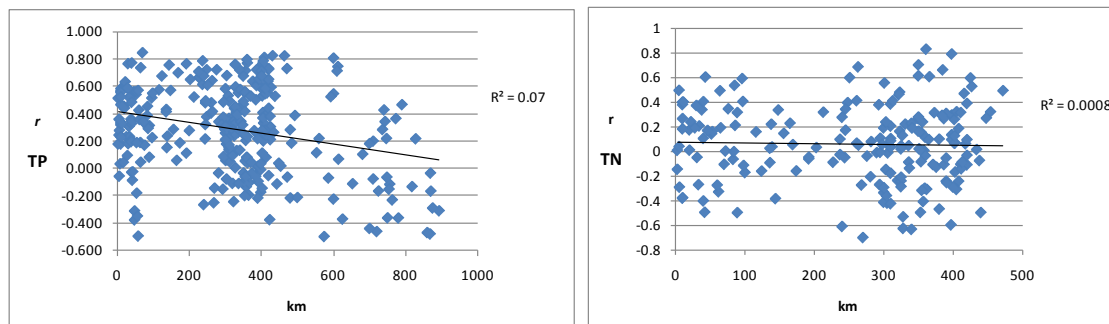
Figure 3.4 Relationship between distance (km) between lake pairs, and TP (left) and TN (right) correlations (r) of all lake pairs with more than 10 years concurrent data.

Dependence of nutrient coherence on lake water retention time

At the full scale, coherence of TN among lakes was uniformly low for lakes with WRT <1year (r=0.083, SD 0.315, n=20), between 1 and 5 years (r=0.116, SD 0.262, n=18) and those with WRT greater than 5 years (r=0.061, SD 0.302, n=14) (Appendix 8A). Similarly, TP coherence among lake pairs with WRT <0.75years (r=0.334, SD=0.262, n=15) was not different from lake pairs with WRT between 0.75 and 1.2 years (r=0.138, SD=0.288, n=15), those with WRT greater than 1.2 and 5 years (r=0.212, SD=0.392, n=13) or those with WRT greater than 5 years (r=0.319, SD=0.285, n=17) (Appendix 8B). Thus, for the lakes examined, coherence of TN nor TP, could be explained on the basis of lake water residence time.

Dependence of nutrient coherence on nutrient concentration

Among all lakes, temporal coherence of TN was uniformly low. However, to determine whether coherence might be greater among lakes with similar spring TN concentrations, I calculated coherence for lakes divided relatively evenly into 3 broad concentration ranges: <200 µg/L, 200-400 µg/L and >400 µg/L. Coherence among lakes with <200 µg/L was greater than the 200-400 µg/L group, but not significantly so

(p=0.08), and not different than the >400 µg/L lake group (Figure 3.5, Table 3.4, Appendix 9a). Overall there was no significant difference (p=0.2) among the TN concentrations groups. (Appendix 9A).

Table 3.4 Average temporal coherence (*r*) for total phosphorus (TP) and total nitrogen (TN) between all lake pairs grouped by nutrient concentration (µg/L).

Variable	Lake group	# lake pairs	*average r*	SE
TP	<10 µg/L	20	0.380	0.071
	Lizard removed	15	0.561	0.045
	10-20 µg/L	26	0.536	0.042
	>20 µg/L	42	0.113	0.047
	Charlie removed	32	0.147	0.052
TN	<200 µg/L	14	0.167	0.064
	200-400 µg/L	28	-0.040	0.058
	>400 µg/L	16	0.103	0.082

In contrast, TP coherence was significantly lower for the >20 µg/L lake group, than for <10µg/L and 10-20 µg/L lake groups (p<0.0001) (Table 3.4; Figure 3.5; Appendix 9B). To evaluate the influence of the anomalous lakes, I retested the TP lake groups after exclusion of Lizard Lake from the <10µg/L group, and Charlie Lake from the >25 µg/L group. Removal of these lakes increased coherence of each group (Table 3.4), however, coherence of the >25 µg/L group remained significantly lower (p<0.0001) than that of <10 µg/L and 10-20 µg/L lake groups (Appendix 9B). Thus, although the average distance between site pairs was significantly greater (p=0.0001) for the >20µg/L group due to Charlie Lake, TP coherence for this group, with Charlie Lake removed, was still significantly different (lower) (p <0.0001) from the lower concentration groups. I assessed whether TP groups were also significantly different in WRT. The three TP concentration groups were not significantly different in terms of WRT (p=0.63). I concluded that TN coherence shows no clear dependence on concentration. However for TP, coherence is significantly greater among lakes below 20 µg/L than among lakes above this value.
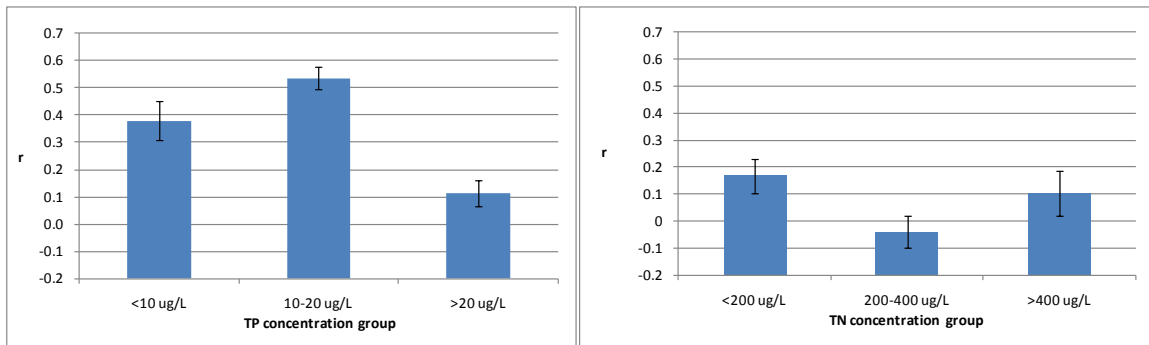
Figure 3.5 Coherence (*r*) and standard errors bars for all lake pairs, grouped by spring nutrient concentration ranges TP (<10 µg/L, 10- 20 µg/L and >25 µg/L) and TN (<200 µg/L, 200-400 µg/L, >400 µg/L).

DISCUSSION

I assessed to what extent interannual variation in catchment discharge was synchronous within and among lake districts, and helped explain TN and TP concentrations or coherence among representative BC lakes. Furthermore, I tested whether nutrient coherence could be explained by lake pair proximity, similarity in water residence time, or nutrient concentration.

The influence of hydrology

Coherent behavior of variables among lakes requires that an external driver impose a common dynamic to lakes across the spatial scale of interest (Magnuson *et al*., 2006). In this study I demonstrated that coherence of stream hydrographs, as estimated by average annual stream discharge, was strongly related to proximity. Coherence was high among sites separated by 10's of kilometers but was weak among sites separated by distances of more than a few hundred kilometers. In addition to this direct relationship between discharge and scale, similar interannual periods of alternating high and low discharge were evident for coastal and southern interior stream hydrographs, but not Skeena and Peace hydrographs. Despite discharge coherence, strong relationships between lake nutrient concentration and local catchment discharge variation were limited.

Catchment export of nitrogen and phosphorus are known to be linked to annual water yield (Jaworski *et al*., 1992; Schindler *et al*., 1996; Sorrano *et al*., 2000). However, lag effects between timing of input and complete mixing, or internal cycling of nutrients, may partially account for the lack of clear and direct links between run-off and lake concentrations. Lake concentrations may also be strongly influenced by magnitude and duration of extreme discharge events, antecedent catchment conditions (Vanni *et al*. 2001) or linked to discharge averaging periods other than the annual average discharge estimate employed here. For example, within lake districts in the Upper Great Lakes region, relationships between precipitation and lake nutrient concentrations were not consistent among districts, and varied in strength and direction (negative or positive) depending on averaging period (Webster *et al.,* 2000).

Coherence of nutrients

Over decadal time scales, and among a diversity of lakes, I observed four important spatial patterns of TN and TP coherence among BC lakes. First, TN was consistently less coherent than TP. Direct comparison of these findings with work elsewhere is constrained by the limited reporting of TN and TP coherence to date. Nevertheless, coherence of TN among BC lakes at all spatial scales was weak, and generally less than reported elsewhere for nitrate nitrogen (Baron & Caine, 2000; George *et al.,* 2000; Sorrano *et al.,* 1999), TN (Kratz *et al*., 1998; Webster *et al.,* 2000) or particulate nitrogen (Kling *et al*., 2000).

In contrast, the TP coherence reported here, particularly among the freshet dominated interior lakes, was moderate and similar to that reported for ELA, Red Lake and Dorset study areas (Webster *et al.,* 2000), but less than for SRP among Arctic LTER lakes (Kling *et al*., 2000) or for TP among Southern Wisconsin or English Lake District lakes (George *et al*., 2000; Sorrano et al., 1999). Strength of coherence between lakes is expected to be greater for limnological variables directly affected by climatic factors, than for those influenced by a complexity of factors (Magnuson *et al.,* 1990). Low coherence could result from some combination of little variation over time in the

variable of interest, weak linkages between variation in the driver and the variable of interest, or strong spatial patterns (Kling *et al.,* 2000). That coherence for TP is consistently greater than TN among BC lakes suggests TN demonstrates greater intrinsic variation than TP, and climate more clearly affects TP across these landscapes. That coherence of TN is similar to or greater than TP in other settings such as ELA, Dorset and Red Lake study areas (Webster *et al*., 2000) suggests the influence of regional drivers such as atmospheric deposition or other regional drivers not influencing TN dynamics of BC lakes.

Second, coherence of neither TN nor TP were clearly dependent on BC lake pair proximity, even at the drainage scale. This is somewhat contradictory with previous findings which show coherence of reactive variables is greatest among proximate lake pairs within drainages (Baron & Caine, 2000; George *et al*., 2000; Kling *et al*., 2000). For example, among Arctic LTER lakes along a common drainage path of approximately 10 kilometers, nutrient coherence was greater among proximate pairs than distant pairs (Kling *et al*., 2000). Webster reports coherence for TN (r=0.426-0.689) and TP (r=0.267-0.476) within ELA, Red Lake and Dorset lake districts over distances of 10's of kilometers. Here I report that TP coherence was moderate and positive (r>0.4) among lake pairs over distances of a few hundred kilometers. Negative correlations among lake pairs containing either Lizard or Charlie lakes located at the boundaries of the study area, suggest spatial limits to coherence or the influence of drivers not explored in this study.

Third, while WRT is central to phosphorus mass balance models, at the large spatial scale examined here, no relationship could be established between nutrient coherence and water residence time other than a weak and inverse relationship among coastal lakes. This is inconsistent with the conceptual model put forward by Sorrano *et al*. (1999) showing coherence of dissolved reactive ions inversely related to WRT. Water residence time is strongly linked to nutrient dynamics in lakes (Reckhow & Chapra, 1983). However, lake TP is also known to be strongly linked to inflow concentration (Brett *et al.,* 2008). Thus, within a series of proximate lakes, high coherence might

logically occur where riverine conditions and very short WRT (days-weeks) constrain the potential of within-lake dynamics. Although I was not able to explore this condition fully in this study, highest TP coherence was observed for the connected Shuswap lakes, having relatively short water residence times.

Finally, in this study, coherence of TP was strongly and inversely related to lake pair spring TP concentrations. TP coherence was significantly greater among lakes with < 20 µg/L TP, than among those having >20 µg/L TP at spring overturn. Importantly, coherence of TP was moderate among low TP lakes across distances of several hundred kilometers in southern BC including coastal, Columbia and Fraser drainage areas. Moreover, a number of low TP lakes from Coastal, Columbia and Fraser drainages were moderately coherent with all other lakes. These findings are unique, as the few previous studies to include TP, have either found no relationship between TP coherence and trophic state (Bleckner et al., 2007) or have reported greater coherence among lakes in disturbed catchments with higher nutrient loading and lake concentrations (George *et al*., 2000; Kratz *et al*., 1998).

In this study, all the BC lakes with > 20µg/L spring TP, have some combination of intrinsic drivers such as high levels of catchment disturbance (Jensen & Epp, 2001; Zirnhelt *et al*., 1997), internal loading (French & Petticrew, 2007; Rieberger, 2003) or poor stratification (McPherson, 2006). This study suggests that as lake TP increases through internal cycling or catchment specific loading, sensitivity to interannual variation of hydrology and external load diminishes, and coherence of TP among lakes decreases. Conversely, low to moderate TP lakes with little catchment specific or internal nutrient load, respond more directly to variability in catchment TP flux and demonstrate coherence across significant spatial scales in southern BC. I can not exclude the possibility that coherence may also be a function of other factors not examined here.

In summary, this examination of temporal coherence of a restricted variable group, across a diversity of lakes and spatial scales, has provided new insights into nutrient

coherence in general and that of nutrient dynamics among BC lakes in relation to extrinsic forces. Dependence of TP coherence on nutrient concentration potentially provides a new organizing concept to explore TP dynamics among lakes. Importantly, the temporal coherence of TP among low to moderate productivity BC lakes, should be considered when interpreting trends to local stressors and setting lake management objectives.

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CHAPTER 4
SIGNIFICANCE OF FINDINGS AND NEXT STEPS

INTRODUCTION

Temporal coherence of parameters among lakes across significant spatial scales, offers a means of assessing the role of climate, on lake dynamics, and development and testing of organizing concepts to explain nutrient variation. Importantly, temporal coherence, where demonstrated has practical value, as it enables extrapolation of results from one lake to other lakes, and aids prediction of lake dynamics in the future (Magnuson *et al*., 2004). I assessed to what spatial extent interannual variation in hydrology was synchronous among 6 drainage areas and could explain TN and TP concentrations and coherence among 26 BC lakes over multi-decadal time frames.

My results showed that an important extrinsic driver, catchment discharge, was highly coherent among coastal, and southern interior drainages. Strong dependence of nutrient concentrations on antecedent average annual discharge was limited to a few interior lakes. However relationships between TP and TN and antecedent discharge tended to be positive and negative respectively. TN coherence was very low among lakes and could not be explained by proximity, or similarity in flushing or trophic state. Coherence of TP however, demonstrated low to moderate coherence over a wide area, and varied inversely and significantly with lake TP concentration. Oligotrophic and mesotrophic lakes (<20 µg/L) were significantly more coherent than eutrophic lakes (>20 µg/L). These finds have importance in terms of providing a broader understanding of coherence for nutrients, as well as application to lake management in BC. I will discuss these separately and then consider next steps.

SIGNIFICANCE OF FINDINGS

Developing a broader understanding of nutrient coherence

This work expands the spatial exploration of temporal coherence, as no other work to date has been reported for lakes in western Canada or the Pacific Northwest of North America. Previous coherence studies have examined long term data collections from Arctic, Colorado, and Wisconsin LTER lake networks, or Upper Great Lakes research areas such as ELA, Dorset, and Red Lake areas. Thus this study fills an important spatial gap in the studies of nutrient coherence among lakes.

This study also significantly adds to the understanding of coherence of TN and TP among lakes. Few other coherence studies to date have focused on these important variables. TN coherence reported here, is consistently less than reported elsewhere for nitrate nitrogen (Baron & Caine, 2000; George *et al.,* 2000; Sorrano *et al.,* 1999), TN (Kratz *et al*., 1998; Webster *et al.,* 2000), or particulate nitrogen (Kling *et al*., 2000). The weak coherence of TN among BC lakes, suggests weak linkages between climate and TN variability either through intrinsic variation, or strong spatial patterns, which are perhaps less apparent in other areas due to regional stressors such as atmospheric deposition of nitrogen (Baron & Caine, 2000) or fertilizer application to catchments (George *et al*., 2000).

My findings do not support the hypothesis that coherence of nutrients among these study lakes is linked to WRT. Only a weak and negative relationship between TP coherence and water residence time could be found among coastal lakes. Thus the conceptual model put forward by Sorrano *et al*. (1999) showing coherence of dissolved reactive ions inversely related to WRT may not be applicable to TP or to the lakes examined here. My findings are also unique in that they show TP coherence among BC lakes was strongly and inversely related to lake pair spring TP concentrations. Previous studies have either found no dependence between nutrient coherence and trophic state (Bleckner *et al*., 2007) or have reported greater coherence among lakes in disturbed

catchments with higher nutrient loading and lake concentrations (George *et al*., 2000; Kratz *et al*., 1998). Results of my study suggest that as lake TP increases through internal cycling or catchment specific loading, sensitivity to interannual variation of external load diminishes and the potential for coherence of phosphorus is reduced among high TP lakes. Conversely, low to moderate TP lakes (<20 µg/L) with limited internal nutrient cycling, and lower external loading, respond more directly to significant variation in climate driven external load and demonstrate coherence across significant spatial scales.

Application of findings to BC lake management

These findings can be readily incorporated into two key aspects of the BC lake monitoring and assessment network. First, because decadal scale time series incorporate more climate variability, and have been shown to provide higher estimates of coherence (see Chapter 2) I suggest that trend assessments using less than 10 years of data may be compromised due to climate variation, particularly among lakes with < 20 µg/L TP. And second, as a significant portion of the variability of spring TP among low TP lakes is shown here to be linked to climate variation, this variable and these lakes can now provide important trend assessment potential, and should be central to a provincial lake monitoring network. In conceptual terms, individual lakes which shift toward becoming more coherent with reference lakes would suggest decreasing intrinsic control. For example, success of external phosphorus load reductions to Okanagan lakes (Jensen & Epp, 2001), or internal load reductions through hypolimnetic aeration of lakes such as St. Mary Lake (Rieberger,1992) could be evaluated in part by comparing lake specific trends against the regional norm. Conversely, individual lakes which become less coherent with a population of interest, would suggest increasing intrinsic or catchment specific control over TP variability.

Finally, given that spring TP is a common water quality objective established as a BC lake and nutrient management target, temporal coherence of this variable should be considered during the objectives setting and attainment monitoring processes.

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NEXT STEPS

Developing a broader understanding of nutrient coherence

Clearly the relationship between TP coherence and lake status requires further exploration to determine whether this relationship contributes to a broader conceptual understanding of factors governing coherence. Phosphorus is not well represented in coherence studies to date. Therefore, I suggest that combining the BC data with that of other lake drainages previously reported, and testing a hypothesis that TP coherence is dependent on lake status would be a logical next step in developing an organizing concept for TP coherence among lakes.

As a preliminary step to further this ambition, I assembled readily available TP coherence and phosphorus concentration estimates for all forms of phosphorus and lake groupings reported to date (Table 4.1).

Table 4.1 Average coherence and concentrations for TP, TDP and SRP among various lake groupings.

Lake grouping	P form	µg/L	r
Northern Wisconsin LTER	TP	22	0.139
Northern Wisconsin LTER[a]	TDP	22	0.39
Southern Wisconsin	TP	63	0.674*
Northern and Southern Wisconsin[b]	TP	47	0.15
Northern and Southern Wisconsin[b]	TDP	47	0.22
Arctic LTER[c]	SRP	3.8	0.7
Arctic LTER[c]	PP	3.8	0.18
ELA[d]	TP	8.3	0.267
Dorset[d]	TP	6	0.385
Red Lake[d]	TP	9.5	0.467
BC[e]	TP	10	0.561
BC[e]	TP	15	0.536
BC[e]	TP	20	0.113

all data from Sorrano *et al* ., (1999) or as indicated; a-Magnuson *et al* ., (1990); b-Kratz *et al* ., (1998); c-Kling *et al* ., (2000); Webster *et al* ., (2000); e-Jensen (see Chapter 3); * anomalous value excluded from Figure 4.1

As various Wisconsin lakes groupings are reported in the literature, multiple coherence and concentration estimates are possible. Adirondack, Colorado and the English Lake district were not included, as phosphorus concentrations were not readily available or phosphorus was not included in the coherence study. Nevertheless, using all data in Table 4.1 the relationship between lake status and coherence is insignificant (r2=0.003; p=0.8). However, removal of the single data value (*r*=0.674) for the South Wisconsin lakes, due to the strong anthropogenic influence on nutrients, yields a significant relationship (r2=0.253; p=0.095) for the remainder of the data (Figure 4.1).
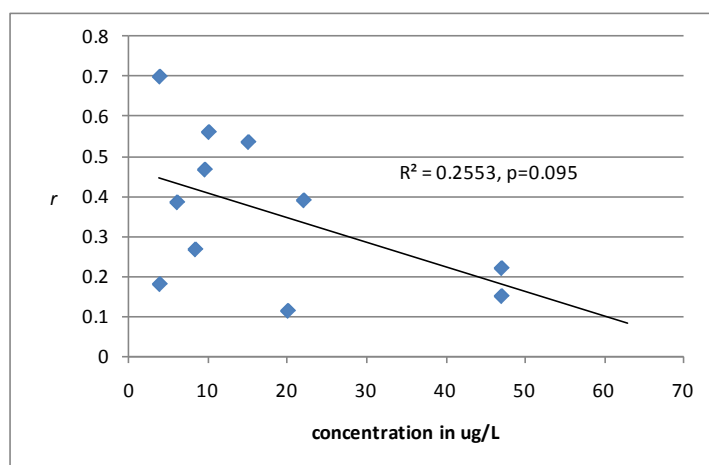
Figure 4.1 Dependence of coherence (*r*) on phosphorus concentration from multiple coherence studies and lake districts.

These results are intriguing and warrant further evaluation by considering lake pair TP concentration and coherence values over concurrent time series and at various spatial groupings.

Application of findings to BC lake management

My findings indicate that a measurable portion of the interannual TP variation in oligotrophic and mesotrophic lakes in this study is driven by climate variation over significant spatial scales. However, the boundaries of this relationship are poorly defined. Lizard and Charlie lakes may be responding to spatial boundaries of climate expression or to other intrinsic drivers. Therefore, I recommend incorporating new or existing data for low nutrient lakes from central and northern areas of BC to further define the spatial scale of TP coherence. I also recommend continued spring TP data collection from low TP lakes to verify and track coherence among these lakes.

I suggest it is important to incorporate these findings when interpreting lake specific TP trends in relation to landuse, nutrient management or other lake management considerations. Lake managers are interested in the underlying water quality signals and trends, as opposed to year to year variability or noise. Therefore, regionalization or

the extrapolation of results from a few intensively studied sites to other lakes is a logical outcome where predictable coherence occurs. Certainly for BC lakes with < 20 µg/L TP, comparison of TP trends relative to that of neighbouring lakes of similar status should provide a useful reference for trend assessment purposes. To facilitate this and to provide a more spatially robust reference signal indicative of TP and climate interaction, I suggest a single standarized TP coherence value or index, joining the TP dynamics common to a number of key lakes, over a longer averaging period such as a 2-3 year moving averaging, could prove beneficial to regionalization of results from a few lakes to other lakes within the spatial scale of interest. As with other indices, the TP index would integrate spring measurements over appropriate spatial and temporal scales, to demonstrate a common signal. Further evaluation of this concept is necessary to establish and validate optimal spatial and temporal aspects of the index.

At the regional and provincial scale it appears that TP coherence among low TP lakes is governed by extrinsic controls related to climate. What is not entirely clear from my study is how climate and catchments interact to enable coherence. I recommend other discharge and nutrient averaging periods be explored to clarify the relationships between TP coherence and hydrology. Moving averages of more than one antecedent year might better reflect underlying lake response to climate variation. As well, my study did not consider whether variation in regional drivers such as temperature could be contributing to coherence. Air and surface water temperature are highly coherent over large distances and are strong drivers of ecosystems over large spatial scales (Livingstone, 2008). Systematic or episodic variation in atmospheric temperature alone, or combined with precipitation, could contribute to synchronized patterns of snow accumulation, timing of snow melt, or nutrient uptake in terrestrial (George *et al*., 2000) or aquatic ecosystems (Anneville *et al*., 2005; Schindler, 2001). Climate indices such as NAO and ENSO reduce complex spatial and temporal variability into measures depicting underlying climate patterns (Stenseth *et al*., 2003), and in the case of NAO, is useful in understanding TP variability among European lakes (Anneville *et al*., 2005). Considerable information exists for ENSO, and its index is known to reflect timing of snow melt and volume of catchment discharge (Cayan *et al*., 1999; Moore &

McKendry, 1996) and material transport (Kiffney *et al*., 2002) in drainages of the Pacific Northwest. Therefore, I suggest examining whether TP coherence among BC lakes is dependent on ENSO might prove beneficial to predicting TP variability in the future.

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APPENDICES

APPENDIX 1A Variation in coherence of a hypothetical data set following substitution of non-detect values with the minimum detectable concentration (mdc), substitution of half the mdc, or pairwise deletion.

% data < mdc	high r mdc	high r mdc/2	high r delete mdc	med r mdc	med r mdc/2	med r delete mdc	low r mdc	low r mdc/2	low r delete mdc
0	0.843	0.843	0.843	0.580	0.580	0.580	0.237	0.237	0.237
20	0.843	0.858	0.758	0.580	0.584	0.514	0.237	0.253	0.136
30	0.798	0.827	0.611	0.569	0.580	0.386	0.205	0.227	-0.023
35	0.756	0.767	0.541	0.550	0.556	0.411	0.176	0.195	-0.040
50	0.753	0.756	0.929	0.552	0.550	0.373	0.149	0.176	-0.225

APPENDIX 1B Variation in coherence for spring total dissolved phosphorus (TDP) in Christina and Sugar lakes following substitution of non-detect values with the minimum detectable concentration (mdc), substitution of half the mdc, or pairwise deletion (underlined values are below the mdc value of 3 µg/L).

TDP in µg/L

Christina	Sugar
	3
	5
6	5
5	4
5	6
	4
3	3
	_3_
4	_3_
	_3_
_3_	_3_
_3_	_3_
_3_	_3_
3	3
4	5
_3_	5
17	3
14	7
9	_2_
11	4
13	6
7	_2_
4	2
6	3
3	_2_
_2_	3
4	4
6	4

Correlation matrix
substitute mdc

	Christina	*Sugar*
Christina	1	
Sugar	0.337269	1

substitute mdc/2

	Christina	*Sugar*
Christina	1	
Sugar	0.404238	1

pair-wise deletion of < mdc

	Christina	*Sugar*
Christina	1	
Sugar	0.327166	1

APPENDIX 2 Map of hydrometric and lake sites.

Lakes	
1	Christina
2	Ellison
3	Kalamalka
4	Okanagan
5	Osoyoos
6	Skaha
7	Wood
8	Mabel
9	Mara
10	Sugar
11	Fork
12	Glen
13	Lizard
14	Maxwell
15	Prospect
16	Quamichan
17	Shawnigan
18	St Mary
19	Stocking
20	Chimney
21	Horse
22	Lac La Hache
23	Tabor
24	Williams
25	Charlie
26	Kathlyn

Hydrographs	
A	Alces
B	Beatton
C	Bulkley
D	Chilcotin
E	Cowichan
F	Criss
G	Goathorn
H	Mission
I	Okanagan
J	San Jose
K	Shawnigan
L	South Thompson

78
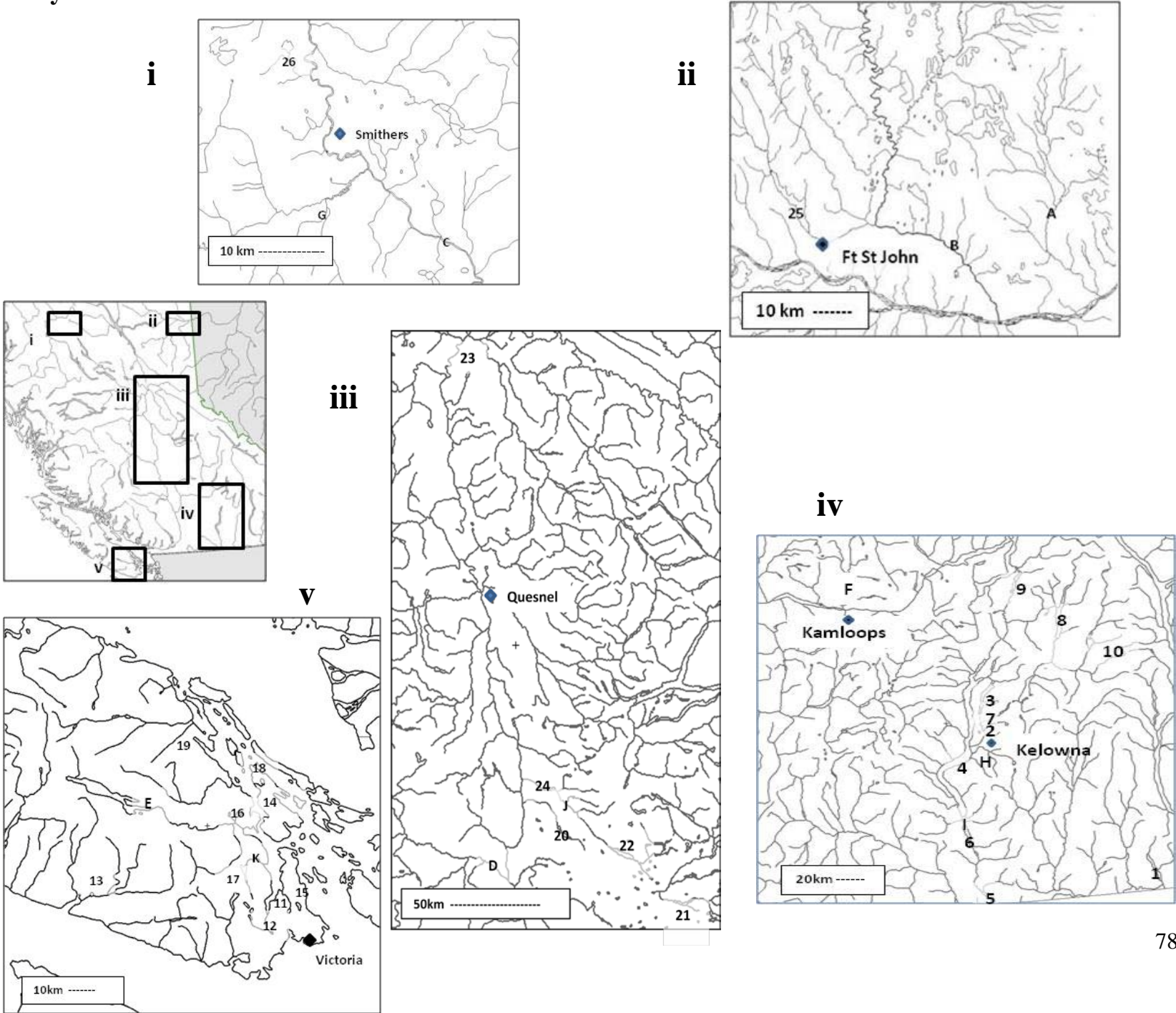
APPENDIX 3A Spring total nitrogen concentrations (µg/L) for selected coastal and interior lakes of BC

Lake district	Lake	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Count	Maximum	Minimum	Mean	Std Dev.
Coastal	Shawnigan		340	257	260			227	223		290	295	170	230	203	163	223	240	300	210		225	230	235	260	263	300	250	313	233	277	200	26	340	26	230	72
	St Mary			413	750	670	503	385	370		266	385					267	285	687	460		495	290	400	410	365	340	355	470	470	683	483	23	750	23	423	177
	Prospect				497			267	383		400	365	353	313			485	560	430			405	380	325	370	390	285	405	420	420		363	20	560	20	366	129
	Quamichan																385					365	410	345	485	390	405		485		495	730	10	730	10	403	206
	Lizard									30	150	80	40	80	90	70	120		110	60										133			11	150	11	81	46
	Stocking									80	170	110	80	350	90	120														130			8	350	8	136	111
	Maxwell					190		260		300	320	250	200	360	230	240	190						330	325	280	300	250	270	260	260	290	230	20	360	20	249	85
	Glen								293		267	400	323	233	290		440	320	380	360										280	330		12	440	12	292	124
	Fork																					267	260	215	240	290	300	323	290		220	200	10	323	10	227	100
Interior	Ellison			510	640	390	460	680	530	370	450	390	440	560	370	320	330	320	600	370	360	340	340	390		360	440	530	500	500	540	400	28	680	28	422	145
	Osoyoos	125	115	115	440	280	357	355	400	365	365	358	340	335	365	320	460	385	360	355	178	230	265	325	290	305	305	305	260	295	310	350	31	460	31	315	95
	Skaha	217	275	310	343	280	380	340	290	303	315	340	320	320	345	285	330	240	265	155	190	215	225	230	250	215	225	210	230	215	220	225	31	380	31	256	82
	Okanagan	295	235	238	257	200	209	243	215	198	183	207	173	160	180	182	150	207	205	242	190	208	235	220	218	218	212	222	228	217	249	242	31	257	31	200	51
	Kalamalka	282	260	215	253	289	248	295	272	284	265	274	283	248	273	222	263	232	268	228	357	322	345	353	377	357	377	357	327	333	388	347	31	388	31	287	85
	Wood		840	560	660	528	581	572	583	508	565	452	454	440	440	320	460	310	380	340	460	450	450	460	450	440	430	510	450		380	480	29	840	29	448	149
	Christina		160			55		140	120		90		135		110	115	190	120	110	110	90	90	85	130	75	110	80	95	85	90	125	120	24	190	24	104	38
	Sugar		193		200	205		207	175	180	210	165	135	145	185	120	315	245	240	230	250	165	185	155	165	155	155	140	170	190	195	165	28	315	28	181	62
	Mabel		215	150	195	125	130	195	185	150	135	150	100	120	155	140	125	140	160	150	140	145	175	140	155	120	165	205	140	180	170	130	30	215	30	145	40
	Mara	155	230	180	235	195	245	280	200	185	200	180	170	130	190	205	150	195	245	160	245	260	220	190	185	150	185	170	170	195	170	220	31	280	31	189	55
	Lac La Hache		650	610	490	410	470	463	515	490			430	404			450		556	468	550	540	537							491	508	557	19	650	19	451	158
	Chimney			770	910	810		780	770		780						627			1072	1100	1275	1022	1003					833				13	1275	13	819	376
	Horse			370		350		370	350										458	430	398	390	403		456	398	378	359	366		377	321	16	458	16	350	124
	Williams									606		850	659		631	1010	755	733	892	674		651	619		858	880	815	783	673	894	826	907	19	1010	19	717	250
	Charlie									703	713	760				1007	840																5	1007	5	630	377
	Tabor									490		395			600	480	500	413	483	490													8	600	8	406	197
	Kathlyn									410	505	395					390	240												363		320	7	505	7	314	171

APPENDIX 3B Spring total phosphorus concentrations (µg/L) for selected coastal and interior lakes of BC

Area	Lake	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Count	Maximum	Minimum	Mean	Std Dev.
Coastal	Shawnigan	6	4	9	9		7	7	8		6	5	5	4	4	4	4	4	3	3		6	7	6	7	9	5	4	2	2	3	6	28	28	2	6.7	6.3
	St Mary			14	48	41	33	25	18	16	20	33	28	17	17	22	14	18	26	12	9	30	14	17	18	16	14	12	16	26	46	33	29	48	9	23.4	10.2
	Prospect	19		20	12		14	16		12	9	12	11	8			4	12	7	9	24	28	17	13	16	17	7	12	10	16		18	25	28	4	14.0	6.5
	Quamichan																20	24	7	13	12	27	6	21	20	21	12		39	16	19	54	15	54	6	21.3	13.9
	Stocking									7	7	8	5	7	5	6	3		5	3		11	3.5			5		5.5		5			15	15	3	6.6	3.5
	Fork												9		11	8						15	8	14	13	10	8	8	7		7	8	13	15	7	10.1	2.9
	Glen					25		30	22	28	31	15	15	12	20	18	32	12	6	12	48	20	24	30	31	10	19	12	19	12	9		25	48	6	21.1	10.8
	Maxwell				9		12			12	11	7	9	12	9	9	8		13	5			10	10	12	14	7	7	8	5	8	10	22	22	5	10.2	4.2
	Lizard									7	5	5	3	4	5	4	5	4	5	8			5	4	5	3	12	3		2			18	18	2	6.0	4.4
Interior	Ellison			35	57	47	52	40	41	20	20	27	38	36	38	43	37	49	11	14	35	37	29	45	34	42	36	27	38	23	30	31	29	57	11	34.6	11.3
	Osoyoos	25	22	20	22	17	39	26	33	26	25	24	38	31	24	24	24	23	18	10	14	16	13	17	16	16	14	19	11	6	11	17	31	39	6	20.8	9.1
	Skaha	24	30	25	26	18	16	24	27	20	16	15	12	12	11	5	9	10	6	10	10	12	3	9	10	12	3	9	6	3	8	7	31	31	3	12.6	7.7
	Okanagan	8	8	11	10	10	12	11	10	9	7	6	7	6	5	6	7	4	4	7	7	9	11	8	11	7	5	5	4	5	3	5	31	31	3	8.6	6.5
	Wood	70	93	54	82	72	82	76	79	53	48	40	53	44	38	28	35	16	38	34	27	46	29	34	42	54	45	50	41	38	34	66	31	93	16	47.2	18.8
	Kalamalka	5	7	12	10	10	12	10	12	11	11	8	7	7	6	7	6	6	7	4	22	13	6	8	10	12	8	6	5	3	4	7	31	31	3	9.8	6.8
	Christina		6			8		10	11		8		8		3	4	4	4	5	3	16	14	11	13	16	9	5	6	4	2	4	9	24	24	2	8.6	6.0
	Sugar		4		9	7		5	8	5	3	3	4	3	3	3	3	5	5	4	4	11	4	6	7	3	2	3	6	2	3	4	28	28	2	5.9	6.3
	Mabel		6	7	6	5	7	5	9	8	5	3	3	3	4	3	4	9	4	3	10	8	5	5	8	5	3	3	4	2	2	5	30	30	2	6.4	6.7
	Mara	7	10	10	12	12	15	16	13	12	10	6	6	8	6	9	4	9	8	5	25	22	12	11	11	9	7	5	6	5	2	5	31	31	2	10.6	7.5
	Williams		78	76	68	50	68	86	85	71	83	75	56	53	68	72	51	48	54	83	87	87	44		54	70	71	56		60	65	77	28	87	28	65.0	16.7
	Chimney			12	17	17		20	21		22											24		35	30	23	19	29	18	8	7	7	16	35	7	19.6	8.9
	Tabor									27	30	16		23	27	18	22	30	26	22	67	32	28	38	35	27	27	20	21	22	9	22	22	67	9	27.5	13.4
	Lac La Hache		14	15	13	19	16	16	22	14	16	13	13	11	12	9	11	14	9	13	18	17	2						8	4	9		24	24	2	13.2	5.9
	Horse			15		15		16	19										14	17	35	32	14		24		17	21	22		17	20	15	35	14	20.3	6.8
	Kathyln									28	25	25	19	40	17	20	23	20									22						10	40	10	22.8	8.7
	Charlie									33	35	20	47	38	74	38	48	50	38	38									59	61	44		14	74	14	42.5	17.3

APPENDIX 4 One way analysis of long term spring nutrient concentration by area

Oneway Analysis of Long term mean spring TN By CNI
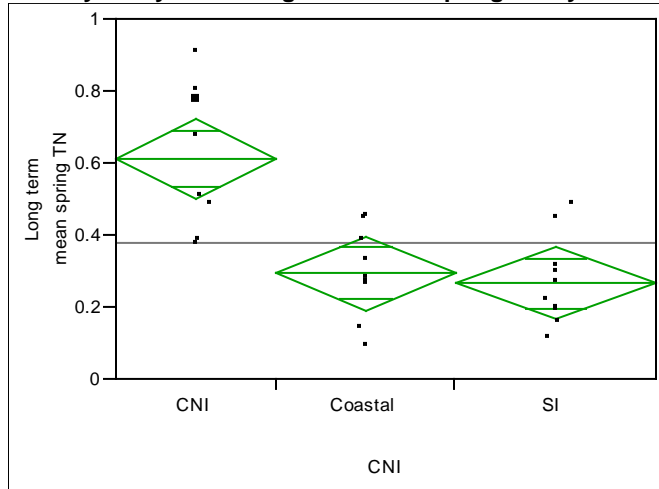
CNI- central and northern interior; SI-southern interior

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
CNI	2	0.6264266	0.313213	13.8414	0.0001
Error	24	0.5430881	0.022629		
C. Total	26	1.1695147			

Oneway Analysis of Long term mean spring TP By CNI
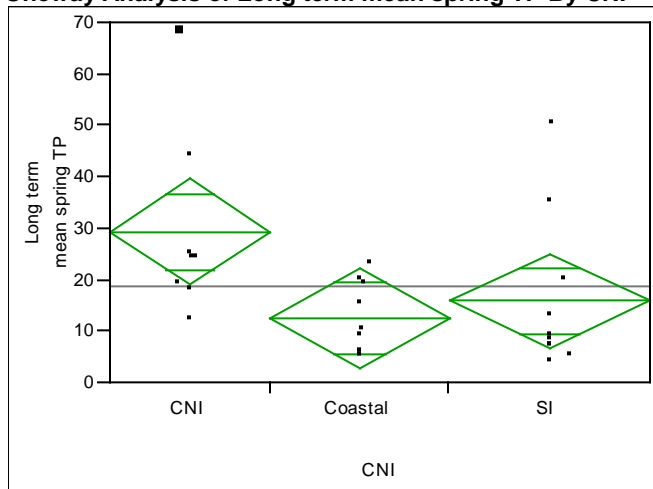
CNI- central and northern interior; SI-southern interior

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
CNI	2	1326.6778	663.339	3.3227	0.0532
Error	24	4791.3222	199.638		
C. Total	26	6118.0000			

APPENDIX 5A Correlation (r) between lake annual spring TN concentration (µg /L) and antecedent (yr-1) annual mean discharge (m3/s) at proximate river sites.

Area	Drainage	River	Lake	*r*
Coastal	Coastal	Cowichan	Shawnigan	-0.275
			St Mary	0.046
			Prospect	-0.080
			Quamichan	0.450
			Lizard	-0.547
			Stocking	-0.292
			Maxwell	-0.030
			Glen	0.219
			Fork	-0.559
Interior	Columbia	Okanagan	Ellison	-0.198
			Osoyoos	-0.051
			Skaha	-0.098
			Okanagan	0.201
			Kalamalka	0.215
			Wood	-0.082
			Christina	-0.009
	Shuswap	South Thompson	Sugar	-0.185
			Mabel	0.070
			Mara	0.079
	Fraser	Chilcoten	Lac La Hache	-0.227
			Chimney	0.541
			Horse	0.445
			Williams	-0.028
			Tabor	-0.127
	Skeena	Bulkley	Kathlyn	-0.851
	Peace	Beatton	Charlie	0.989

APPENDIX 5B Correlation (r) between lake annual spring TP concentration (μg /L) and antecedent (yr-1) annual mean discharge (m3/s) at proximate river sites.

Area	Drainage	River	Lake	*r*
Coastal	Coastal	Cowichan	Shawnigan	0.111
			St Mary	0.060
			Prospect	0.308
			Quamichan	0.110
			Stocking	-0.081
			Fork	0.020
			Glen	0.443
			Maxwell	-0.049
			Lizard	0.020
Interior	Columbia	Okanagan	Ellison	-0.083
			Osoyoos	-0.003
			Skaha	0.021
			Okanagan	0.569
			Wood	-0.034
			Kalamalka	0.206
			Christina	0.557
	Shuswap	South Thompson	Mara	0.228
			Sugar	0.109
			Mabel	0.215
	Fraser	Chilcoten	Williams	-0.280
			Chimney	0.390
			Lac la Hache	-0.165
			Horse	0.329
			Tabor	-0.004
	Skeena	Bulkley	Kathyln	-0.024
	Peace	Beatton	Charlie	0.245

APPENDIX 6A Pearson product moment correlations (*r*) for spring total nitrogen among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Chimney	Lac La Hache	0.205	10	0.570
Chimney	Christina	-0.243	11	0.472
Chimney	Ellison	-0.696	12	0.012
Chimney	Kalamalka	0.682	12	0.015
Chimney	Sugar	-0.332	12	0.291
Chimney	Osoyoos	-0.307	13	0.307
Chimney	Skaha	-0.622	13	0.023
Chimney	Okanagan	0.079	13	0.797
Chimney	Skaha	-0.272	13	0.369
Chimney	Mabel	-0.038	13	0.902
Chimney	Mara	0.097	13	0.751
Christina	Ellison	0.035	22	0.877
Christina	Wood	0.219	23	0.314
Christina	Osoyoos	0.314	24	0.135
Christina	Skaha	0.403	24	0.051
Christina	Okanagan	-0.159	24	0.457
Christina	Kalamalka	-0.382	24	0.065
Fork	Osoyoos	-0.417	10	0.230
Fork	Skaha	-0.411	10	0.238
Fork	Okanagan	-0.529	10	0.116
Fork	Kalamalka	0.236	10	0.512
Fork	Wood	0.263	10	0.462
Fork	Christina	-0.594	10	0.070
Fork	Sugar	-0.494	10	0.147
Fork	Mabel	0.387	10	0.269
Fork	Mara	-0.308	10	0.387
Fork	St Mary	-0.492	10	0.149
Fork	Prospect	0.008	10	0.982
Glen	Christina	0.786	10	0.007
Glen	Wood	-0.297	11	0.374
Glen	Ellison	-0.405	12	0.191
Glen	Osoyoos	0.552	12	0.063
Glen	Skaha	-0.012	12	0.970
Glen	Okanagan	0.046	12	0.887
Glen	Kalamalka	-0.166	12	0.605
Glen	Sugar	0.593	12	0.042
Glen	Mabel	-0.074	12	0.818
Glen	Mara	0.061	12	0.851
Glen	Shaw nigan	0.173	12	0.590
Horse	Chimney	0.141	10	0.698
Horse	Lac La Hache	0.335	11	0.314
Horse	Ellison	-0.051	15	0.857
Horse	Kalamalka	-0.088	15	0.756
Horse	Christina	-0.127	15	0.651
Horse	Sugar	0.394	15	0.147
Horse	Osoyoos	0.006	16	0.984
Horse	Skaha	-0.234	16	0.383
Horse	Okanagan	-0.205	16	0.447
Horse	Wood	-0.606	16	0.013
Horse	Mabel	-0.026	16	0.925
Horse	Mara	0.031	16	0.910
Kalamalka	Ellison	0.039	27	0.848
Kalamalka	Osoyoos	-0.171	30	0.365
Kalamalka	Skaha	-0.495	30	0.005
Kalamalka	Okanagan	0.182	30	0.336
Lac La Hache	Christina	0.099	14	0.737
Lac La Hache	Sugar	0.066	17	0.800
Lac La Hache	Ellison	0.171	18	0.497
Lac La Hache	Kalamalka	0.276	18	0.268
Lac La Hache	Wood	0.341	18	0.166
Lac La Hache	Osoyoos	-0.630	19	0.004
Lac La Hache	Skaha	-0.359	19	0.131
Lac La Hache	Okanagan	0.409	19	0.082
Lac La Hache	Mabel	0.595	19	0.007
Lac La Hache	Mara	0.317	19	0.186
Lizard	Wood	0.294	10	0.410
Lizard	Shaw nigan	0.601	10	0.066
Lizard	Ellison	0.306	11	0.359
Lizard	Osoyoos	0.152	11	0.655
Lizard	Skaha	0.004	11	0.991
Lizard	Okanagan	-0.106	11	0.757
Lizard	Kalamalka	0.258	11	0.444
Lizard	Sugar	0.490	11	0.126
Lizard	Mabel	0.319	11	0.339
Lizard	Mara	0.269	11	0.424
Mabel	Christina	0.055	24	0.799
Mabel	Ellison	0.533	28	0.004
Mabel	Sugar	0.010	28	0.960
Mabel	Kalamalka	0.190	29	0.322
Mabel	Wood	0.490	29	0.007
Mabel	Osoyoos	-0.157	30	0.406
Mabel	Skaha	-0.091	30	0.632
Mabel	Okanagan	0.588	30	0.001
Mara	Christina	-0.060	24	0.779
Mara	Ellison	0.210	28	0.283
Mara	Sugar	0.160	28	0.416
Mara	Wood	0.344	29	0.067
Mara	Kalamalka	-0.104	30	0.584
Mara	Mabel	0.371	30	0.043
Mara	Osoyoos	-0.047	31	0.804
Mara	Skaha	0.146	31	0.434
Mara	Okanagan	0.157	31	0.399
Maxw ell	Lac La Hache	0.825	10	0.003
Maxw ell	Horse	0.604	10	0.065
Maxw ell	Prospect	-0.269	12	0.398
Maxw ell	Williams	-0.109	15	0.699
Maxw ell	St Mary	-0.289	15	0.297
Maxw ell	Christina	-0.240	17	0.353
Maxw ell	Shaw nigan	0.239	18	0.340
Maxw ell	Ellison	0.220	19	0.365
Maxw ell	Wood	0.021	19	0.933
Maxw ell	Osoyoos	-0.267	20	0.254
Maxw ell	Skaha	-0.240	20	0.309
Maxw ell	Okanagan	0.204	20	0.388

Appendix 6A continued. Pearson product moment correlations (*r*) for spring total nitrogen among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Maxwell	Kalamalka	0.227	20	0.335
Maxwell	Sugar	-0.285	20	0.224
Maxwell	Mabel	0.184	20	0.438
Maxwell	Mara	-0.107	20	0.654
Okanagan	Ellison	0.378	28	0.047
Okanagan	Osoyoos	-0.400	31	0.026
Okanagan	Skaha	-0.377	31	0.036
Osoyoos	Ellison	0.105	28	0.594
Prospect	Horse	0.067	11	0.845
Prospect	Williams	-0.103	11	0.762
Prospect	Ellison	-0.086	14	0.771
Prospect	Wood	0.164	14	0.576
Prospect	Christina	0.265	14	0.360
Prospect	Shawnigan	-0.375	14	0.187
Prospect	Osoyoos	0.377	15	0.166
Prospect	Skaha	0.190	15	0.498
Prospect	Okanagan	-0.208	15	0.456
Prospect	Kalamalka	-0.493	15	0.062
Prospect	Sugar	0.468	15	0.079
Prospect	Mabel	-0.032	15	0.910
Prospect	Mara	-0.287	15	0.299
Prospect	St Mary	0.399	15	0.141
Quamichan	Osoyoos	0.103	10	0.776
Quamichan	Skaha	-0.145	10	0.689
Quamichan	Okanagan	0.478	10	0.162
Quamichan	Kalamalka	0.022	10	0.953
Quamichan	Wood	0.189	10	0.600
Quamichan	Christina	-0.054	10	0.883
Quamichan	Sugar	-0.140	10	0.699
Quamichan	Mabel	-0.086	10	0.812
Quamichan	Mara	0.135	10	0.710
Quamichan	St Mary	0.399	10	0.254
Quamichan	Prospect	-0.049	10	0.893
Shawnigan	Chimney	-0.465	10	0.175
Shawnigan	Horse	0.097	13	0.753
Shawnigan	Lac La Hache	0.658	15	0.008
Shawnigan	Williams	0.067	17	0.799
Shawnigan	Christina	0.321	21	0.156
Shawnigan	Ellison	0.611	24	0.002
Shawnigan	Sugar	0.094	24	0.661
Shawnigan	Wood	0.699	25	0.000
Shawnigan	Kalamalka	-0.036	26	0.861
Shawnigan	Mabel	0.524	26	0.006
Shawnigan	Osoyoos	-0.422	27	0.028
Shawnigan	Skaha	0.049	27	0.807
Shawnigan	Okanagan	0.163	27	0.417
Shawnigan	Mara	0.314	27	0.111
Skaha	Ellison	0.278	28	0.152
Skaha	Osoyoos	0.383	31	0.034
St Mary	Chimney	-0.314	12	0.321
St Mary	Lac La Hache	0.115	15	0.683
St Mary	Horse	0.096	15	0.734
St Mary	Williams	0.313	15	0.256

Lake pair		Pearson *r*	Years	*p*
St Mary	Christina	-0.251	19	0.299
St Mary	Sugar	-0.010	21	0.967
St Mary	Shawnigan	0.191	21	0.407
St Mary	Ellison	0.460	22	0.031
St Mary	Kalamalka	-0.135	22	0.548
St Mary	Wood	0.128	22	0.570
St Mary	Osoyoos	-0.007	23	0.974
St Mary	Skaha	0.045	23	0.838
St Mary	Okanagan	0.409	23	0.053
St Mary	Mabel	0.125	23	0.569
St Mary	Mara	0.291	23	0.177
Sugar	Christina	0.335	24	0.110
Sugar	Ellison	-0.064	26	0.757
Sugar	Wood	0.003	27	0.987
Sugar	Osoyoos	0.228	28	0.244
Sugar	Skaha	0.026	28	0.894
Sugar	Okanagan	-0.113	28	0.567
Sugar	Kalamalka	-0.326	28	0.091
Williams	Lac La Hache	0.170	11	0.617
Williams	Horse	-0.002	11	0.996
Williams	Christina	0.016	17	0.953
Williams	Ellison	0.238	18	0.341
Williams	Wood	-0.292	18	0.240
Williams	Osoyoos	0.033	19	0.894
Williams	Skaha	-0.082	19	0.737
Williams	Okanagan	0.084	19	0.732
Williams	Kalamalka	0.107	19	0.663
Williams	Sugar	-0.176	19	0.472
Williams	Mabel	0.056	19	0.821
Williams	Mara	0.051	19	0.836
Wood	Ellison	0.494	27	0.009
Wood	Kalamalka	-0.144	28	0.464
Wood	Osoyoos	-0.272	29	0.153
Wood	Skaha	0.402	29	0.030
Wood	Okanagan	0.266	29	0.164

APPENDIX 6B Pearson product moment correlations (*r*) for spring total phosphorus among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Charlie	Christina	-0.230	11	0.496
Charlie	Williams	-0.375	13	0.207
Charlie	Tabor	0.213	13	0.486
Charlie	Lac La Hache	-0.212	13	0.487
Charlie	Ellison	0.430	14	0.125
Charlie	Osoyoos	-0.132	14	0.652
Charlie	Skaha	-0.362	14	0.203
Charlie	Okanagan	-0.462	14	0.096
Charlie	Wood	-0.076	14	0.796
Charlie	Kalamalka	-0.439	14	0.116
Charlie	Sugar	0.105	14	0.722
Charlie	Mabel	-0.111	14	0.706
Charlie	Mara	-0.371	14	0.192
Chimney	Christina	0.814	14	0.000
Chimney	Williams	0.232	14	0.425
Chimney	Sugar	0.326	15	0.236
Chimney	Ellison	-0.144	16	0.594
Chimney	Osoyoos	0.041	16	0.880
Chimney	Skaha	0.004	16	0.987
Chimney	Okanagan	0.343	16	0.193
Chimney	Wood	-0.252	16	0.346
Chimney	Kalamalka	0.643	16	0.007
Chimney	Mabel	0.724	16	0.002
Chimney	Mara	0.789	16	0.000
Christina	Ellison	0.237	23	0.276
Christina	Osoyoos	0.082	24	0.702
Christina	Skaha	0.225	24	0.289
Christina	Okanagan	0.678	24	0.000
Christina	Wood	0.152	24	0.478
Christina	Kalamalka	0.758	24	0.000
Fork	Williams	0.334	11	0.316
Fork	Prospect	0.515	11	0.105
Fork	Tabor	0.809	12	0.001
Fork	Ellison	0.412	13	0.162
Fork	Osoyoos	0.062	13	0.840
Fork	Skaha	0.585	13	0.036
Fork	Okanagan	0.598	13	0.031
Fork	Wood	-0.033	13	0.915
Fork	Kalamalka	0.716	13	0.006
Fork	Christina	0.739	13	0.004
Fork	Sugar	0.731	13	0.005
Fork	Mabel	0.725	13	0.005
Fork	Mara	0.748	13	0.003
Fork	Shaw nigan	0.456	13	0.118

Lake pair		Pearson *r*	Years	*p*
Fork	St Mary	-0.087	13	0.778
Glen	Kathyln	-0.116	10	0.749
Glen	Fork	0.586	12	0.045
Glen	Horse	0.569	13	0.042
Glen	Chimney	0.531	14	0.051
Glen	Charlie	-0.006	14	0.982
Glen	Quamichan	-0.027	14	0.926
Glen	Stocking	0.046	15	0.871
Glen	Lac La Hache	0.410	20	0.073
Glen	Tabor	0.747	21	0.000
Glen	Christina	0.640	22	0.001
Glen	Shaw nigan	0.440	22	0.040
Glen	Prospect	0.320	22	0.146
Glen	Williams	0.304	23	0.158
Glen	Ellison	0.205	25	0.325
Glen	Osoyoos	0.059	25	0.780
Glen	Skaha	0.271	25	0.190
Glen	Okanagan	0.555	25	0.004
Glen	Wood	0.083	25	0.694
Glen	Kalamalka	0.669	25	0.000
Glen	Sugar	0.210	25	0.313
Glen	Mabel	0.529	25	0.007
Glen	Mara	0.638	25	0.001
Glen	St Mary	-0.311	25	0.130
Horse	Tabor	0.723	11	0.012
Horse	Lac La Hache	0.362	11	0.274
Horse	Chimney	0.540	12	0.070
Horse	Christina	0.639	14	0.014
Horse	Sugar	0.379	14	0.181
Horse	Williams	0.454	14	0.103
Horse	Ellison	0.216	15	0.439
Horse	Osoyoos	-0.136	15	0.630
Horse	Skaha	-0.110	15	0.697
Horse	Okanagan	-0.034	15	0.906
Horse	Wood	-0.266	15	0.339
Horse	Kalamalka	0.668	15	0.007
Horse	Mabel	0.616	15	0.014
Horse	Mara	0.652	15	0.008
Kalamalka	Ellison	0.245	29	0.200
Kalamalka	Osoyoos	0.179	31	0.335
Kalamalka	Skaha	0.313	31	0.086
Kalamalka	Okanagan	0.468	31	0.008
Kalamalka	Wood	0.179	31	0.334

Appendix 6B continued. Pearson product moment correlations (*r*) for spring total phosphorus among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Kathyln	Ellison	-0.362	10	0.304
Kathyln	Osoyoos	0.217	10	0.547
Kathyln	Skaha	0.365	10	0.299
Kathyln	Okanagan	0.219	10	0.543
Kathyln	Wood	0.344	10	0.330
Kathyln	Kalamalka	0.285	10	0.424
Kathyln	Sugar	-0.153	10	0.674
Kathyln	Mabel	-0.064	10	0.860
Kathyln	Mara	0.200	10	0.580
Lac La Hache	Chimney	0.232	11	0.492
Lac La Hache	Tabor	0.481	16	0.059
Lac La Hache	Christina	0.500	18	0.034
Lac La Hache	Sugar	0.482	22	0.023
Lac La Hache	Ellison	0.322	23	0.134
Lac La Hache	Williams	0.563	23	0.005
Lac La Hache	Osoyoos	0.443	24	0.030
Lac La Hache	Skaha	0.681	24	0.000
Lac La Hache	Okanagan	0.406	24	0.049
Lac La Hache	Wood	0.496	24	0.014
Lac La Hache	Kalamalka	0.677	24	0.000
Lac La Hache	Mabel	0.611	24	0.002
Lac La Hache	Mara	0.524	24	0.009
Lizard	Kathyln	0.183	10	0.612
Lizard	Quamichan	-0.377	10	0.283
Lizard	Lac La Hache	0.372	13	0.211
Lizard	Charlie	-0.289	13	0.338
Lizard	Stocking	-0.120	14	0.682
Lizard	Christina	-0.113	15	0.688
Lizard	Prospect	-0.495	16	0.051
Lizard	Williams	0.382	17	0.130
Lizard	Tabor	0.068	17	0.794
Lizard	Shaw nigan	-0.024	17	0.927
Lizard	Maxwell	-0.180	17	0.489
Lizard	Ellison	-0.217	18	0.388
Lizard	Osoyoos	-0.198	18	0.430
Lizard	Skaha	-0.058	18	0.820
Lizard	Okanagan	0.046	18	0.855
Lizard	Wood	0.034	18	0.894
Lizard	Kalamalka	0.114	18	0.654
Lizard	Sugar	-0.062	18	0.807
Lizard	Mabel	0.018	18	0.944
Lizard	Mara	0.040	18	0.875
Lizard	St Mary	-0.349	18	0.155
Lizard	Glen	0.190	18	0.449

Lake pair		Pearson *r*	Years	*p*
Mabel	Christina	0.702	24	0.000
Mabel	Sugar	0.600	28	0.001
Mabel	Ellison	0.309	29	0.103
Mabel	Osoyoos	0.187	30	0.321
Mabel	Skaha	0.433	30	0.017
Mabel	Okanagan	0.517	30	0.003
Mabel	Wood	0.191	30	0.313
Mabel	Kalamalka	0.739	30	0.000
Mara	Christina	0.767	24	0.000
Mara	Sugar	0.566	28	0.002
Mara	Ellison	0.294	29	0.122
Mara	Mabel	0.768	30	0.000
Mara	Osoyoos	0.112	31	0.547
Mara	Skaha	0.286	31	0.118
Mara	Okanagan	0.576	31	0.001
Mara	Wood	0.171	31	0.359
Mara	Kalamalka	0.849	31	0.000
Maxw ell	Chimney	0.772	11	0.005
Maxw ell	Horse	-0.106	11	0.757
Maxw ell	Quamichan	0.034	12	0.916
Maxw ell	Fork	0.523	12	0.081
Maxw ell	Charlie	-0.166	13	0.589
Maxw ell	Stocking	0.279	14	0.334
Maxw ell	Lac La Hache	0.232	16	0.388
Maxw ell	Christina	0.623	19	0.004
Maxw ell	Tabor	0.468	19	0.043
Maxw ell	Prospect	0.307	19	0.201
Maxw ell	Williams	-0.052	20	0.827
Maxw ell	Shaw nigan	0.635	20	0.003
Maxw ell	Glen	0.210	21	0.362
Maxw ell	Ellison	0.132	22	0.559
Maxw ell	Osoyoos	0.376	22	0.085
Maxw ell	Skaha	0.385	22	0.077
Maxw ell	Okanagan	0.368	22	0.092
Maxw ell	Wood	0.323	22	0.142
Maxw ell	Kalamalka	0.723	22	0.000
Maxw ell	Sugar	0.353	22	0.107
Maxw ell	Mabel	0.645	22	0.001
Maxw ell	Mara	0.608	22	0.003
Maxw ell	St Mary	-0.057	22	0.802
Okanagan	Ellison	0.335	29	0.075
Okanagan	Osoyoos	0.328	31	0.072
Okanagan	Skaha	0.569	31	0.001
Osoyoos	Ellison	0.348	29	0.064

Appendix 6B continued. Pearson product moment correlations (*r*) for spring total phosphorus among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Prospect	Charlie	-0.034	12	0.918
Prospect	Horse	0.769	13	0.002
Prospect	Chimney	0.654	15	0.008
Prospect	Lac La Hache	0.255	18	0.307
Prospect	Tabor	0.547	19	0.015
Prospect	Christina	0.725	21	0.000
Prospect	Williams	0.390	22	0.073
Prospect	Shaw nigan	0.559	23	0.006
Prospect	Ellison	0.265	24	0.211
Prospect	Sugar	0.554	24	0.005
Prospect	Mabel	0.652	24	0.001
Prospect	St Mary	0.233	24	0.273
Prospect	Osoyoos	-0.152	25	0.469
Prospect	Skaha	0.260	25	0.209
Prospect	Okanagan	0.443	25	0.027
Prospect	Wood	0.255	25	0.219
Prospect	Kalamalka	0.562	25	0.003
Prospect	Mara	0.716	25	0.000
Quamichan	Lac La Hache	0.219	10	0.544
Quamichan	Horse	0.202	10	0.576
Quamichan	Williams	0.279	13	0.355
Quamichan	Shaw nigan	0.044	14	0.883
Quamichan	Prospect	0.182	14	0.534
Quamichan	Ellison	0.344	15	0.209
Quamichan	Osoyoos	0.139	15	0.620
Quamichan	Skaha	0.181	15	0.520
Quamichan	Okanagan	-0.243	15	0.383
Quamichan	Wood	0.580	15	0.023
Quamichan	Kalamalka	-0.096	15	0.733
Quamichan	Christina	0.013	15	0.965
Quamichan	Sugar	0.246	15	0.377
Quamichan	Mabel	0.080	15	0.777
Quamichan	Mara	-0.175	15	0.532
Quamichan	Tabor	-0.224	15	0.422
Quamichan	St Mary	0.331	15	0.228
Shaw nigan	Horse	-0.010	13	0.973
Shaw nigan	Charlie	-0.310	13	0.303
Shaw nigan	Chimney	0.277	14	0.337
Shaw nigan	Tabor	0.527	20	0.017
Shaw nigan	Lac La Hache	0.504	21	0.020
Shaw nigan	Christina	0.788	22	0.000
Shaw nigan	Sugar	0.442	25	0.027
Shaw nigan	Williams	0.280	25	0.175
Shaw nigan	Ellison	0.470	26	0.015

Lake pair		Pearson *r*	Years	*p*
Shaw nigan	Mabel	0.594	27	0.001
Shaw nigan	Osoyoos	0.307	28	0.112
Shaw nigan	Skaha	0.533	28	0.004
Shaw nigan	Okanagan	0.764	28	0.000
Shaw nigan	Wood	0.492	28	0.008
Shaw nigan	Kalamalka	0.799	28	0.000
Shaw nigan	Mara	0.567	28	0.002
Skaha	Ellison	0.318	29	0.093
Skaha	Osoyoos	0.485	31	0.006
St Mary	Kathyln	-0.165	10	0.649
St Mary	Charlie	-0.480	14	0.083
St Mary	Horse	-0.196	15	0.485
St Mary	Chimney	0.056	16	0.836
St Mary	Tabor	-0.499	22	0.018
St Mary	Christina	-0.095	23	0.666
St Mary	Lac La Hache	0.079	23	0.720
St Mary	Shaw nigan	0.095	26	0.644
St Mary	Sugar	0.323	27	0.101
St Mary	Williams	-0.035	27	0.861
St Mary	Ellison	0.280	29	0.141
St Mary	Osoyoos	0.089	29	0.646
St Mary	Skaha	0.239	29	0.213
St Mary	Okanagan	0.049	29	0.802
St Mary	Wood	0.453	29	0.014
St Mary	Kalamalka	-0.110	29	0.571
St Mary	Mabel	-0.146	29	0.450
St Mary	Mara	-0.059	29	0.761
Stocking	Christina	0.580	12	0.048
Stocking	Charlie	-0.469	12	0.124
Stocking	Lac La Hache	0.561	13	0.046
Stocking	Prospect	0.572	13	0.041
Stocking	Tabor	0.220	14	0.450
Stocking	Shaw nigan	0.197	14	0.500
Stocking	Ellison	0.134	15	0.634
Stocking	Osoyoos	0.220	15	0.431
Stocking	Skaha	0.494	15	0.061
Stocking	Okanagan	0.094	15	0.739
Stocking	Wood	0.396	15	0.144
Stocking	Kalamalka	0.678	15	0.006
Stocking	Sugar	0.588	15	0.021
Stocking	Mabel	0.548	15	0.034
Stocking	Mara	0.680	15	0.005
Stocking	Williams	0.532	15	0.041
Stocking	St Mary	0.591	15	0.020

Appendix 6B continued. Pearson product moment correlations (*r*) for spring total phosphorus among BC lakes.

Lake pair		Pearson *r*	Years	*p*
Sugar	Christina	0.573	24	0.003
Sugar	Ellison	0.388	27	0.045
Sugar	Osoyoos	0.060	28	0.761
Sugar	Skaha	0.415	28	0.028
Sugar	Okanagan	0.552	28	0.002
Sugar	Wood	0.345	28	0.073
Sugar	Kalamalka	0.360	28	0.060
Tabor	Chimney	0.712	11	0.014
Tabor	Christina	0.715	19	0.001
Tabor	Williams	0.278	20	0.235
Tabor	Ellison	0.187	22	0.406
Tabor	Osoyoos	-0.070	22	0.758
Tabor	Skaha	0.116	22	0.608
Tabor	Okanagan	0.389	22	0.073
Tabor	Wood	-0.215	22	0.336
Tabor	Kalamalka	0.826	22	0.000
Tabor	Sugar	0.285	22	0.199
Tabor	Mabel	0.733	22	0.000
Tabor	Mara	0.827	22	0.000
Williams	Christina	0.264	22	0.236
Williams	Sugar	0.172	26	0.402
Williams	Ellison	-0.076	27	0.705
Williams	Osoyoos	0.017	28	0.930
Williams	Skaha	0.418	28	0.027
Williams	Okanagan	0.154	28	0.433
Williams	Wood	0.310	28	0.108
Williams	Kalamalka	0.487	28	0.009
Williams	Mabel	0.290	28	0.135
Williams	Mara	0.417	28	0.027
Wood	Ellison	0.362	29	0.054
Wood	Osoyoos	0.428	31	0.016
Wood	Skaha	0.774	31	0.000
Wood	Okanagan	0.524	31	0.002

APPENDIX 7A Testing null hypothesis: lake pair correlations for spring TN not different from zero.

- o H_0: correlations not significantly different from zero using all years and lakes for those lake pairs with more than 9 yrs of concurrent data.
- o H_A: correlations different from zero.

Distributions
TN
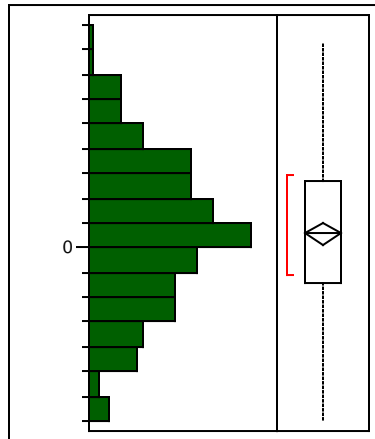
Test Mean=value

Hypothesized Value	0
Actual Estimate	0.05797
df	191
Std Dev	0.30783

	t Test
Test Statistic	2.6092
Prob > |t|	0.0098
Prob > t	0.0049
Prob < t	0.9951
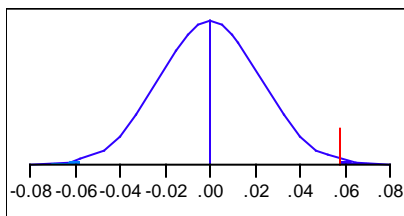
- o Result: t=2.609, p<0.01, df=191
- o Conclusion: reject H_0; mean of correlation significantly different than zero

APPENDIX 7B Testing null hypothesis: lake pair correlations for spring TP not different from zero.

- o H_0: correlations not significantly different from zero using all years and lakes for those lake pairs with more than 9 yrs of concurrent data.
- o H_A: correlations different from zero.

Distributions of Pearson Correlations (r)
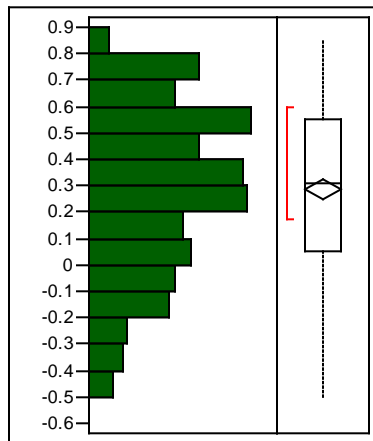
Test Mean=value

Hypothesized Value	0
Actual Estimate	0.28435
df	295
Std Dev	0.31924

	t Test
Test Statistic	15.3244
Prob > |t|	<.0001
Prob > t	<.0001
Prob < t	1.0000
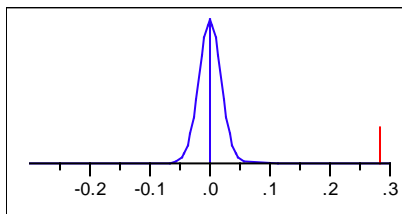
- o   Result: t=15.32, p<0.0001, DF=295
- o   Conclusion: reject H_0; mean of correlation significantly different than zero

APPENDIX 8A Spring total nitrogen coherence (r) grouped by three ranges of lake water residence time (<1 yr, >1 yr to 5 yr, >5 yrs).

Water residence time $\leq$1 year

	Sugar	Mara	Williams	Tabor	Prospect	Fork	Glen	Lizard	Stocking
Osoyoos	0.228	-0.047	0.033	id	0.377	-0.417	0.552	0.152	id
Sugar		0.16	-0.176	id	0.468	-0.4494	0.593	0.49	id
Mara			0.051	id	-0.268	-0.308	0.061	0.269	id
Williams				id	-0.103	id	id	id	id
Tabor					id	0.008	id	id	id
Prospect						id	id	id	id
Fork							id	id	id
Glen								id	id
Lizard									id
Stocking									

mean r = 0.083; standard deviation=0.315; n=20; ; id=insufficient data (< 10 pairs)

Water residence time >1 year to < 5 years

	Skaha	Christina	Mabel	Horse	Kathlyn	Charlie	Quamichan	Shawnigan
Ellison	0.278	0.035	0.533	-0.051	id	id	id	0.616
Skaha		0.403	-0.091	-0.234	id	id	-0.154	0.049
Christina			0.055	-0.127	id	id	-0.045	0.32
Mabel				-0.026	id	id	-0.086	0.524
Horse					id	id	id	0.097
Kathlyn						id	id	id
Charlie							id	id
Quamichan								id

mean r = 0.116; standard deviation=0.262; n=18 ; id=insufficient data (< 10 pairs)

Water residence time > 5 years

	Kalamalka	Okanagan	Chimney	St Mary	Maxwell
Wood	-0.144	0.266	-0.272	0.128	0.021
Kalamalka		0.182	0.682	-0.326	0.227
Okanagan			0.079	0.409	0.204
Chimney				-0.314	id
St Mary					-0.289
Maxwell					

mean r =0.061; standard deviation=0.302; n=14; ; id=insufficient data (< 10 pairs)

APPENDIX 8B Spring total phosphorus coherence (*r*) grouped by approximate lake pair quartiles with water residence times of < 0.75 years, 0.75-1.2 years, 1.2 -5 years, and > 5 years.

Water residence time ≤0.75 year

	Mara	Glen	Sugar	Williams	Osoyoos
Fork	0.748	0.586	0.731	0.334	0.062
Mara		0.638	0.566	0.417	0.112
Glen			0.21	0.304	0.059
Sugar				0.172	0.06
Williams					0.017

mean *r* = 0.334; standard deviation=0.262; n=15; id=insufficient data (< 10 pairs)

Water residence time 0.75-1.2 years

	Lizard	Prospect	Stocking	Ellison	Skaha
Tabor	0.068	0.547	0.22	0.187	0.116
Lizard		-0.495	-0.12	-0.217	-0.058
Prospect			0.572	0.265	0.26
Stocking				0.134	0.494
Ellison					0.092

mean *r* = 0.138; standard deviation=0.288; n=15; id=insufficient data (< 10 pairs)

Water residence time 1.2 - 5 years

	Shawnigan	Quamichan	Mabel	Horse	Christina	Charlie
Kathlyn	id	id	-0.064	id	id	id
Shawnigan		0.044	0.594	-0.01	0.788	-0.31
Quamichan			0.08	id	0.013	id
Mabel				0.616	0.702	-0.111
Horse					0.639	id
Christina						-0.23

mean *r* = 0.212; standard deviation=0.392; n=13; id=insufficient data (< 10 pairs)

Water residence time >5 years

	Lac La Hache	St Mary	Chimney	Wood	Kalamalka	Okanagan
Maxwell	id	id	id	0.323	0.723	0.368
Lac La Hache		id	0.232	0.495	0.677	0.406
St Mary			-0.095	0.453	-0.11	0.049
Chimney				-0.252	0.643	0.343
Wood					0.179	0.524
Kalamalka						0.468

mean *r* = 0.319; standard deviation=0.285; n=17; id=insufficient data (< 10 pairs)

APPENDIX 9A Spring total nitrogen coherence (*r*) among lake pairs grouped by 3 ranges of TN concentration: < 200 μg /L, 200-400 μg /L, and >400 μg /L.

Spring mean total nitrogen concentration < 200 ug/L

	Christina	Stocking	Mabel	Sugar	Mara	Okanagan
Lizard	id	id	0.319	0.49	0.29	-0.106
Christina		id	0.055	0.335	-0.06	-0.159
Stocking			id	id	id	id
Mabel				0.01	0.371	0.588
Sugar					0.16	-0.113
Mara						0.157

mean r=0.167; standard deviation=0.238; n=14; ; id=insufficient data (< 10 pairs)

Spring mean total nitrogen concentration range: 200-400 ug/L

Fork	Shawnigan	Maxwell	Skaha	Kalamalka	Glen	Kathlyn	Osoyoos	Horse	Prospect
Fork	id	id	-0.411	id	id	id	-0.417		0.008
Shawnigan		0.239	0.049	-0.036	0.173	id	-0.422	0.097	-0.375
Maxwell			-0.24	0.227	id	id	-0.267	0.604	-0.269
Skaha				-0.495	-0.012	id	0.387	-0.234	0.19
Kalamalka					-0.166	id	-0.171	-0.088	-0.493
Glen						id	0.552	id	id
Kathlyn							id	id	id
Osoyoos								0.006	0.377
Horse									0.067

mean r=-0.04; standard deviation=0.0.309; n=28; ; id=insufficient data (< 10 pairs)

Spring mean total nitrogen concentration range: > 400 ug/L

Quamichan	Tabor	Ellison	St Mary	Wood	Lac La Hache	Charlie	Williams	Chimney
Quamichan	id	id	0.399	0.189	id	id	id	id
Tabor		id	id	id	id	id	id	id
Ellison			0.46	0.494	0.171	id	0.238	-0.696
St Mary				0.128	0.115	id	0.3123	-0.314
Wood					0.341	id	-0.292	-0.272
Lac le Hache						id	0.17	0.205
Charlie							id	id
Williams								id

mean r=0.103; standard deviation=0.329; n=16; id=insufficient data (< 10 pairs)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
<200 ug/L	14	2.337	0.166929	0.056748
200-400 ug/L	26	-0.11	-0.00423	0.092673
>400 ug/L	16	1.6483	0.103019	0.108216

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.292206	2	0.146103	1.655361	0.200746	3.171626
Within Groups	4.677799	53	0.08826			
Total	4.970005	55				

APPENDIX 9B Spring total phosphorus coherence (*r*) among lake pairs grouped by 5 ranges of TP concentration: <10 μg /L, 10-20 μg /L, and >25 μg /L.

Spring TP < 10 ug/L

	Sugar	Lizard	Mabel	Stocking	Okanagan	Christina
Shawnigan	0.442	-0.024	0.594	0.194	0.764	0.788
Sugar		-0.062	0.600	0.588	0.552	0.573
Lizard			0.018	-0.120	0.046	-0.113
Mabel				0.279	0.517	0.702
Stocking					id	0.580
Okanagan						0.678

all sites: mean *r*= 0.380; standard deviation 0.317; n=20; id = insufficient data (lake pairs < 10)
Lizard data removed: mean *r* =0.561, standard deviation 0.0.167; n=14

Spring TP 10-20 ug/L

	Fork	Maxwell	Mara	Skaha	Lac la Hache	Prospect	Chimney
Kalamalka	0.716	0.723	0.849	0.313	0.677	0.562	0.643
Fork		0.527	0.748	0.585	id	0.515	id
Maxwell			0.608	0.385	0.611	0.307	0.772
Mara				0.286	0.524	0.716	0.789
Skaha					0.681	0.260	0.004
Lac la Hache						0.255	0.232
Prospect							0.654

all sites: mean *r*= 0.536; standard deviation 0.216; n=26

Spring TP > 20 ug/L

	Osoyoos	Glen	Quamichan	Kathyln	St Mary	Tabor	Ellison	Charlie	Wood	Williams
Horse	-0.136	id	id	id	id	0.723	0.216	id	-0.266	0.454
Osoyoos		0.059	0.139	0.217	0.089	-0.070	id	-0.132	0.428	0.017
Glen			id	-0.116	-0.311	0.747	0.205	-0.006	0.083	0.304
Quamichan				id	0.331	-0.224	0.344	id	0.580	0.279
Kathyln					id	id	-0.362	id	0.344	id
St Mary						-0.499	0.280	-0.480	0.453	-0.035
Tabor							0.187	0.213	-0.215	0.278
Ellison								0.430	0.362	-0.076
Charlie									-0.076	-0.315
Wood										0.310

all sites: mean *r*= 0.110; standard deviation 0.0.307; n=42
Charlie data removed: mean *r* =0.147, standard deviation 0.294; n=32

Anova: Single Factor with all data

SUMMARY

Groups	Count	Sum	Average	Variance
<10 ug/L	20	7.596	0.3798	0.100649
10-20 ug/L	26	13.942	0.536231	0.046451
> 20 ug/L	42	4.6279	0.110188	0.094182

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.09086691	2	1.545433	18.94174	1.57337E-07	3.103839
Within Groups	6.93504754	85	0.081589			
Total	10.0259145	87				