Drivers of Lake Water Quality in the Beaver River Watershed of Alberta

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Prepared for: Beaver River Watershed Alliance & Alberta Environment and Sustainable Resource Development

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Executive Summary

The primary goal of this report was to identify potential suitable watershed-scale landscape indicators that influence lake water chemistry. Relationships were derived between the water quality of 25 lakes in the Beaver River Watershed and lake morphometry (i.e., size and shape), natural watershed metrics, and land cover and use. Models were derived for each water quality parameter that best describe the variability in the dataset. The following summarizes key messages from the results of the analyses.

In general, both natural landscape factors, such as lake depth, as well as indicators of human disturbance, such as agricultural intensity metrics and disturbance-associated land use cover, were significantly related to nutrients, ions and metals in lakes.

Nutrients and algal biomass

Nutrient concentrations are higher in shallow lakes where the water column mixes during the summer months. The same pattern exists for algal biomass and water clarity, which are highly related to phosphorus concentrations. This pattern is so striking that we suggest that shallow and deep lakes be managed separately since it has been shown that they respond differently to climate warming and eutrophication.

Nutrient concentrations increase in response to watershed disturbance and agricultural intensity metrics, although this response varied depending on the fractionation of nutrients. That is, dissolved phosphorus is a good indicator of agricultural use but particulate phosphorus is not. The relatively poor relationship between total phosphorus and agricultural use metrics is due to this dual response in the phosphorus fractions.

Salts

The larger the watershed, the more dilute the lake water, which reflects the greater flushing of minerals and ions. In addition, salt concentrations were related to how much peatland and agriculture a watershed contains. The effect of a recent period of water-deficit was detected in areas where permanent cover (trees, peatlands) are less prominent. Peatlands seem to buffer watersheds from an increase in salinity.

Landscape position is also an important predictor of minerals and ions in Beaver River watershed lakes, but the relationship to it is somewhat complex. That is, lakes that are in high landscape position (more connected to climate and evaporation) and lakes that are low in landscape position (connected with regional groundwater systems) had higher salt concentrations and may be both at greater risk for salinization due to drought and/or climate change.

Some morphological variables associated with the 20-year drought seem to have a strong effect on water quality and future research should examine partitioning natural and climatic sources from anthropogenic sources of variation in water quality to aid in planning, land us management and risk assessment due to both climate shifts and human activity and development.

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Metals

In general metals tended to be related both to agricultural land cover and use metrics. Other metals (Zinc, Nickel, Cobalt, Chromium, and Iron) are related to maximum depth and water column mixing. The lower sample sizes for metals prevented derivation of water quality models.

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Introduction

In November 2010, the Beaver River Watershed Alliance (BRWA) released a report entitled "A Plan for Healthy Aquatic Ecosystems in the Beaver River Watershed," with the goal of protecting and managing the aquatic ecosystems within the Beaver River Watershed (BRW) while recognizing stakeholder values. Objectives stated in this plan include:

1. Describing and tracking aquatic ecosystem health over time;
2. Relating health to stressors which will support decision-making; and
3. Identifying strategies for managing the impact of stressors (identify conservation, mitigation and restoration opportunities).

This report addresses the second objective. Studying the relationship between people and environment health over time fosters a greater understanding of the innate nature of the watershed, what drives it to change, and what is the direction of this change. This understanding can support decisions about the future of human settlements, resource management, environmental protection, human health, economic development, etc. through balancing various private interests with public interests and identifying viable, workable options.

The overall goal of this report is to identify landscape metrics correlated with lake water quality parameters that may be used to monitor and model watershed-scale effects on lakes. Examining indicators of water quality characteristics will help determine natural and anthropogenic drivers of water quality such as natural watershed geography and land use practices. Suitable landscape indicators of water quality will help identify possible drivers of water quality degradation. Indicators of water quality can be used in conjunction with biotic indicators to aid in the management of lakes in the watershed and identify conservation, mitigation and restoration opportunities.

Methods

Data – Beaver River watershed metrics

Landscape metrics that were expected to influence water quality were tested against a suite of water quality parameters. Landscape metrics were categorized into three broad groups based on 1) lake morphometry, 3) watershed geography and 2) land cover and use.

Lake morphometry

- Lake morphometry (shape and size): Values for this metric were based on measurements reported in the Atlas of Alberta Lakes (http://sunsite.ualberta.ca) and Lakewatch Reports by the Alberta Lake Management Society (www.alms.ca).
- Lake mixing regime: These resources were also used to determine physical water mixing regimes of lakes. "Polymictic" lakes are those that have multiple water column mixing events during the summer. "Dimictic" lakes are those that only mix in the spring and fall.

Watershed geography

- Lake watershed area: This metric was defined based on Alberta Environment and Sustainable Resource Development's (AESRD) Base Features Derived Datasets for Watersheds, Digital Elevation Model (DEM), and Hydrography (Single Line Network, Hydropoints and Hydropolygons) layers.
- Lake landscape position: Each watershed polygon is associated with a Base Features Single Line Network stream, which has associated Strahler Order code (i.e., stream order) based on the connectivity within the stream network. Stream order increases with each stream confluence from the headwaters to the mouth of a river. Lake landscape position was established based on this stream order. Landscape positions 1 to 5 correspond to outflowing streams orders of 1 to 5. A landscape position of 0 is a lake that has no outflowing stream. Since there were unequal numbers of lakes in each landscape position, dummy variables were used to define landscape position, where lakes in positions 0-3 were grouped in one category and position 4 and 5 were grouped in another.
- Soils: Data was obtained from the Agricultural Land Resources Atlas of Alberta (2005). Soil group polygons from the Alberta Soil Survey were used to derive soil metrics using GIS analysis. Since soil groups in the BR Watershed are dominated by Gray Luvisols/Organics, soil group was expressed as the percentage of Gray Luvisols/Organics in the watershed.

Land cover & use

- Land cover: Metrics were derived in Arc View Spatial Analyst, a Geographical Information System (GIS), from data obtained from Ducks Unlimited Canada's Canadian Wetland Inventory (CWI). Sub-watershed boundaries were used to clip Ducks Unlimited Land Cover Inventory. All land cover variables were calculated as a percentage within each watershed polygon. Percentage land cover types are described in Table 1. Linear density of the watershed area was expressed as the linear kilometers of roads, railroads and cutlines, divided by watershed area.
- Agricultural use metrics: Five metrics, fertilizer expense, chemical expense, manure production, cultivation intensity and agricultural intensity, were obtained from the Alberta Department of Agriculture and Rural Development's 2001 Census of Agriculture. All agriculture metrics were based on soil landscape polygons (Soil Landscapes of Canada Version 1.9) and expressed as a ratio per unit area for each metric. Expense metrics measured the amount farmers spent on fertilizers, lime and agrochemicals per soil landscape polygon. Fertilizer expense estimates the degree to which agriculture may affect nutrient loading, and chemical expense estimates potential levels of water contamination. Manure production is also an indicator of nutrient loading and pathogen contamination. The Agricultural Intensity Index estimates overall intensity by integrating the above metrics (Alberta Department of Agriculture and Rural Development 2013). All agriculture metrics were ranked on a scale from 0 to 1, where 0 represents no impact and 1 represents the highest intensity.

Table 1: Landscape metrics (N = 21) developed for testing against water quality parameters.

Group	Metric indicator
Lake morphometry	Lake surface area (lakeSA)
	Lake volume (LVolume)
	Lakemean depth (Z_{mean})
	Lake maximum depth (Z_{max})
	Lake mixing regime (mixing)
Watershed Geography	Lake watershed area (WAarea)
	Watershed area to surface area (WASA)
	Watershed area to lake volume (WALV)
	Lake landscape position (Lndpsn)
	Soil group (STexGL)
Land cover & use	% of watershed as agriculture (ag)
	% of watershed as built-up (anthro)
	% of watershed as agriculture + built-up (dist)
	% of watershed as total disturbance including fire (totdist)
	% of watershed as wetlands (totwetl)
	% of watershed as peatlands (peat)
	Density of linear disturbances in the watershed (lin.dens)
	Fertilizer expense (Fert_expense)
	Chemical expense (Chem_expense)
	Manure production (Manure_prod)
	Agricultural intensity index (AgIntensity)

Data – Water quality lake data

Water quality parameters from 25 lakes (Figure 1) were collated from Alberta Environment's lake monitoring program and the Alberta Lake Management Society. We used a summer data set that included 25 sites sampled mainly between 2002 and 2011, although two sites were sampled in the late 1990's. Summer measurements took the average of at least three data points collected during the field season in the most recent sampling year. Data for some lakes were incomplete. For example, only 18 of these sites had available metals data. Water quality was categorized into four groups as shown in Table 2: 1) nutrients; 2) routine limnology; 3) algal productivity; and 4) metals. Secchi disk depth estimated water turbidity in the water column, which is mainly determined by algal biomass. Microcystin-LR is a naturally-occurring toxin produced and released by cyanobacteria, and is one of the most common toxins found in water bodies around the world (Health Canada 2013).

Table 2: Water quality metrics used in this study (N = 37).

Water quality group	Water quality metrics	
Nutrients & algal productivity	Total phosphorus (P)	Total nitrogen (TN)
	Total dissolved P	Nitrate + nitrite (NO_2 + NO_3)
	Particulate phosphorus (PP)	Ammonia (NH_3)
	Secchi depth	Microcystin-LR
	Chlorophyll *a* (chl-a)	Dissolved organic carbon (DOC)
Routine limnology	Sodium (Na)	Total anions
	Magnesium (Mg)	Alkalinity
	Chloride (Cl)	pH
	Potassium (K)	Water hardness
	Calcium (Ca)	Total dissolved solids (TDS)
	Sulphate (SO_4)	Bicarbonate (CHO_3^-)
	Conductivity	Carbonate (CO_3^{-2})
	Total cations	
Metals	Aluminum (Al)	Manganese (Mn)
	Arsenic (As)	Nickel (Ni)
	Cadmium (Cd)	Lead (Pb)
	Cobalt (Co)	Uranium (U)
	Cromium (Cr)	Zinc (Zn)
	Copper (Cu)	Iron (Fe)

Data Analyses

Metrics within each landscape group were analyzed against water quality parameters to determine potential landscape indicators of each water quality parameter. Simple linear regressions were performed between each water quality and landscape metric to identify candidate landscape metrics to include in subsequent model analyses. Regressions were assessed using diagnostic plots, including Q-Q plots, residual plots and leverage plots and extreme outlier lakes were excluded from analyses. Stepwise Akaiki's Information Criteria (AIC) was then performed to test each water quality parameter against several candidate landscape metrics. A Spearman's correlation matrix was performed that included all landscape metrics and highly-correlated metrics ($p < 0.05$) were not redundantly included in AIC models. Final variables from the AIC model were included in a multiple regression model for each water quality parameter. Water quality metrics (response variable) were log10 (x + 1) transformed prior to analysis to meet assumptions of normality. Some morphometric variable were also log10 (x + 1) transformed where necessary and land cover metrics were arcsine-square root transformed. Metals were only analyzed using simple linear regression due to lower sample size (N = 18). All analyses were performed using packages 'MASS' and 'stepAIC' for R v. 2.15.3.

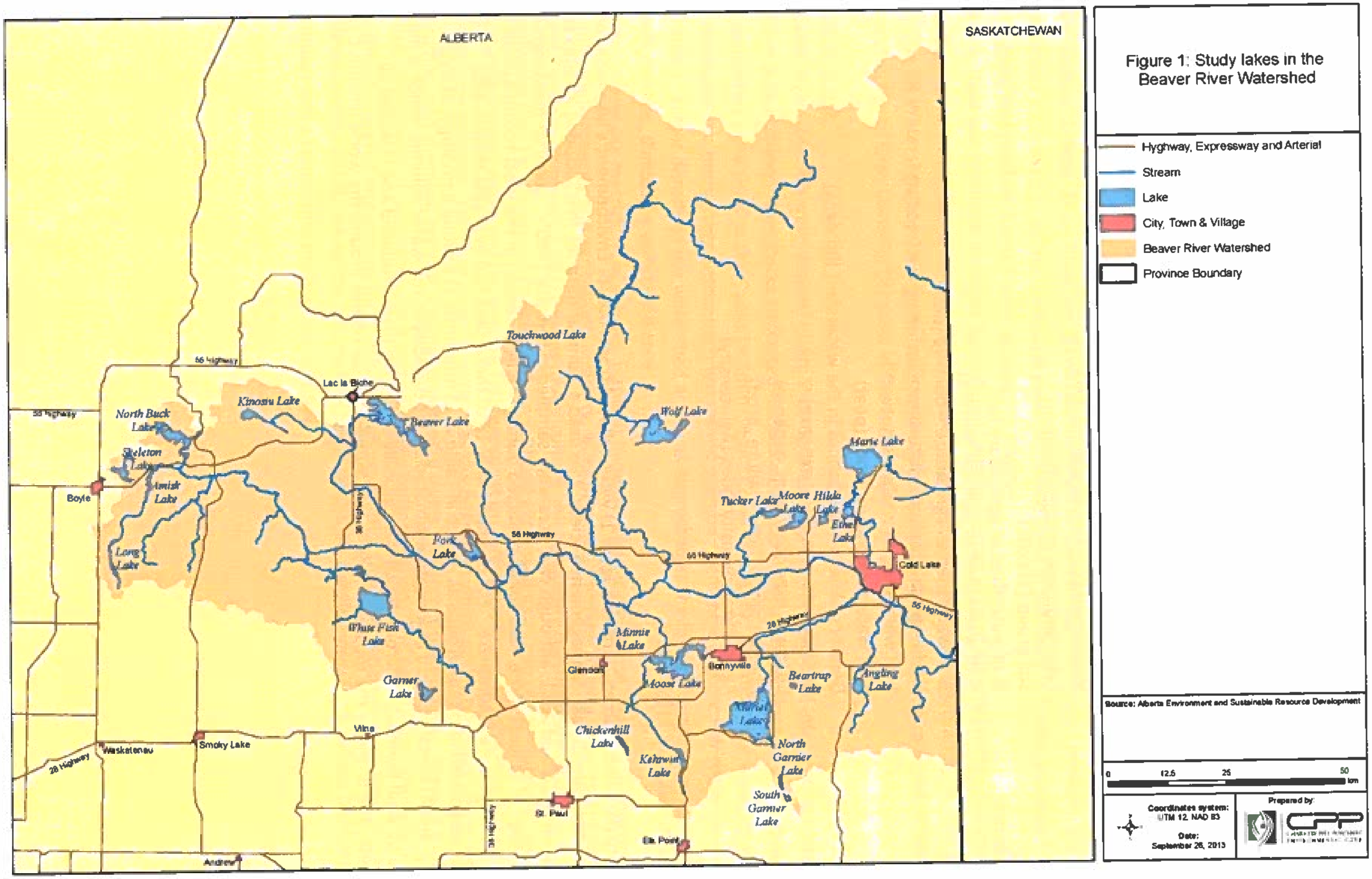

Figure 1: Study lakes in the Beaver River Watershed

Source: Alberta Environment and Sustainable Resource Development

Coordinates system: UTM 12, NAD 83

Date: September 26, 2013

Results and Discussion

A total of 988 simple regressions were run to the relationship between water quality metrics and landscape variables. Significant, non-correlated landscape variables were then included in re-analysis using AIC step selection. Multiple regressions were performed on the final variables selected in the AIC model to obtain R^2-values for each water quality model. Appendices A4 and A5 include water quality models that can be used to predict the water quality of lakes in the Beaver River watershed.

Nutrients & Algal Biomass

Nutrient concentrations increase inversely with lake depth. In other words, phosphorus and nitrogen concentrations are higher in shallow lakes where the water column mixes during the summer (Figure 2, Figure 3). The same pattern exists for algal biomass (and also water clarity as measured as Secchi depth), which is not surprising since it is highly related to phosphorus concentrations (Figure 7). Recent studies in Alberta (Taranu et al. 2012) have shed light on the importance of lake mixing on nutrients and algal productivity. It is understood now that shallow lakes with water columns that mix frequently during the summer behave differently than deep lakes that only mix in fall and spring turnover events, so much so that these two types of lakes are expected to respond differently to climate warming and eutrophication. Total phosphorus has no relationship with agricultural intensity in mixed lakes (N=13, $p>0.05$, $R^2=0.01$) whereas the relationship is substantially stronger when only dimictic lakes are included in the analysis (N=11, $p<0.01$, $R^2=0.51$). This supports previously reported results (Taranu et al. 2012; Taranu & Gregory-Eaves 2008) supporting the statement that mixed and stratified lakes in the Beaver River Watershed should be examined and managed separately with respect to nutrients & algal productivity.

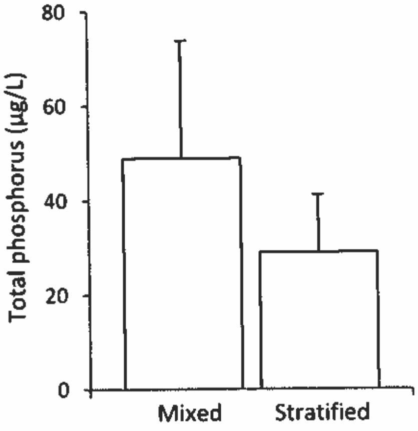

Figure 2: Total phosphorus concentration in lakes with mixed and stratified water columns. The two groups are significantly different (t-test, $p<0.01$).

In addition to a relationship with lake depth, nutrients also increased in response to higher amounts of disturbance and agricultural use metrics (see Figure 4 for an example with dissolved phosphorus). In terms of agricultural use metrics, chemical expense and manure production were the best predictors of dissolved and total phosphorus, respectively. Agricultural intensity was the best agricultural use metric for total nitrogen whereas manure production was the best predictor of dissolved nitrogen (i.e., nitrate-nitrite and ammonia). In general, the total amount of disturbance excluding forest fire ("dist") explained more variability in the data than did disturbance + forest fire, meaning that forest fires did not export nutrients to lakes.

Because Alberta surface waters are naturally nutrient-rich, they are more prone to the negative effects of eutrophication (e.g., algal blooms). Land use has a well-documented influence on nutrient export and eutrophication. Lands with human activities such as logging, linear disturbance, urban development, and agriculture export nutrients at relatively higher rates than forested drainage basins (Neufeld 2005; Cooke and Prepas 1998). These activities can all increase the export of sediment, which carries nutrients in particulate form. Dissolved nutrients, which are easily transportable in water, tend to be associated with the build-up of nutrients in soil when manure and other fertilizers are applied at rates faster than can be used by vegetation (Soil Phosphorus Limits Committee and Landwise, Inc. 2006, Olson et al. 2010). In a province-wide study of small watersheds (Anderson et al. 1998, Lorenz et al. 2008), agricultural intensity (chemical and fertilizer expenses and manure production percentiles) increases the concentrations of phosphorus and nitrogen (mainly the dissolved fraction) in streams. Watersheds with high agricultural intensity generally have higher proportions of cropland compared to watersheds with low or moderate intensity. Our results on lakes are in agreement with these studies on small streams. In our study of lakes, the dissolved and particulate fractions of phosphorus were highly related, and not significantly related to agricultural use metrics, respectively. Dissolved phosphorus is a good indicator of agricultural use metrics in the Beaver River watershed, while particulate phosphorus is not. Thus, dissolved and particulate mixed and stratified lakes should be examined and managed separately in the Beaver River Watershed.

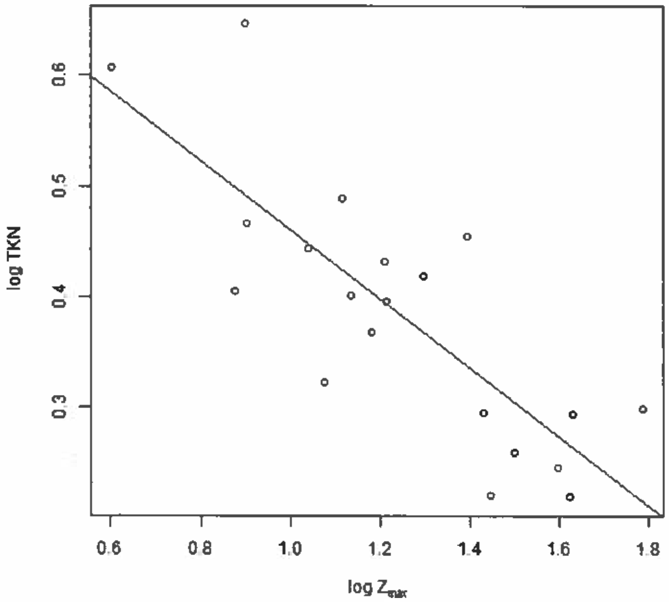

Figure 3: Total kjehldahl nitrogen (TKN) concentrations in relation to maximum depth (Zmax). Note that nitrogen concentrations increase as lakes get shallower. Both parameters are log-transformed.

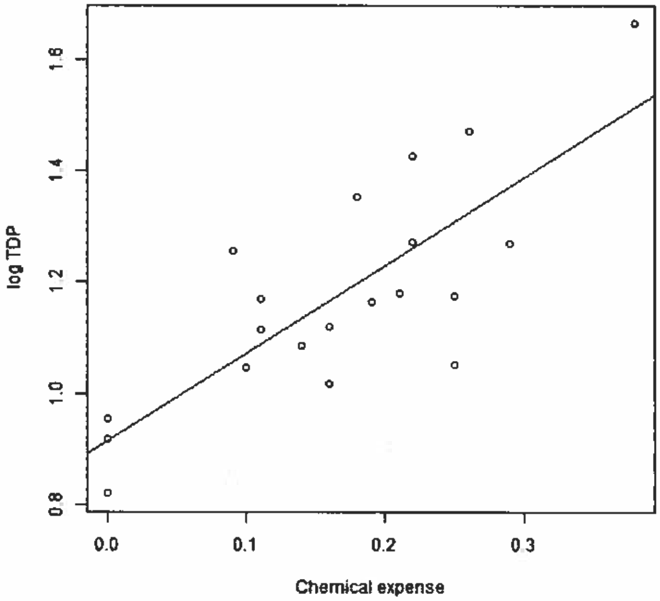

Figure 4: Dissolved phosphorus (TDP) concentrations increase with chemical expense, an indicator of agricultural use.

Water quality models for nutrients include both lake depth/mixing and land use metrics. Out of all land use metrics, agricultural metrics had the strongest relationship to nutrients, likely because agriculture is the most widespread land use in the Beaver River watershed (nearly 85% of disturbed land in the BR watershed.), and high-intensity agriculture is among the most intensive land uses. Since agricultural use metrics had slightly better correlations with nutrients than land cover metrics, the final predictive model tended to preferentially include agricultural use metrics (see Appendix A4). Water quality models for dissolved phosphorus and nitrogen were relatively good since a high proportion of variation in the water quality data was represented (52, and 86% of variability for dissolved phosphorus and total nitrogen, respectively). The model for total phosphorus only explained 40% of the variability in the data, indicating more variability in total phosphorus concentrations among lakes. Some of this variability is caused by the polarized responses of the dissolved and particulate fractions.

Agriculture is not the only land use that adds nutrients to watersheds. Stormwater runoff and leaking septic systems can be an important source of nutrients. Also, fertilizer from lawns of recreational properties may be a source of nutrients to Alberta lakes, but loads are not well documented (Association of Summer Villages of Alberta n.d.). Land-use effects depend on many factors, such as the density of disturbance, slope, the presence of wetlands in the watershed, and differences in land use practices. When a watershed has little development, nutrient loading is typically not a problem. For example, the less developed Milk River has dissolved phosphorus through its entire reach that is comparable to the upper reaches of other southern rivers (Younge 1988). Surface waters near urbanized areas can have elevated pollutants, including salts, metals, and nutrients. Population centers in the Beaver River watershed tend to be small, thus the effects would be localized and are not likely to be detected in a regional-scale analysis.

Human activities such as agriculture, mining and urban development contribute to nonpoint source (NPS) pollution in the BR watershed. NPS pollution includes pollutants from multiple sources that discharge over a wide area and do not have a single point of origin (U.S. Environmental Protection Agency, 2010; U.S. Geological Survey, 2011). NPS pollutants such as nutrients, metals, salts, pesticides and fecal coliforms may reach waterbodies via surface runoff, groundwater contamination and atmospheric deposition (Charette and Trites, 2011). Agricultural land use can have harmful effects on water quality depending on farming practices. Fertilizer, pesticide and manure use, as well as tilling and irrigation can contribute to loading of nutrients, pathogens, pesticides, metals and total suspended solids (TSS). Lakes near urbanized areas also tend to have elevated NPS pollutants, including salts, metals, and nutrients. The effects of land use changes and associated input of NPS pollution on water quality can affect human health and livelihood, aesthetic and recreation value of aquatic resources, and habitat degradation for organisms. For example, cyanobacterial blooms (blue-green algae), which have been found to be related to interactions between elevated nutrients and natural factors (Taranu et al., 2012), can cause illness and death to both humans and aquatic organisms.

Salts

Natural waters contain cations and anions that combine to form salts. The major cations in surface waters are calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). The major anions are bicarbonate (HCO^{3-}), carbonate (CO_3^{2-}), chloride (Cl^-), and sulphate (SO_4^{2-}). Dissolved salt concentrations are naturally high in many areas of Alberta because of the underlying marine-derived geology and because of the semi-arid climate. Springs, seeps, and groundwater are natural sources of ions to rivers in Alberta (Hillman et al. 1997).

The larger the watershed, the more dilute the lake water (with respect to total dissolved solids, conductivity, alkalinity, pH, sodium, potassium, sulphate, calcium, magnesium, carbonate, and bicarbonate; Figure 5), which reflects the greater flushing of minerals and ions. Minerals and ions also decrease with watershed peatland cover (Figure 6). This is not surprising since peatlands in the Beaver River watershed are generally low in alkalinity (Vitt et al. 1990). Bogs, which make up about a third of the peatlands in the watershed (Ducks Unlimited, unpublished data), have no alkalinity. That said, peatland and agricultural land cover were inversely related, meaning that the patterns seen in the data may be related to one or the other or both explanatory variables. The best models for predicting total salt and mineral (TDS and conductivity) concentrations included both size of the watershed and % agricultural cover in the watershed, meaning that both variables contribute to salt concentrations. However, % peatlands and % agriculture are each stronger predictors of different specific ions that contribute to total salts. Models for sodium, potassium, sulphate, chloride, magnesium, alkalinity, and carbonate included % of watershed covered by peatlands and not agricultural metrics, meaning that agricultural metrics were redundant. Models for bicarbonate concentrations included % agriculture and not peatlands, meaning that these were redundant. In general, lakes surrounded by more peatland cover tended to have low ion and mineral concentrations, indicating that peatlands may play a role in buffering natural concentrations or that land conversion to agriculture and other land uses elevates these concentrations.

Salinization of soils takes place where the following conditions take place together: 1) the presence of soluble salts in the soil, 2) a high water table, and 3) a high rate of evaporation (Eilers et al. 1995). With respect to agricultural practices, cropping practices that enhance surface evaporation and facilitate deep percolation of precipitation (e.g., summerfallowing, etc.) increase the risk of salinization. Permanent cover (e.g., forage, trees, etc.) represent the lowest risk of increasing soil salinity (Huffman et al. 2000).

In general, almost any region in Alberta has the potential to develop saline soils due to the naturally saline geology and a widespread potential water deficit (annual potential evapotranspiration exceeds precipitation in most of Alberta). Thus, Alberta soils can be naturally susceptive to the risk of increasing soil salinity. Saline soils are rare in the Beaver River Watershed (Agricultural Land Resource Atlas of Alberta) and salinity increases due to agriculture are typically associated with irrigation (Little et al. 2010), which is not a widespread practice in the Beaver River Watershed. Thus, it is unlikely that agricultural practices are solely responsible for the observed patterns in salinity in the Beaver River watershed. The use of road salt as a de-icer on roads is common practice in Alberta, although less so than most other provinces. The cheapest and most commonly used de-icing salt is sodium chloride (NaCl). Sodium

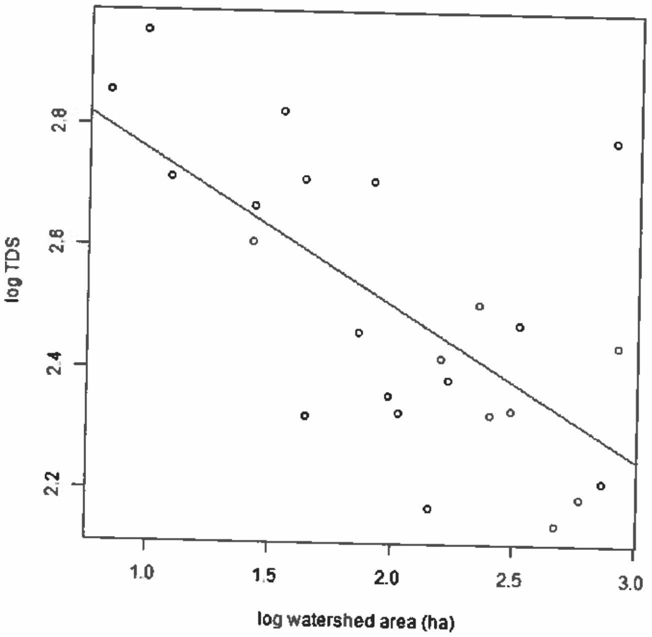

Figure 5: Total dissolved solids (TDS) is lower in lakes located in larger watersheds, demonstrating relatively greater flushing of water in these systems.

chloride dissociates in aquatic systems into Chloride ions and sodium cations. While sodium may bond to negatively charges soil particles or be taken up in biological processes, chloride ions are less reactive and can be transported to surface water through soil and groundwater. The boreal transition zone is estimated to have relatively high loads of road salts, as compared to other areas in the province (Mayer et al. 1999). In the BR watershed, linear density was positively related to chloride concentration, suggesting that salt runoff from roads has a negative effect on salinization of lakes. A significant upward trend in salts in the Beaver River near the AB-SK border (AENV 2006a) indicates that regional climatic factors are also likely at play. Thus, it is likely that the long-term water-deficit that occurred in from the mid-1980s to the mid-2000s has increased the risk of increasing salt concentrations in the Beaver River watershed. The effects of this climate-driven change were detected in areas where permanent cover (trees, peatlands) are less prominent. Peatlands seem to protect watersheds from an increase in salinity during long-term drought.

Landscape position is also an important predictor of minerals and ions in Beaver River watershed lakes, but the relationship to it is somewhat complex. In general, lakes that were relatively high in the landscape tended to have high minerals and ions. Lakes higher up in the landscape are hydrologically better connected with atmospheric/climatic processes (precipitation and evaporation) (Winter 2001). In the Beaver River Basin, as in most of Alberta, there is a well-documented increase in lake salt concentrations over the past two decades, which is thought to be caused by an imbalance in evaporation relative to precipitation (AENV 2006a, Casey 2011). That said, Muriel Lake and Moose Lake are outliers in that they also had relatively high ion concentrations despite being in lower landscape positions. These two lakes are hydrologically connected to regional groundwater systems, which are known in Alberta to have high dissolved solids. Thus, lakes that are in high landscape position and lakes that are low in landscape position and are connected with regional groundwater systems may be both at greater risk for salinization due to drought and/or climate change. Lakes that are higher in the landscape have the added challenge of also being more susceptible to fish winterkills (Danylchuk and Tonn 2003). Lakes that meet these conditions and that are in areas with less permanent cover (e.g., cropland, etc.) would be the most vulnerable to the effects of drought and/or climate change.

Most water quality models explained over 50% of the variation in water chemistry parameters (Appendix A5). The best models for predicting total salts and minerals (TDS and conductivity) concentrations included the size of the watershed, % agricultural cover in the watershed, and lake surface area. Sodium, chloride, sulphate, and pH were best explained by % of watershed covered by peatlands alone. In addition to % peatlands, the alkalinity model also included watershed area. The best model for potassium included agricultural intensity, % peatlands and mixing, whereas the magnesium model included chemical expense and watershed area.

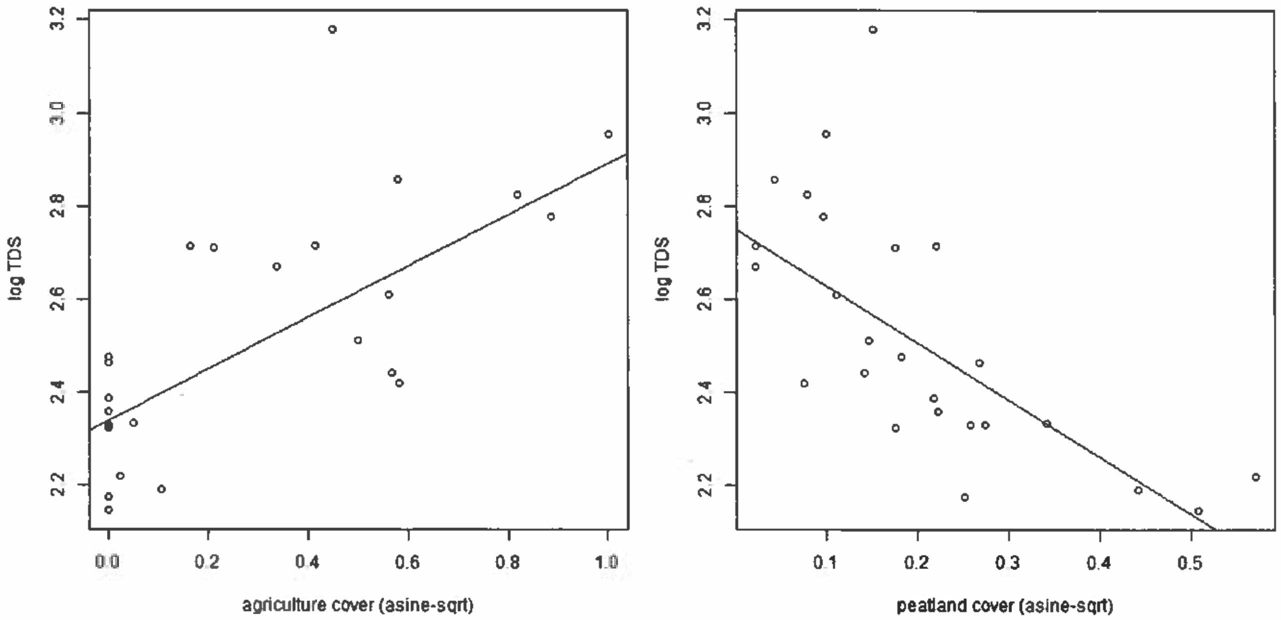

Figure 6: Total dissolved solids (TDS) is related to increasing agricultural cover and decreasing peatland cover. Peatland and agricultural cover are inversely related.

Metals

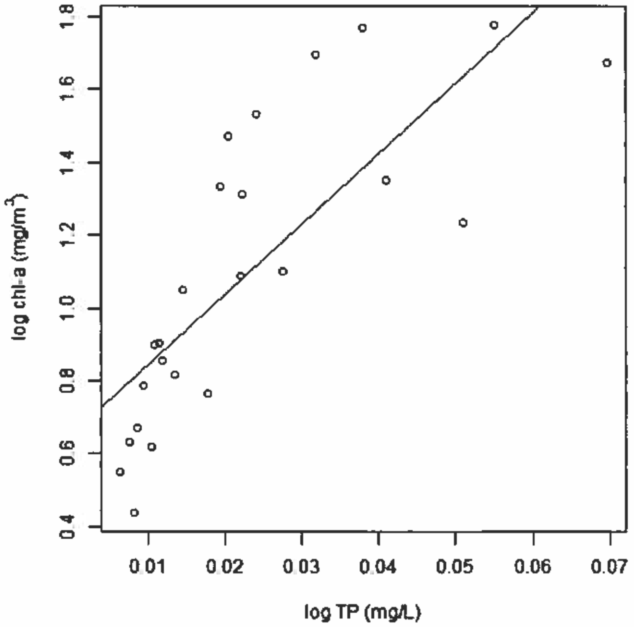

Figure 7: Regulation of algal biomass, as shown by the predictive relationship between phosphorus and chlorophyll-*a*.

Although some metals had significant relationship to landscape variables, most metals were influenced by one to a few data points with high leverage, high Cook's distance, large residuals, or non-normal data. Best effort was made to eliminate sites that were highly influential, although regressions continued to be problematic after outlier removal due to low sample size. Best discretion was used to report some likely predictors of metals. Sampling metals at more sites in the future will help alleviate these issues. Table A3 includes regression statistics for a list of reported metal relationships. In general metals tended to be related both to agricultural land cover and use metrics (Arsenic, Chromium, Copper, Uranium). Other metals (Zinc, Nickel, Cobalt, Chromium, and Iron) are related to maximum depth and water column mixing. Patterns in Cobalt and Chromium concentrations were consistent with that of dissolved organic carbon (R>0.76), which is not surprising since these metals can form strong bonds with dissolved organic carbon. Dissolved organic carbon was best explained by maximum depth, which may explain the patterns in Cobalt and Chromium.

The main source of metals is the parent material from which soils are derived. Heavy metals can become concentrated by natural processes, for instance, in regional groundwater discharge areas. Heaver metal concentrations in soils are related to soil texture. They are greatest in clay, followed by clay loam, loam, and sand (Webber and Singh 1995). Other than natural erosion or weathering of local geology, heavy metals can originate from fertilizers, pesticides, household products, wastewater, solid waste, sewage sludge and landfills (Environmental Alberta, 2006). Agricultural cover and use, and a few morphometric metrics were related to metal concentration in lakes. Although most metal concentrations decreased over the last two decades, a 2006 report by AENV found that the Prairie Provinces Water Board (PPWB) objectives were exceeded for Cu, Fe, Mn, and to a lesser degree, dissolved Fe, Cd, Cr, and Zn (Alberta Environment, 2006b). Analyses on metals would highly benefit from a greater sample size. This would help to determine whether anthropogenic sources of metals can be distinguished from natural sources.

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Appendix A1

Landscape metrics that had statistically significant relationships with nutrients and algal productivity metrics, based on simple linear regression. N.B. Mixing regime and landscape position were assessed using t-tests.

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
TDP	Chem_expense	0.99	0.94	0.52	< 0.001
	Fert_expense	1.0	0.80	0.50	<0.001
	Manure_prod	0.99	0.61	0.50	<0.001
	dist	0.94	0.44	0.45	<0.005
	Ag_intensity	0.98	0.80	0.44	<0.05
	totdist	0.93	0.45	0.44	<0.01
	LVolume	1.49	-0.18	0.39	<0.02
	STypeGL	1.34	-0.0027	0.37	<0.001
	peat	1.26	-0.52	0.24	<0.05
	totwetl	1.32	-0.47	0.21	<0.05
P particulate	Zmax	0.023	-0.01	0.40	<0.01
	mixing				<0.05
	dist	0.001	0.006	0.23	<0.05
TP	dist	1.35	0.39	0.28	<0.01
	totdist	1.34	0.40	0.27	<0.02
	Zmax	1.90	-0.30	0.25	<0.02
	Manure_prod	1.40	0.47	0.23	<0.05
	Chem_expense	1.41	0.68	0.20	<0.05
	mixing				<0.05
TKN	dist	0.13	0.19	0.59	<0.001
	Zmax	0.63	-0.22	0.52	<0.001
	totdist	0.22	0.28	0.46	<0.005
	Ag_intensity	0.26	0.47	0.40	<0.005
	totwetl	0.50	-0.38	0.38	<0.01
	peat	0.44	-0.38	0.36	<0.01
	Chem_expense	0.28	0.46	0.34	<0.01
	Fert_expense	0.29	0.37	0.30	<0.05
	Manure_prod	0.28	0.29	0.30	<0.05
	LVolume	0.49	-0.082	0.33	<0.05
	STypeGL	0.46	-0.001	0.24	<0.05
	WArea	0.51	-0.07	0.23	<0.05
	mixing				<0.05
NO_2NO_3	Manure_prod	0.65	0.92	0.32	<0.01
	Fert_expense	0.69	1.08	0.26	<0.05
	Chem_expense	0.69	1.22	0.25	<0.05
	WArea	1.33	-0.21	0.21	<0.05
	Ag_intensity	0.68	0.99	0.21	<0.05
	totdist	0.66	0.51	0.19	<0.05

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
TN					
	Zmax	0.63	-0.22	0.52	<0.001
	dist	0.23	0.28	0.50	<0.001
	totdist	0.28	0.28	0.47	<0.001
	Ag_intensity	0.26	0.47	0.41	<0.005
	totwetl	0.50	-0.38	0.38	<0.005
	peat	0.45	-0.39	0.36	<0.01
	Chem_expense	0.28	0.47	0.35	<0.01
	LVolume	0.49	-0.08	0.33	<0.05
	Fert_expense	0.29	0.38	0.30	<0.02
	Manure_prod	0.28	0.29	0.30	<0.02
	WArea	0.51	-0.073	0.24	<0.05
	STypeGL	0.46	-0.0013	0.24	<0.05
	anthro	0.29	0.25	0.23	<0.05
	mixing				<0.05
NH$_4$					
	dist	0.0047	0.013	0.28	<0.05
	totdist	0.0045	0.013	0.26	<0.05
	Manure_prod	0.0068	0.016	0.24	<0.05
	mixing				<0.05
Dissolved Organic Carbon					
	Zmax	1.60	-0.28	0.43	<0.005
	totwetl	1.42	-0.46	0.28	<0.02
	dist	1.02	0.18	0.27	<0.02
	WArea	1.49	-0.11	0.27	<0.05
	peat	1.35	-0.44	0.23	<0.05
	lakeSA	1.4	-0.15	0.22	<0.05
	Lndpsn				0.03
August Chlorophyll *a*					
	Zmax	2.0	-0.77	0.57	<0.001
	anthro	0.97	0.012	0.27	<0.01
	WASA	0.59	0.45	0.20	<0.02
	totdist	0.9	0.01	0.19	<0.05
	STypeGL	1.48	-0.0045	0.16	<0.05
	Ag_intensity	0.84	1.4	0.16	<0.05
	mixing				<0.001
August Secchi Disk					
	Zmax	0.14	0.31	0.58	<0.001
	mixing				<0.02
	anthro	0.53	-0.004	0.21	<0.05
	LakeSA	0.35	0.14	0.19	<0.05
	WASA	0.67	-0.16	0.17	<0.05
August Microcystin-LR					
	totdist	0.04	0.0017	0.24	<0.05
	dist	0.038	0.0017	0.23	<0.05
	Ag_intensity	0.024	0.25	0.23	<0.05

Appendix A2

Landscape metrics that had statistically significant relationships with ions, based on simple linear regression.

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
TDS					
	Ag	2.3	0.55	0.59	<0.001
	peat	2.7	-1.22	0.57	<0.001
	WArea	3.0	-0.25	0.43	<0.001
	dist	2.2	0.60	0.41	<0.001
	totdist	2.2	0.59	0.37	<0.005
	totwetl	2.8	-0.97	0.37	<0.002
	Ag_intensity	2.3	0.88	0.31	<0.005
	Chem_expense	2.3	1.04	0.31	<0.005
	lakeSA	2.8	-0.30	0.29	<0.01
	Fert_expense	2.3	0.84	0.29	<0.01
	Manure_prod	2.3	0.61	0.25	<0.05
	Lndpsn				<0.001
Conductivity					
	Ag	2.6	0.22	0.59	<0.001
	peat	3.0	-1.1	0.57	<0.001
	WArea	3.2	-0.22	0.43	<0.0005
	dist	2.4	0.30	0.38	<0.005
	totwetl	3.0	-0.87	0.37	<0.005
	totdist	2.5	0.51	0.34	<0.005
	Ag_intens	2.5	0.78	0.30	<0.01
	Chem_expense	2.6	0.92	0.30	<0.01
	LakeSA	3.0	-0.27	0.29	<0.01
	Fert_expense	2.6	0.74	0.28	<0.01
	Manure_prod	2.6	0.54	0.24	<0.02
	STypeGL	2.9	-0.002	0.17	<0.05
	Lndpsn				<0.001
Cations					
	Ag	0.73	0.46	0.53	<0.001
	Peat	1.06	-0.94	0.52	< 0.001
	WArea	1.29	-0.20	0.45	<0.005
	totwetl	1.13	-0.75	0.36	<0.01
	Fert_expense	0.71	0.77	0.34	<0.01
	AgIntensity	0.67	0.85	0.33	<0.01
	Chem_expense	0.70	0.88	0.33	<0.01
	lakeSA	1.10	-0.26	0.32	<0.01
	dist	0.63	0.47	0.32	<0.01
	totdist	0.63	0.45	0.29	<0.05
	Manure_prod	0.72	0.51	0.25	<0.05
	Lndpsn				<0.001
Anions					
	Ag	0.73	0.45	0.53	<0.001
	Peat	1.06	-0.93	0.53	<0.001
	WArea	1.3	-0.21	0.46	<0.001
	totwetl	1.12	-0.75	0.36	<0.005
	lakeSA	1.1	-0.25	0.32	<0.01

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
	AgIntensity	0.68	0.80	0.31	<0.05
	Fert_expense	0.72	0.73	0.31	<0.01
	dist	0.64	0.44	0.30	<0.05
	Chem_expense	0.71	0.83	0.30	<0.05
	totdist	0.64	0.42	0.26	<0.05
	Manure_prod	0.72	0.47	0.22	<0.05
	Lndpsn				<0.001
Na					
	peat	1.9	-1.85	0.50	<0.001
	Ag	1.3	0.80	0.49	<0.001
	totwetl	2.0	-1.44	0.31	<0.005
	WArea	2.2	-0.31	0.25	<0.05
	dist	1.2	0.72	0.23	<0.05
	lakeSA	1.9	-0.4	0.20	<0.05
	totdist	1.2	0.71	0.21	<0.05
	Chem_expense	1.3	1.33	0.20	<0.05
	Ag_int	1.2	1.1	0.19	<0.05
	Fert_expense	1.3	1.08	0.18	<0.05
	Manure_prod	1.3	0.8	0.17	<0.05
	Lndpsn				<0.001
K					
	Peat	1.4	-1.8	0.66	<0.001
	dist	0.51	1.0	0.65	<0.001
	totdist	0.50	1.0	0.60	<0.001
	Ag_intens	0.6	1.6	0.56	<0.001
	totwetl	1.6	-1.6	0.55	<0.001
	Manure_prod	0.7	1.1	0.43	<0.001
	Chem_expense	0.7	1.6	0.42	<0.001
	Ag	0.85	0.6	0.38	<0.005
	Fert_expense	0.76	1.2	0.34	<0.005
	STypeGL	1.4	-0.005	0.29	<0.05
	WArea	1.6	-0.27	0.28	<0.01
	Zmax	1.5	-0.4	0.17	<0.05
	Lndpsn				<0.01
	mixing				<0.01
Cl					
	Peat			0.35	< 0.01
	lin.dens	0.22	0.21	0.29	<0.01
	Ag_intens	0.55	1.06	0.17	<0.05
	Lndpsn				<0.001
SO_4					
	Peat	1.97	-2.78	0.48	<0.001
	dist	0.64	1.55	0.43	<0.001
	totwetl	2.3	-2.57	0.42	<0.001
	totdist	0.63	1.54	0.40	<0.001
	Ag	1.11	0.99	0.31	<0.005
	Ag_intens	0.85	2.22	0.31	<0.005
	Chem_expense	0.91	2.52	0.30	<0.01
	Manure_prod	0.96	1.42	0.22	<0.05
	WA	2.26	-0.42	0.20	<0.05
	Fert_expense	1.02	1.76	0.20	<0.05

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
	STypeGL	1.87	-0.007	0.18	<0.05
	Lndpsn				<0.01
Ca					
	WArea	1.14	0.12	0.38	<0.005
	totwetl	1.2	0.46	0.31	<0.005
	peat	1.3	0.46	0.30	<0.01
	WASA	1.18	0.16	0.24	<0.05
	lin.dens	1.54	-0.06	0.21	<0.05
	Ag	1.43	-0.15	0.18	<0.05
	Lndpsn				<0.05
Mg					
	peat	1.86	-1.47	0.57	<0.001
	Ag	1.37	0.65	0.57	<0.001
	WArea	2.24	-0.34	0.54	<0.001
	dist	1.2	0.72	0.40	<0.001
	LakeSA	1.9	-0.42	0.38	<0.005
	totwetl	1.97	-1.19	0.38	<0.005
	totdist	1.2	0.7	0.36	<0.005
	Chem_expense	1.3	1.3	0.34	<0.01
	Fert_expense	1.32	1.07	0.32	<0.005
	Ag_intens	1.29	1.08	0.31	<0.005
	Lvolume	1.97	-0.26	0.28	<0.05
	Manure_prod	1.32	0.76	0.28	<0.01
	STypeGL	1.77	-0.003	0.17	<0.05
	Lndpsn				<0.001
Alk					
	Peat	2.6	-0.92	0.48	<0.001
	Ag	2.3	0.41	0.47	<0.001
	WArea	2.8	-0.21	0.44	<0.001
	lakeSA	2.6	-0.26	0.32	<0.005
	totwetl	2.7	-0.71	0.29	<0.01
	dist	2.2	0.33	0.18	<0.05
	lin.dens	2.2	0.08	0.17	<0.05
	Lndpsn				<0.001
pH					
	Peat	1.0	-0.054	0.56	< 0.001
	totwetl	1.0	-0.047	0.44	<0.001
	WArea	1.0	-0.01	0.34	<0.005
	lin.dens	0.97	0.006	0.34	<0.01
	ag	0.98	0.18	0.33	<0.005
	dist	0.97	0.024	0.32	<0.005
	totdist	0.97	0.024	0.31	<0.01
	lakeSA	1.0	-0.012	0.26	<0.05
	Chem_exp	0.98	0.035	0.18	<0.05
	Lndpsn				<0.05
Carbonate					
	Peat	1.63	-2.21	0.52	<0.001
	ag	0.87	0.43	0.51	<0.001
	dist	0.30	0.70	0.46	<0.001
	WArea	2.11	-0.46	0.41	<0.001

Response variable	Explanatory variable	Intercept	Slope	R^2	p-value
	lakeSA	1.78	-0.64	0.36	<0.005
	totwetl	1.80	-1.77	0.34	<0.005
	totdist	0.66	1.04	0.32	<0.005
	lin.dens	0.49	0.24	0.28	<0.01
	LVolume	1.76	-0.38	0.26	<0.05
	Fert_expense	0.88	1.41	0.23	<0.02
	Chem_expense	0.85	1.67	0.23	<0.02
	Manure_prod	0.85	1.07	0.22	<0.05
	Lndpsn				<0.001
Bicarbonate					
	Ag	2.3	0.17	0.53	<0.001
	Peat	2.6	-0.77	0.44	<0.001
	WArea	2.8	-0.17	0.41	<0.001
	lakeSA	2.6	-0.22	0.29	<0.01
	totwetl	2.6	-0.58	0.25	<0.05
	anthro	2.6	-0.17	0.20	<0.05
	dist	2.2	0.17	0.18	<0.05
	Lndpsn				<0.001

Appendix A3

Landscape metrics that had statistically significant relationships with metals, based on simple linear regression.

Response variable	Landscape variable	Intercept	Slope	R^2	p-value
Al	NONE				
As	Ag	0.36	0.21	0.37	<0.01
	Manure_prod	0.32	0.71	0.34	<0.02
	LVolume	1.0	-0.26	0.32	<0.05
	Fert_expense	0.34	0.86	0.31	<0.02
	dist	0.11	0.33	0.27	<0.05
	Chem_expense	0.34	0.94	0.28	<0.05
Cd	NONE				
Co	Chem_expense	0.0042	0.045	0.48	<0.002
	AgIntensity	0.0028	0.045	0.47	<0.002
	dist	-0.007	0.016	0.47	<0.005
	Fert_expense	0.0048	0.037	0.45	<0.005
	Manure_prod	0.0043	0.029	0.43	<0.005
	totdist	0.00003	0.0025	0.43	<0.005
	peat	0.019	-0.034	0.34	<0.02
	Zmax	0.03	-0.016	0.33	<0.02
	totwetl	0.022	-0.03	0.28	<0.05
	Ag	0.008	0.006	0.27	<0.05
	mixing				0.04
Cr	Zmax	0.21	-0.1	0.38	<0.01
	Ag	0.06	0.04	0.31	<0.02
	lin.dens	0.01	0.029	0.31	<0.02
	peat	0.13	-0.17	0.25	<0.05
	dist	0.012	0.065	0.22	<0.05
Cu	Ag	0.1	0.1	0.39	<0.01
	Manure_prod	0.086	0.31	0.31	<0.02
	Fert_expense	0.093	0.39	0.30	<0.02
	Chem_expense	0.097	0.41	0.25	<0.05
	dist	-0.008	0.14	0.25	<0.05
	Lin.dens	0.021	0.053	0.23	<0.05
Fe	Zmax	2.0	-0.68	0.41	<0.005
	mixing				0.03
Mn	anthro	0.69	1.62	0.45	<0.005
Ni	Zmax	0.12	-0.07	0.39	<0.01
	lin.dens	-0.027	0.021	0.36	<0.01
	dist	-0.031	0.053	0.32	<0.02

	totdist	-0.0065	0.083	0.28	<0.05
	AgIntensity	0.0051	0.14	0.26	<0.05
	totwetl	0.072	-0.11	0.23	<0.05
	mixing				0.02
Pb					
	NONE				
U					
	ag	0.059	0.15	0.64	<0.001
	Chem_expense	0.046	0.66	0.45	<0.005
	Fert_expense	0.053	0.56	0.44	<0.005
	peat	0.28	-0.59	0.43	<0.005
	Manure_prod	0.05	0.42	0.39	<0.01
	AgIntensity	0.041	0.59	0.35	<0.01
	dist	-0.087	0.21	0.34	<0.02
	totdist	0.0094	0.32	0.30	<0.02
	totwetl	0.32	-0.43	0.26	<0.05
	anthro	0.31	-0.18	0.24	<0.05
	WArea	0.37	-0.1	0.23	<0.05
Zn					
	Zmax	0.69	-0.31	0.23	<0.05
	mixing				0.04

Appendix A4

Multiple regression analysis of nutrients and algal productivity metrics using variables selected in AIC models.

Variable	Model	R^2	p-value	AIC
TDP	Log$_{10}$(TDP+1)= 0.99 + 0.94(Chem_expense) + 0.046	0.52	< 0.001	-79.9
P particulate	Log$_{10}$(PP+1)= 0.012 – 0.0049(Mixing) + 0.0016	0.27	<0.05	-195
TP	Log$_{10}$(TP+1)= 1.48 + 0.38(Manure_prod) – 0.14(Mixing) + 0.066	0.40	0.001	-83.7
TKN	Log$_{10}$(TKN+1)= 0.45 -0.061(L$_{10}$(WArea+1)) + 0.15(asin(sqrt(dist/100))) -0.066(Mixing) + 0.040	0.85	< 0.001	-118
NO_2NO_3	Log$_{10}$(NO_2NO_3+1)= 0.968 - 0.13(L$_{10}$(WArea+1)) + 0.75(Manure_prod) + 0.233	0.39	<0.01	-60.7
TN	Log$_{10}$(TN+1)= 0.56 - 0.023(L$_{10}$(WArea+1)) – 0.18(L$_{10}$(Zmax+1)) + 0.39(AgIntensity) + 0.048	0.86	<0.001	-118
NH_4	Log$_{10}$(NH_4+1)= 0.01 + 0.016(Manure_prod) – 0.0054(Mixing) + 0.0025	0.41	<0.05	-185
Dissolved Organic Carbon	Log$_{10}$(DOC+1) = (L$_{10}$(Zmax+1)) + (asin(sqrt(totdist/100))) – 0.06(L$_{10}$(WArea+1)) + 0.12	0.62	<0.005	-81.7
Chlorophyll a	Log$_{10}$(chla+1) = 1.18 – 0.53(L10(Zmax+1)) + 0.74(asin(sqrt(totdist/100))) + 0.31 L10(WASA+1) + 0.71(AgIntensity) – 0.31(Mixing) + 0.36	0.83	<0.005	-46.8
Secchi	Log$_{10}$(Secchi+1) = 0.29 + 0.29(L$_{10}$(Zmax+1)) – 0.1(L$_{10}$(WASA+1)) + 0.1	0.64	<0.001	-108
Microcystin-LR	Log$_{10}$(Microcyst) = 0.0049 + 0.15(asin(sqrt(totdist/100))) + 0.033	0.25	<0.05	-107

Appendix A5

Multiple regression analysis of water chemistry using variables selected in AIC models.

Variable	Model	R^2	p-value	AIC
TDS	Log$_{10}$(TDS+1) = 1.24 – 0.056(asin(sqrt(ag/100))) + 0.96(L$_{10}$(lakeSA)) + 0.21	0.62	< 0.001	-100.5
Conductivity	Log$_{10}$(Cond+1) = 2.94 – 0.17(L$_{10}$(WArea+1)) + 0.40(asin(sqrt(ag/100))) + 0.028(L$_{10}$(lakeSA+1)) + 0.092	0.76	< 0.001	-100.5
Cations	Log$_{10}$(tot_cat+1) = 1.08 – 0.16(L$_{10}$(Warea+1)) + 0.37(asin(sqrt(ag/100))) + 0.018(L10(lakeSA+1)) + 0.093	0.76	<0.001	-84.5
Anions	Log$_{10}$(tot_cat+1) = 1.09 – 0.17(L$_{10}$(Warea+1)) + 0.36(asin(sqrt(ag/100))) + 0.027(L$_{10}$(lakeSA+1)) + 0.089	0.78	<0.001	-85.9
Na	Log$_{10}$(Na+1) = 1.92 – 1.85(asin(sqrt(peat/100))) + 0.10	0.50	<0.001	-56.9
K	Log$_{10}$(K+1) = 1.14 – 1.23(asin(sqrt(peat/100))) + 0.72(AgIntensity) – 0.10(Mixing) + 0.12	0.79	<0.001	-81.3
Cl	Log$_{10}$(Cl+1) = 1.16 - 1.68(asin(sqrt(peat/100))) + 0.11	0.41	<0.001	-54.5
SO_4	Log$_{10}$(SO4+1) = 1.97 – 2.78(asin(sqrt(peat/100))) + 0.16	0.47	<0.001	-36.0
Ca	Log$_{10}$(Ca+1) = 1.14 + 0.12(L$_{10}$(WArea+1)) + 0.069	0.38	<0.01	-110
Mg	Log$_{10}$(Mg+1) = 1.97 – 0.27(L$_{10}$(WArea+1)) + 0.68(Chem_expense) + 0.19	0.61	<0.001	-78.6
Alkalinity	Log$_{10}$(Alk+1) = 2.78 – 0.12(L$_{10}$(Warea+1)) – 0.60(asin(sqrt(peat/100))) + 0.10	0.57	<0.001	-93.9
pH	Log$_{10}$(pH+1) = 0.99 - 0.054(asin(sqrt(peat/100))) + 0.0025	0.56	<0.001	-232
Carbonate	Log$_{10}$(Carb+1) = 1.84 – 0.33(L$_{10}$(lakeSA+1)) – 1.71(asin(sqrt(peat/100))) + 0.15	0.59	<0.001	-52.0
Bicarbonate	Log$_{10}$(Bicarb+1) = 2.63 – 0.13(L$_{10}$(Warea+1)) + 0.27(asin(sqrt(ag/100))) + 0.09	0.65	0.001	-104