Wabamun Lake phosphorus budget during the 2008 runoff and open water season

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1. Executive Summary

In concert with the initiation of the Wabamun Watershed Management Council (WWMC) and a formal watershed management planning process in 2007, an update of a 1980-82 eutrophication study was undertaken at Wabamun Lake, a large recreational lake approximately 60 km west of Edmonton, Alberta. A nutrient budget was designed to identify the sources of phosphorus in the lake water, the nutrient most responsible for algae growth in temperate freshwaters. Alberta Environment measured surface runoff, atmospheric deposition, and lake water phosphorus concentrations during the 2008 open water season at Wabamun Lake. These data were used in conjunction with extensive historical data at the lake to produce a representative water and total phosphorus budget for the 2008 runoff and open water seasons.

Results indicated that lake sediments (43%) and precipitation falling directly onto the lake surface (44%) were the largest contributors of phosphorus to the lake water. Regional meteorological conditions during 2008, and in the decade previously, were dry and supplied very little surface runoff to the lake, adding little phosphorus (3%). Relatively dilute water draining from industry-related activities (ash settling lagoon and water treatment plant) provided over 35% of all water to the lake in 2008, but only 3% of the phosphorus. Groundwater (5%) and domestic sewage (1%) additions balanced the phosphorus budget.

Though a significant time period elapsed between eutrophication studies, the contrasting conditions of the early 1980s (heavy precipitation) and the dry 2000s obscured any reliable evaluation of the effect of land cover and population changes in the watershed on phosphorus sources. However, the environmental extremes of the two studies provide a reasonable constraint on the relative contributions of phosphorus sources to the lake.

Wabamun Lake is similar to many other Alberta lakes where addition of phosphorus from lake sediments is a significant source of the nutrient to lake water and, by association, for algae growth. Studies from lakes in North America and Europe have shown mixed results when using short-term sediment treatment solutions, such as dredging, as a means to decrease eutrophication. Until further, long-term study of sediment treatment is performed, reduction and control of external phosphorus input to Wabamun Lake is crucial for the long-term viability of Wabamun Lake water quality.

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2. Introduction

Eutrophication of popular recreational lakes is an important lake management issue across much of Alberta. Recreational use of these lakes in mid to late summer is often ubiquitous with high planktonic algae concentrations in the warm water conditions. Alberta's naturally nutrient rich geology and soils (Schindler et al., 2008), mostly shallow lake bathymetry, and history of agricultural-based development have produced numerous eutrophic recreational lakes across the settled areas of the province. Studies of sediment cores from several of these lakes concluded that they were naturally eutrophic before European settlement in the region, but that eutrophication had been exacerbated by land clearing and agricultural and residential development during the mid-1900s (Blakney, 1998; Manning et al., 1999; Blais et al., 2000).

Phosphorus is understood to be the limiting nutrient to algae growth in most temperate freshwater systems (Smith and Schindler, 2009), and Alberta lakes follow this paradigm. Phosphorus in lake water has many sources including watershed runoff, atmospheric inputs, biological recycling, groundwater seepage, anthropogenic additions, and lake sediments, among others. In terms of lake management, it is critical to understand the proportional sources of phosphorus in lake water to better direct watershed stewardship activities and to prepare long term management plans. For example, without knowing the amount of phosphorus emerging from a small agriculturally-affected stream flowing into a lake, costly remediation projects may be implemented even though the stream may represent less than 1% of all phosphorus delivered to a lake in a given year. Nutrient budgets as a tool to identify the proportional contribution of nutrient sources to lakes have been used in limnology for several decades owing to their potential low cost and practical application in watersheds.

Wabamun Lake, approximately 60 km west of Edmonton, Alberta, is a heavily used lake for recreational and industrial purposes. Though classed as a mildly eutrophic lake (mean chlorophyll-*a* concentration of ~11 µg/L; Casey, 2003), gradual eutrophication of the lake since European settlement has been detected in cores of lake sediment and has been a concern of residents for some time (Mitchell, 1985; Schindler et al., 2004). An extensive eutrophication study was instigated in the early 1980s to investigate the sources of nutrients to the lake and to address public concerns of water quality degradation (Mitchell, 1985). Though the study concluded that water quality degradation at the lake was not occurring, recommendations were made to develop a nutrient control program to preserve the status of the lake. In 2006, the Wabamun Watershed Management Council (WWMC) was formed, comprised of a cross-section of community, business, government and non-government organization representatives. The main goal of the WWMC was to draft a watershed management plan that would protect lake water quality and guide future development and stewardship in the watershed. Lake eutrophication was selected as the primary lake management issue by the WWMC in 2007 and an updated eutrophication study was initiated at Wabamun Lake for 2008 runoff and open water conditions (early March to mid October).

The objectives of the 2008 eutrophication study at Wabamun Lake were to delineate the proportional contributions of phosphorus to the lake through environmental sampling and historical data analyses, compare 2008 results with the early 1980s study, and evaluate nutrient budget results from Wabamun Lake against other lakes in Alberta.

3. Methods

Study Area

Wabamun Lake is located in Alberta's dry mixedwood subregion of the boreal forest (Figure 1; Natural Regions Committee, 2006). Wabamun's watershed area is approximately 273 km^2 with agriculture (~32 %) and forest (~29 %) the major land cover types (Table A1). Soils in the area are generally high-nutrient gray luvisols atop extensive glacial till deposits (Alberta Agriculture, 2009). Drainage from the watershed is mostly ephemeral through approximately 35 defined watercourses but less than 10 substantial streams typically run beyond snowmelt (Mitchell, 1985). Approximately 1,600 people are permanent residents in the watershed with an estimated 2,800 seasonal residents (Tymchyshsyn, 2005). Extensive development has occurred along the majority of the lake's waterfront and coal mines exist north and south of the lake, which supply fuel to two coal-fired power plants in the watershed as of 2009.

Wabamun Lake area covers 80.3 km^2 at the approximate elevation of the outflow weir structure (724.55 m asl). The total watershed-to-lake ratio is approximately 3.4 with the effective watershed area lower due to the diversion of mine and plant-related runoff away from the lake. Wabamun Lake is relatively shallow with a mean depth of about 6 m and a maximum depth of about 11 m in the western basin. Water levels have fluctuated up to 1.5 m throughout the measurement record (1915-present), depending mostly on meteorological conditions. A water treatment plant (Wabamun Water Treatment Plant; WWTP) delivers treated North Saskatchewan River water to the lake to offset surface and groundwater interception due to mining activity and at peak production can contribute up to 20% of all water delivered to the lake annually (Seneka, 2002). The lake is oriented along the prevailing wind direction and its relatively open basin morphology results in a well-mixed water column during open water conditions. Wabamun's trophic classification is best described as mesotrophic to eutrophic with extensive aquatic vegetation growth and moderate to high algae concentrations. Total phosphorus (TP) correlates well with algae concentrations over the 25 year monitoring record at the lake and suggests a phosphorus-limited system for algae growth (Casey, 2003).

Lake phosphorus budget

Water and phosphorus budget calculations

Reliable lake phosphorus budgets require accurate lake water balances. Wabamun Lake is suitable for calculating relatively precise phosphorus budgets due to extensive water balance studies which are likely the most complete of any lake in Alberta (e.g. Seneka, 2002; TransAlta Utilities [TAU], 2006). The general water balance model for the lake can be expressed as:

$$\Delta S = (R+P+G_{in}+A) - (G_{out}+D+O+E) \qquad (1)$$

where ΔS is the change in lake volume (storage) during the 2008 runoff and open water season
R,P,G_{in},A are the water volumes *to* the lake from natural runoff and industry-related water, direct atmospheric deposition, groundwater, and domestic sewage, respectively

G_{out},D,O,E are the water volumes *from* the lake via groundwater, diversions, surface outflow and evaporation, respectively

Lake TP budgets require water balance data and can be calculated using a modified mass budget equation from Vollenweider and Kerekes (1980):

$$\Delta M = (I_R + I_P + I_G + I_A) – (O_G + O_D + O_O) – (LS) \quad (2)$$

where ΔM is the change in lake mass of TP during the 2008 runoff and open water season

$I_{R,P,G,A}$ are the TP mass fluxes *to* the lake from natural runoff and industry-related water, direct atmospheric deposition, groundwater, and domestic sewage, respectively

$O_{G,D,O}$ are the TP mass fluxes *from* the lake via groundwater, diversions and surface drainage

LS is the TP mass flux lost to (+) or released from (-) lake sediments

Data sources and watershed sampling

Lake

Wabamun Lake water levels were monitored by Water Survey of Canada daily throughout 2008 and stage-volume relationships from Seneka (2002) were used to track lake volume changes (ΔS) during the study. Alberta Environment (AENV) sampled Wabamun Lake surface water by snowmobile or boat approximately monthly at 2 sites for routine chemical parameters and nutrients (including TP) between 28-Feb and 16-Oct, 2008. Changes in TP lake mass (ΔM) between sampling intervals were calculated using average TP concentrations of the lake and calculated lake volumes at the time of sampling.

Runoff

Seven natural creeks were identified as “primary” streams (i.e. significant flow draining to Wabamun Lake) using results from Mitchell (1985) and a winter 2008 reconnaissance survey (Figure 1, Table 1). Primary streams were monitored for discharge and water chemistry at least seven times between 26-Mar. and 3-Sep., 2008 and sampling was flow weighted to early spring runoff. Instantaneous discharge was measured near the mouth of each stream by wading and using a Price-type current meter. Water was collected at discharge measurement locations as a subsurface grab using a 4L bulk sampler, except during ice-on conditions where auger holes were drilled at appropriate sites and an integrating bulk sampler was lowered through the hole to collect the water. Water was immediately poured off into several bottles for routine chemistry and nutrient analyses and sent to a contracted laboratory for processing.

Industry-related water draining from a power plant ash settling lagoon (Flyash_04) and the WWTP was monitored throughout the calendar year. Flow from Flyash_04 was monitored continuously by a flume control structure and WWTP discharge was measured continuously using flow meters at the lake-inflow tap. Routine chemistry and nutrients were measured from water samples collected as grabs at each flow site every two weeks by TAU and periodically throughout 2008 by AENV.

Water and phosphorus draining from unmeasured areas (streams + diffuse) of the watershed were estimated using results from measured streams. To estimate unmeasured runoff, total runoff of measured streams was divided by their total drainage area to produce a mean water yield (volume/area) from the majority of the Wabamun watershed. This yield was then multiplied by the unmeasured drainage area to produce an estimate of unmeasured runoff. TP mass fluxes from unmeasured areas were estimated by regressing runoff and TP mass flux from measured streams ($r^2 = 0.96$). This relationship was then used with estimates of unmeasured runoff to produce an estimate of TP mass flux from unmeasured areas of the watershed. Watershed areas were delineated using ArcGIS 9.2, ArcHydro Tools 9, and data from the Government of Alberta.

Runoff (R) was calculated by scaling instantaneous primary stream and industry-related flows to daily flows, linearly interpolating between sampling dates and summing all volumes. Volumes estimated from unmeasured runoff were added to primary stream and industry-related volumes. I_R was calculated as the product of instantaneous TP concentrations and flow on the sampling dates at primary and industrial sampling stations. Daily mass fluxes were calculated and fluxes between sampling dates were estimated using a linear relationship. TP mass fluxes from unmeasured areas were added to summed primary stream and industry-related masses, similar to the R calculation.

Precipitation

Bulk atmospheric deposition (wet + dry) was collected eight times between 21-May and 23-Sep., 2008 in the south-eastern portion of the watershed using replicate Nilu bulk precipitation collectors (P.no. 9713). Samples were collected only after precipitation events of 8 mm or more in a 24 hour period. After an event, each sample was inspected for contamination before being pooled as one bulk sample. The sample was well-mixed then poured off into bottles for analyses similar to streams. All deposition and stream samples were stored in coolers and sent as soon as possible to appropriate contracted laboratories for analysis.

Precipitation (P) was calculated as a product of total rainfall depths during the open water season from two nearby meteorological stations (Stony Plain, AB; Entwistle, AB; Environment Canada, 2009) and Wabamun Lake surface area. I_P was calculated as the product of rainfall depths and measured TP concentrations on sample dates and scaled and summed between 1-May and 16-Oct. using a linear relationship. The water volume and TP load within the snowpack on the lake ice before the ice-off date of 01-May was estimated using mean measured rainwater TP concentrations from 2008 and mean snow-water equivalent measurements provided by the Canadian Cryospheric Information Network (2009). This water and TP load was assumed to go directly into the lake upon ice-off and was added to P and I_P, respectively.

Groundwater, etc.

Groundwater (G) for Wabamun Lake was calculated using annual groundwater inflow (G_{in}) and outflow (G_{out}) volumes from the Seneka (2002) water balance model, scaled to the study period. I_G and O_G were calculated as the product of mean TP concentrations in watershed groundwater (Mitchell, 1985) and G_{in} and G_{out}. Inputs of A and I_A were calculated using residential statistics from Tymchyshsyn (2005), mean household water use and human phosphorus mass production statistics (Mitchell, 1998) and an assumption that 4% of all domestic sewage produced in the watershed enters the lake. This assumption is based on extensive peizometer and septic leachate surveys performed by Mitchell (1985). Diverted water (D) was estimated using historical water license records from AENV and TAU and O_D was calculated as a product of D and mean lake TP concentrations over the 2008 study period. Lake outflow losses (O and O_O) were measured and calculated identically to primary streams at the lake outflow weir at the east end of the lake (Figure 1). E and LS were calculated by remainder in (1) and (2) respectively. E was cross-referenced with modelled values from Seneka (2002) and was within historical variation.

4. Results and Discussion

General hydrological conditions

During the 2008 calendar year, conditions in the Wabamun Lake watershed were dry compared to historical averages experienced at the nearby Stony Plain meteorological station (Environment Canada, 2009). Snowpack depth during March was approximately 50% lower compared to normal and precipitation was 20-30% lower compared to mean conditions. Below average precipitation had been prevalent in the region for the decade previous of 2008 (Environment Canada, 2009). These conditions contributed to a short, ephemeral runoff from the watershed with several primary streams drying or reducing to near-zero flow by late spring or early summer (Figure 2). Compared to measurements taken during the early 1980s (Mitchell, 1985), surface runoff from the watershed was approximately 70% reduced and represented only 3% of all water delivered to the lake in 2008. Most water directed to the lake in 2008 was from atmospheric inputs falling directly onto its surface (~65%) and from industry-related inputs (WWTP and Flyash_04; 27%). Groundwater was estimated as a relatively minor input to the lake at 6%. Most water leaving the lake was from evaporative loss (88 %) with minor losses from groundwater (8%), diversions (3%), and surface outflow from the eastern portion of the lake (<1%). With little precipitation and intense evaporation, Wabamun Lake water levels declined approximately 30 cm during the open water season representing approximately a 5% loss of its water mass over the calendar year.

Phosphorus in watershed streams

Concentrations of TP and total dissolved phosphorus (TDP) in streams draining the Wabamun Lake watershed were generally similar throughout the sampling period. One exception was Fallis_13 which showed steady and very low concentrations of TP and TDP throughout the season (Table 2; Figure 3). Though flow was variable in this stream, there were no distinct seasonal or atmospheric-related patterns as observed in other streams, suggesting that groundwater comprised much of this stream’s chemistry and flow. This contrasts results from the early 1980s where Fallis_13 had the highest TP concentrations among all streams sampled over two years (Mitchell, 1985). This discrepancy may be due to upstream land-use changes, the drier conditions in the broader watershed or possibly beaver damming upstream.

Other streams showed different TP and TDP patterns compared to Fallis_13 with large streams (Seba_22-23, Rosewood_26-27) showing high phosphorus concentrations at the beginning of sampling. These were the only measured streams that were sampled during ice-on conditions and likely had little flow or exchange with the lake during this time based on stream and lake ice depths. This situation likely produced anoxia in bottom sediments causing reducing conditions which support phosphorus release from sediments and may explain observed increases of reduced nitrogen and iron at this time (Wetzel, 1983). Phosphorus concentrations declined after ice-out in these large streams but did remain relatively high during peak runoff (early April). High TP concentrations during runoff were observed in smaller streams, similar to the large streams. These high concentrations correlated well with total suspended solids (TSS; $p<0.001$) which have been shown to be a signature of surface runoff flowing through soil organic layers and soils influenced by agricultural or residential activity (Johnson et al., 1997).

Most streams showed an early summer TP and TDP peak which did not appear to be flow or precipitation related. This may have indicated a combination of increased growth and productivity of organisms and cycling of nutrients as ambient temperatures and irradiation increased. Subsequent sampling showed TP concentrations decreased as streams progressed toward low or zero flow later in the summer or where phosphorus-poor groundwater may have been a larger proportion of stream flow. Seba_20 showed some high TP concentrations which may have been related to bed disturbances within this stream which was rich with loose organic material and had a dense riparian cover. Ascot_09 was an anomaly compared to other streams since water and phosphorus yields were much higher from this watershed compared to all other streams. It was unclear why this was the case and should be investigated further since wet years may transform this creek into a very strong source of TP to the lake. Overall, TP was approximately between 0.05 and 0.30 mg/L across most streams and TDP:TP showed a mean of 54%. These data may suggest some anthropogenic impact on certain streams, though small compared to other, heavily agriculturalized streams in Central Alberta (>1 mg/L TP; Sosiak and Trew, 1996; AXYS, 2005; Lorenz et al., 2008). Water flowing from Wabamun Lake was dilute in TP (mean 0.034 mg/L) and concentrations were mostly steady during the sampling period, reflecting biological utilization in the lake and sequestration in sediments over the long-term.

Phosphorus inputs from industry-related activities were the two highest contributors of phosphorus to the lake next to atmospheric additions (Alberta Environment, 2009a,b). Inputs of phosphorus from industry-related water were significant because of large water volumes, rather than high phosphorus concentrations. Low TP concentrations from Flyash_04 (mean 0.022 mg/L TP) are a product of long water residence times in the flyash holding pond where particles settle out and particle-attached phosphorus is resultantly lower. Water from the WWTP is low in phosphorus (mean 0.006 mg/L TP) as a result of the drinking water treatment process that selectively removes particles and phosphorus.

Phosphorus in atmospheric precipitation

There are several possible sources of TP deposited onto lakes from the atmosphere including dust, organic material, pollen, fossil fuel combustion material, and agricultural sources (e.g. fertilizers), among others (Newman, 1995). Concentrations of TP and TDP measured in this study were highest at the start of sampling and decreased steadily thereafter (Figure 4), similar to results observed at Narrow Lake, Alberta (Shaw et al., 1989). Though this study was not designed to determine atmospheric source apportionment of TP, other studies have suggested pollen and early-season agricultural activities can increase deposition of TP during the spring time towards minimums later in the season (Tsukuda et al., 2006). The dissolved fraction of phosphorus in precipitation samples decreased from 97% at the beginning of sampling toward approximately 15% at end of the sampling period which may reflect increasing contributions of dust from drier land across the watershed and from open-pit mines in the watershed.

Phosphorus in Wabamun Lake

Phosphorus and chlorophyll-*a* concentrations in Wabamun Lake have been monitored consistently during the open water season from 1982-2008 (Figure 5). These data show a statistically significant positive relationship between chlorophyll-*a* and TP concentrations, as observed in many other lakes across Alberta (Figure 6; linear regression, $p<0.01$). Both chlorophyll-*a* and TP also inversely correlate significantly with Secchi disk depth in Wabamun Lake ($p<0.01$). Phosphorus concentrations vary widely over the Wabamun Lake record with statistically significant reductions after 1998 (t-test, $p<0.001$, Casey, 2003). Unlike TP concentrations in the lake, chlorophyll-*a* did not change significantly over time ($p>0.05$), illustrating the multiple factors that affect algae growth. Reductions of TP after 1998 are presumably linked to WWTP inputs of high calcium river water and subsequent co-precipitation of phosphorous with calcite (Casey, 2003; Schindler et al., 2004). Simple dilution may also have played a minor role as WWTP TP concentrations are typically low (~0.006 mg/L) and approximately one-third of Wabamun Lake's water mass has been delivered by the WWTP to date (Alberta Environment, 2009a). Concentrations of TP in 2008 increased steadily from ice-on conditions and generally matched with chlorophyll-*a* concentrations well (Figure 7). During the same period TDP showed a decreasing trend, possibly reflecting the use and tight recycling of dissolved phosphorus in the aquatic environment (Wetzel, 1983). Increases of TSS during this time suggest that much of the measured phosphorus was related to the murky condition of the water due in part to algae communities.

Wabamun Lake phosphorus budget 2008

Phosphorous and chlorophyll-*a* concentrations during 2008 classify Wabamun Lake as moderately eutrophic despite little contribution from watershed TP sources (Figure 7). External phosphorus inputs to Wabamun Lake were dominated by direct precipitation (wet + dry) onto the lake surface (78%) and comprised 43% of phosphorus input to lake water when internal sediment loading was included (Table 3;

Figure **A3**). This relatively high percentage of phosphorus from direct precipitation was more a reflection of the drier watershed conditions rather than high deposition rates from the atmosphere. The annual atmospheric bulk deposition flux of TP to the Wabamun watershed was measured at 20.6 mg/m^2 in 2008, within the lower range of several other studies across the world (Pollman et al., 2002) and similar to previous estimates at Wabamun and other sites in Alberta (21.9 mg/m^2 Wabamun Lake, Mitchell, 1985; 20 mg/m^2 Narrow Lake, Shaw et al., 1989). Natural runoff was an insignificant source of external TP to the lake (6%) despite some additions by streams with concentrations above Alberta Surface Water Quality Guidelines (TP>0.05 mg/L) (Table 2). Extended dry conditions in central Alberta likely meant water falling onto the large watershed (compared to the lake) was mostly conserved in soils and groundwater, or transpired through vegetation with minimal surface overland runoff. Water falling directly onto the lake surface would be a direct addition of TP to the lake system. Other external inputs of TP to the lake from industrial inputs (5%) and domestic sewage (2%) as well as groundwater inputs (9%) were low. With evaporation leaving behind solutes, TP losses from the lake were mostly from groundwater leaving the system (89%) and less from diversions

(10%) and lake outflow (1%). Falling water levels limited the amount of water exiting across the controlled weir structure at the east end of the lake.

Overall, much more TP was delivered to the lake (2,190 kg-TP) than what was lost (490 kg-TP) during 2008. However, observations in the lake itself showed much higher TP concentrations and mass gain (3,371 kg-TP) than would be explained from net external additions alone, leading to an assumption of large releases of TP internally from lake sediments (43%) (LS) or larger contributions by groundwater. Lake sediments as strong source of TP to lakes is thought to be due to natural accumulation of nutrient rich watershed material and land clearing and resulting erosional, agricultural and residential pollution (Schindler et al., 2008). Phosphorus release from sediments at Wabamun Lake has been observed in past studies and was estimated to contribute 55% of all TP inputs to lake water from 1980-82 (Mitchell, 1985). The bioavailability of this TP released from sediments has the potential to be very high considering results from other eutrophic lakes in Alberta that show up to 99% of TP released from sediments is available to biota (Sosiak and Trew, 1996). Though several factors control the extent and duration of algae blooms on lakes, it is reasonable to suggest that TP released from sediments plays an important role in algae productivity in Alberta lakes. Inputs of phosphorus from groundwater may also have contributed more TP than anticipated to Wabamun Lake in 2008 as groundwater is poorly characterized as a phosphorus source at most lakes (Holman et al., 2008). However, previous studies have suggested groundwater is a minor source of water and nutrients to Wabamun Lake (Seneka, 2002; Mitchell, 1985).

Wabamun nutrient budgets: 2008 vs. the early 1980s

Comparing Wabamun Lake nutrient budgets from the early 1980s to 2008 (Table 4) is difficult primarily due to the sharp contrast in hydrological conditions between studies. Under similar environmental conditions, changes in watershed land cover, population, or industrial practices could be scrutinized based on differences between nutrient budgets. However, the early 1980s study, as mentioned previously, was performed during high runoff years where snowmelt would have wide-ranging contact with land throughout the watershed and in turn be chemically altered (e.g. fertilized land, etc.). In 2008, very little runoff occurred throughout the watershed, giving way to increased emphasis on direct atmospheric and groundwater inputs, which have less interaction with the watershed surface where anthropogenic effects largely occur. This hypothesis was supported by comparing percent agricultural cover in primary stream subwatersheds with 2008 stream phosphorus concentrations, which yielded no significant relationship (linear regression, $p>0.53$). Results from countless other studies have established the paradigm that stream nutrient contents increase with increasing agricultural influence (see Carpenter et al., 1998; Lorenz et al., 2008).

What these nutrient budget studies have provided is an effective constraint on nutrient inputs to the lake during hydrological extremes in the watershed. For example, we can be reasonably confident that TP concentrations in Wabamun Lake water are approximately half due to inputs from sediments, regardless of snowpack or rainfall amounts. We also see that watershed inputs of TP, and by conjecture, land use, can be very important factors during years that are particularly wet. This assessment appears to be reasonable since land cover has changed little across the watershed in the past 15+ years when comparing data from Mitchell

(1985) with Landsat TM and 7 ETM imagery in 2000 (e.g. dense forested area in the watershed changed from ~30.7% in early 1980s to ~29.2% in 2008).

Phosphorus budgets: Wabamun and Alberta Lakes

Phosphorus budgets have been estimated at several lakes across Alberta (Table 4), though the majority of lakes are not as well characterized as Wabamun in terms of watershed hydrology and groundwater. Most budgets were estimated by measuring surface runoff and lake chemistry during an open water season, using previously published meteorological data in Alberta, and estimating domestic sewage inputs (often worst-case scenarios). Groundwater and sediment exchanges of phosphorus were usually combined as a single factor and were estimated to close the lake balance (i.e. change in TP mass observed in lake less runoff and atmospheric inputs leaves remainder assumed to be sediment and groundwater additions). In most cases, groundwater was assumed to be a minor TP input to lakes and sediment exchanges were assumed to comprise most of the unaccounted TP in the lakes.

Aside from this study, 15 TP lake budgets have been published by AENV (Table 4), representing a cross-section of popular, mostly eutrophic, recreational lakes. Though each budget component showed variable percentages of TP inputs to lakes, 11 of the 15 budgets showed inputs from lake sediments as the largest source of TP to the lakes. From this small dataset, there appears to be a significant, positive relationship between %TP from sediments and mean algae concentrations (linear regression, $p=0.012$). In a review of 28 shallow lakes across Alberta, Sosiak and Trew (1996) showed that the majority of TP delivered to lakes in their dataset were dominated by inputs from sediments. In a study of several global lakes, Jeppesen et al. (2005) showed that by decreasing external TP loading, it is expected that TP concentrations will decrease in water of productive deep and shallow lakes. However, shallow lakes with high contributions of TP from sediments were shown to take up to 35 years to recover after strict control of external loading. AENV data suggest that Alberta lakes my be slow to recover after a reduction of external TP inputs and may not respond to watershed stewardship and nutrient reduction programs quickly. Short-term efforts to reduce internal TP loading including chemical addition, dredging or biomanipulation have historically shown mixed results in terms of reduced eutrophication and little is known about long term effects of such approaches on ecological function of lakes (Sondergaard, et al., 2007). It is also unclear how such technologies can be applied to very large natural lakes, such as Wabamun Lake. What is clear is that further study into short term treatment of lake sediments in Alberta is warranted before implementation at large recreational lakes. Regardless, it is widely accepted that permanent improvements to lake eutrophication can only be achieved with a component of external TP loading reductions over the long-term (Sondergaard, et al., 2007). Lake sediments in Wabamun Lake currently harbour a memory effect from land clearing, agricultural and industrial activities, and residential development of the lake's waterfront and watershed, much of which occurred mid last century. Sound watershed planning is essential to reduce external TP loading to the lake and to protect the mechanisms which are slowing the algal eutrophication of the lake.

Guidance for stream stewardship in the Wabamun Lake watershed can be taken from the recently published Alberta Environmentally Sustainable Agriculture (AESA) water quality monitoring project (Lorenz et al., 2008). For seven years, the AESA project measured nutrient concentrations from 23 streams across Alberta draining different intensities of agricultural development in their watersheds. Statistically significant differences in flow-weighted TP concentrations between low, moderate and high watershed agriculture intensities were discovered. TP concentrations draining from moderately intensive agricultural streams showed mean TP concentrations of 0.28 mg/L while high agricultural intensity streams showed mean concentrations of 0.51 mg/L. Wabamun Lake streams fall within the moderately intensive agricultural classification. If an approach of no further degradation of streams was agreed to by stakeholders at Wabamun Lake, a reasonable guideline could be set that mean concentrations from streams draining throughout the Wabamun watershed should not approach the 0.5 mg/L level signifying the high agricultural intensity streams as defined in the AESA report.

5. Conclusions and Recommendations

Though a mildly eutrophic system, Wabamun Lake has become more eutrophic since broader European settlement in the region, a trend observed at other lakes throughout Alberta. Eutrophication studies at Wabamun have established lake sediments as a key contributor of phosphorus to the lake water, and likely play an important role in the growth of algae communities. Phosphorus from surface runoff can be an important external addition to lake water depending on precipitation intensity and previous meteorological trends. Phosphorus deposition from the atmosphere onto Wabamun Lake is not different from other regions of the province and plays a variable role on phosphorus additions the lake. Studies from other locations show that shallow lakes with high phosphorus contributions from sediments can take several decades to decrease in productivity if external additions are strictly controlled. Short-term treatment of lakes or sediments through biomanipulation, chemical addition or dredging has shown variable successes in both deep and shallow lakes and long-term effects of these activities are not well understood at present, especially in North American lakes. Further investigation into short-term sediment treatment options at lakes in Alberta is warranted before any potential implementation. Regardless of sediment treatment approaches, it is understood that stabilizing eutrophication in lakes cannot be achieved without reducing additions of phosphorus from the watershed which will require a long term stewardship commitment by all stakeholders with an interest in Wabamun Lake.

External nutrient control programs and watershed stewardship at Wabamun Lake will be key components for long-term protection of the lake from accelerated eutrophication. These programs should concentrate on improving agricultural practices, rehabilitating stream riparian areas and investigating streams with the potential for large phosphorus additions (e.g. Fallis_13, Ascot_09).

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8. Tables

Table 1 Site locations for all measured streams, industry-related water and atmospheric sampling sites. Bolded sample dates represent ice-influenced sampling. Asterisk (*) indicates continuous flow monitoring by a permanent station.

Name	Type	Sampling location	Sample Dates (2008)
Ascot_09	PS	53° 33.6' N 114° 32.3' W	3/26; 4/9,16,29; 5/8,20; 6/2,26; 7/28; 8/3
Coal_12	PS	53° 34.4' N 114° 37.2' W	4/9,14,28; 5/8,20; 6/2,26; 7/28; 9/3
Fallis_13	PS	53° 34.8' N 114° 40.8' W	3/27; 4/9,16; 5/8,20; 6/2,26; 7/28; 9/3
Freeman_05	PS	53° 33.9' N 114° 33.2' W	4/9,14,16; 5/8,20; 6/2
Rosewood_26-27	PS	53° 32.1' N 114° 40.0' W	**3/27**; 4/14,28; 5/8,20; 6/2,26; 7/28; 9/3
Seba_20	PS	53° 33.3' N 114° 44.2' W	3/27; 4/9,16; 5/8,20; 6/2,26; 7/28; 9/3
Seba_22-23	PS	53° 32.8' N 114° 43.8' W	**3/27**; 4/14,28; 5/8,20; 6/2,26; 7/28; 9/3
Wabamun_Outlet	LO	53° 31.9' N 114° 26.7' W	5/8,20; 6/2,26; 7/28; 8/3
Flyash_04*	IND	53° 33.5' N 114° 30.6' W	3/26; 4/9,16; 5/8; 6/2,26; 7/28; 9/3
Wabamun_WTP*	IND	53° 30.9' N 114° 33.1' W	Every approx. 6 days
Highvale_01	P	53° 27.6' N 114° 27.9' W	5/21; 6/9; 7/7,23,29; 8/21; 9/3,23

Key: PS-primary stream; LO-lake outlet; IND-industry-related water station; P-precipitation station

Table 2 Flow-weighted mean concentrations (mg/L) of phosphorus and other relevant measures for the measured portions of nutrient mass balance from 2008.

Parameter	Unit	Tributaries							Outlet	Precip	Industrial		Lake
		Ascot_09	Coal_12	Fallis_13	Freeman_05	Rosewood_26-27	Seba_20	Seba_22-23	Wabamun_Outlet	Highvale_01	Flyash_04	Wabamunn_WTP	Wabamun Lake
Total Phosphorus	mg/L	0.101	0.094	0.021	0.052	0.153	0.102	0.124	0.033	0.069	0.017	0.006	0.021
Total Diss. Phosphorus	mg/L	0.042	0.042	0.011	0.042	0.069	0.056	0.060	0.012	0.054	0.009	0.005	0.008
Total Susp. Solids	mg/L	6.4	7.8	L3	L3	11.4	5.9	8.1	L3	26.5	L3	4.1	5.0
Water Temperature	°C	5.7	5.0	6.9	5.7	15.0	7.3	5.2	16.5	-	12.3	-	13.9
pH	-	7.8	7.9	8.0	8.0	7.8	7.8	7.7	7.9	5.3	8.8	8.1	8.5
Discharge	m3/sec	0.014	0.008	0.002	0.003	0.011	0.002	0.027	0.015	-	0.139	0.366	-
Dissolved Oxygen	mg/L	9.6	10.2	10.3	11.1	7.5	10.1	9.9	6.7	-	9.8	-	8.7
Specific Conductance	µS/cm	645	596	761	723	577	604	437	571	16	606	573	583

Table 3 Water and total phosphorus mass budgets for Wabamun Lake from 28-February to 16-October, 2008.

LAKE WATER BUDGET (,000s of m3 unless otherwise stated)

Lake Sample Date	R		P	G_{IN}	A	G_{OUT}	D	O	Lake Level	Lake volume (V)	ΔV	Σ I - ΣO	E
	nat.	*ind.*							*(m asl)*				
28-Feb	-	-	-	-	-	-	-	-	724.55	499,969	-	-	-
29-May	874	4,146	6,782	811	2	1,721	611	76	724.64	506,935	6,966	-	-
23-Jun	97	1,068	3,759	225	1	478	170	40	724.63	506,161	-774	-	-
22-Jul	37	1,056	5,188	261	1	555	197	18	724.58	502,291	-3,870	-	-
19-Aug	28	1,010	3,991	252	1	536	190	1	724.47	493,777	-8,514	-	-
16-Sep	40	1,083	2,626	252	1	536	190	0	724.42	489,907	-3,870	-	-
16-Oct	29	1,534	1,735	270	1	574	204	0	724.35	484,489	-5,418	-	-
TOTAL	11,002		24,081	2,071	7	4,400	1,562	135	-	-	-15,480	31,064	46,544
Input%	3	27	65	6	<1	-	-	-	-	-	-	-	-

LAKE TOTAL PHOSPHORUS BUDGET (kg unless otherwise stated)

Lake Sample Date	I_R		I_P	I_G	I_A	O_G	O_D	O_O	Lake Level	Lake volume (V)	TP in Lake	TP in Lake	ΔM	LS (to +) or (from -)
	nat.	*ind.*							*(m asl)*	*(,000 m3)*	*(mg/L)*			
28-Feb	-	-	-	-	-	-	-	-	724.55	499,969	0.017	8499	-	-
29-May	59	98	440	81	15	171	18	3	724.64	506,935	0.020	9885	1,386	-885
23-Jun	12	10	699	22	4	48	5	1	724.63	506,161	0.021	10629	744	-50
22-Jul	14	4	348	26	5	55	6	1	724.58	502,291	0.022	11050	421	-85
19-Aug	11	3	124	25	5	53	6	0	724.47	493,777	0.016	7654	-3,397	+3,505
16-Sep	8	4	60	25	5	53	6	0	724.42	489,907	0.024	11758	4,104	-4,061
16-Oct	11	3	35	27	5	57	6	0	724.35	484,489	0.025	11870	112	-95
TOTAL	237		1,706	206	39	437	47	5	-	-	-	-	3,370	-1,671
Input %	3	3	44	5	1	-	-	-	-	-	-	-	-	43

I_R = input, runoff; I_A = input, domestic sewage; I_p = input, precipitation; I_G = input, groundwater; nat.=natural runoff (tributary+diffuse); ind.=industry-related

O_G = loss, groundwater; O_D = loss, diversions; O_O = loss, outflow; O_E = loss, evaporation

LS is the TP mass fluxes lost to (+) or regenerated from (-) lake sediments

Water budget: $\Delta V = (R+P+G_{IN}+A) - (G_{OUT}+D+O+E)$

Phosphorus budget: $\Delta M = (I_R + I_P + I_G + I_A) - (O_G + O_D + O_O) - (LS)$

Table 4 Review of phosphorus loading sources to lakes across Alberta.

Alberta Lake	**Time Period**	**Runoff (%)**	**Atmospheric Deposition (%)**	**Sediments / Other(%)**	**Domestic Sewage (%)**	**Diversions(%)**	**Ground-water* (%)**	**Mean Chlorophyll-*a* (μg/L)**
Burnstick[1]	1995	90	6	-	4	-	-	2.6
Gull[2]	1999-00	31	11	52	7	-	-	7.5
Isle[3]	1996	49	2	42	7	-	-	38.6
Lesser Slave[4]	1991-93	28	7	65	-	-	-	40.3
Lower Mann[5]	Various	12	1	69	18	-	-	96.5
Moose[6]	Various	61	6	32	1	-	-	20.6
Pakowki[7]	1996	9	2	90	-	-	-	34.6
Pine[8]	1992	36	3	55	6	-	-	22.2
Ste. Anne[3]	1996	36	4	55	5	-	-	43.8
Sandy[9]	Various	21	6	73	1	-	-	82.5
Sylvan[10]	2005	32	20	11	13	-	24	4.4
Thunder[11]	1992-1996	13	8	55	-	24	-	28.8
Upper Mann[5]	Various	21	1	55	24	-	-	37.0
Wabamun[12]	1980-82	23	13	55	1	6	2	11.3
Wabamun[13]	2008	3	44	43	1	3	5	
Wizard[14]	Various	35	4	46	15	-	-	22.7
Mean	**-**	**31**	**8**	**50**	**8**	**2**	**-**	**32.9**

*Groundwater only evaluated at 2 lakes within lake set whereas groundwater inputs to other lakes was assumed to be a small portion of "other" category.
[1,2,3,6,9,11,12,14]Mitchell 1995, 2003, 1997, 1992, 1993, 1998, 1985, 1998, respectively; [4] Noton, 1998; [5]Anderson, 1993; [7,8] Sosiak, 1997, 1996, respectively; find all reports at Alberta Environment Information Centre http://environment.gov.ab.ca/info/home.asp; [10] unpublished data-Alberta Environment; [13] this study.
Burnstick-1991, 93,94,1999, 2004; assume all domestic sewage enters lake
Gull-1983-85, 1987-99, 2006; assume all domestic sewage enters lake
Isle-1983-85, 1988, 96-98, 2002; assume all domestic sewage enters lake
Lesser Slave-1991-93, 2000; assume all domestic sewage enters lake
Mann- assume all domestic sewage enters lake; 1983-84; 1992
Moose-1983-1997, 2003-2006; domestic sewage included in sediments/other
Pine-1983, 1995, 2003-2006; domestic sewage included in sediments/other
Sandy-assume 4% of domestic sewage to lake; chla 1988, 1989, 1993, 2000, 2006;
Ste. Anne-1984-85, 1988, 1996-98; assume all domestic sewage enters lake
Sylvan-1983-1990, 1992-1997, 2003, 2006 chla; domestic sewage-% lots with septic
Thunder-domestic sewage included in sediments/other; chla 1983-2000; 2002, 2007
Wabamun-4% domestic sewage enters lake; 1980-2007
Wizard-assumed all domestic sewage went into lake, updated runoff based on 1981-84 runoff coefficients; chlorophyll from Atlas of Alberta Lakes + lakewatch reports (1981-82; 1984; 1996; 2006)

9. Figures

Figure 1 The Wabamun Lake watershed in west-central Alberta (approx. 53.5° N; 114.5° W). Primary stream subwatersheds (black lines) and primary stream, precipitation, lake outlet, and industry-related sampling sites (shaded circles) are shown.

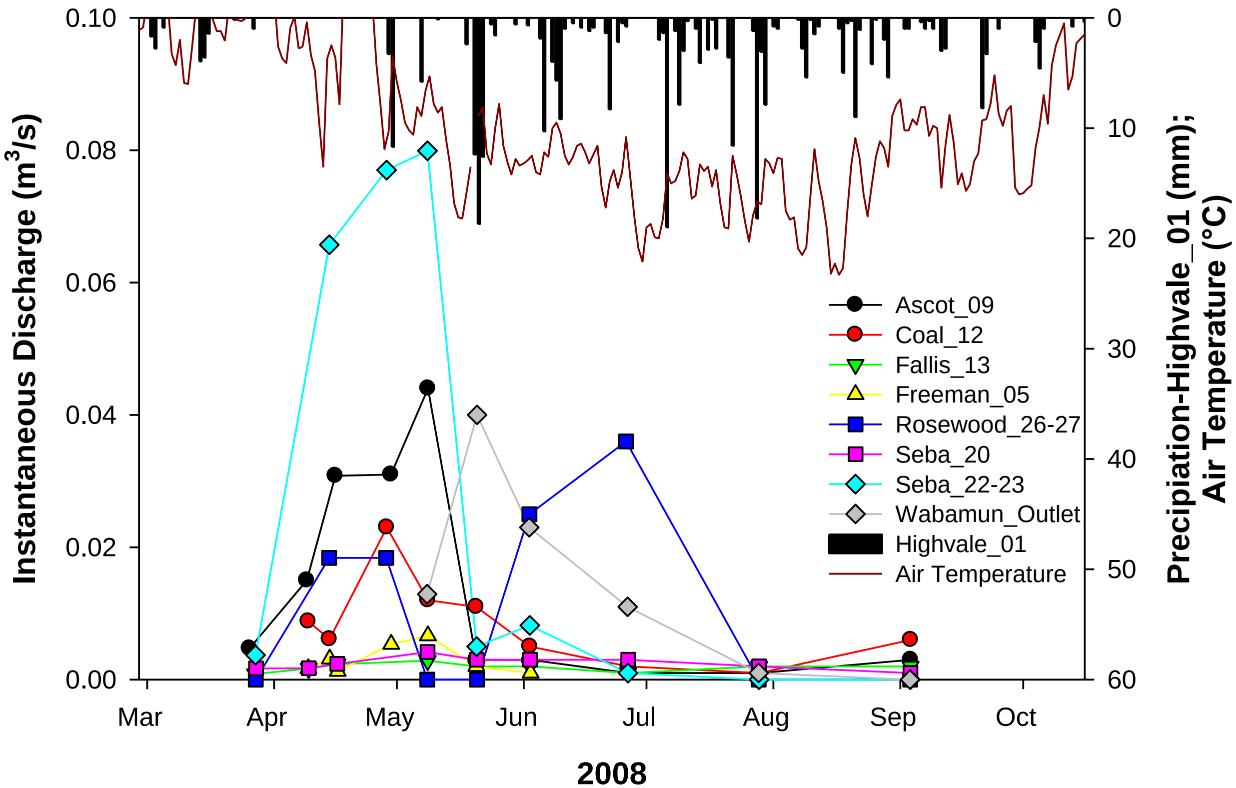

Figure 2 Wabamun Lake watershed atmospheric and hydrological measurements during the 2008 sampling period.

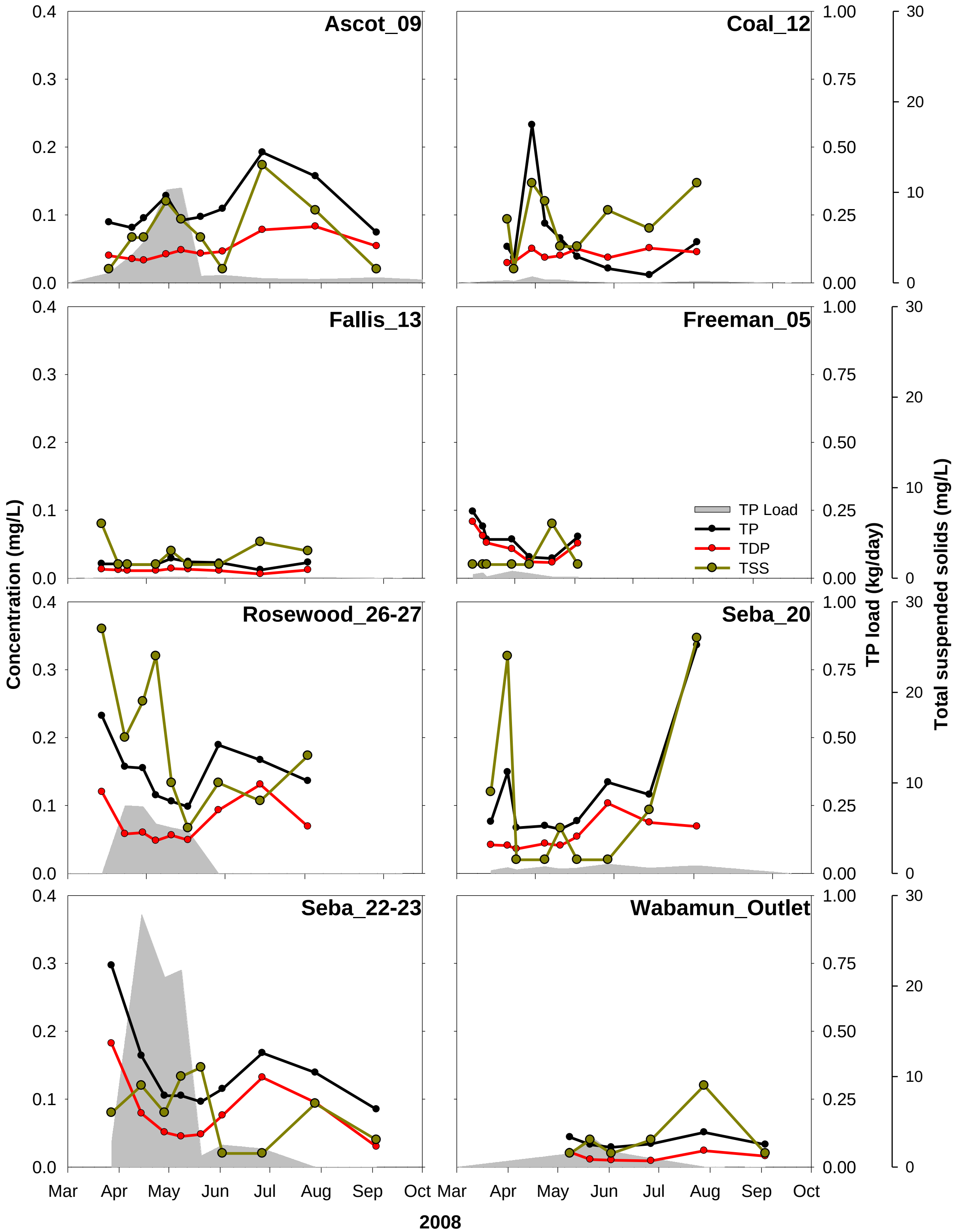

Figure 3 Phosphorus and suspended sediment concentrations and total phosphorus loads from all streams draining the Wabamun Lake watershed in 2008.

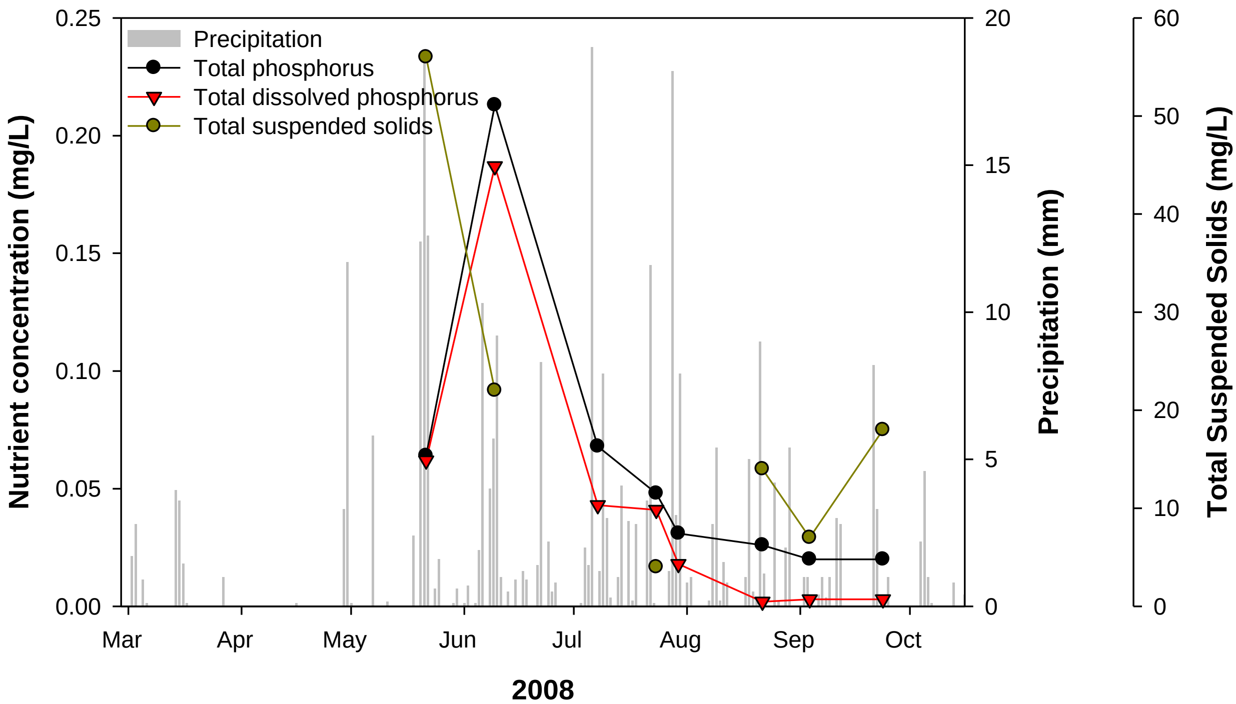

Figure 4 Bulk precipitation chemistry from samples collected in the southeast portion of the Wabamun Lake watershed during the 2008 sampling period.

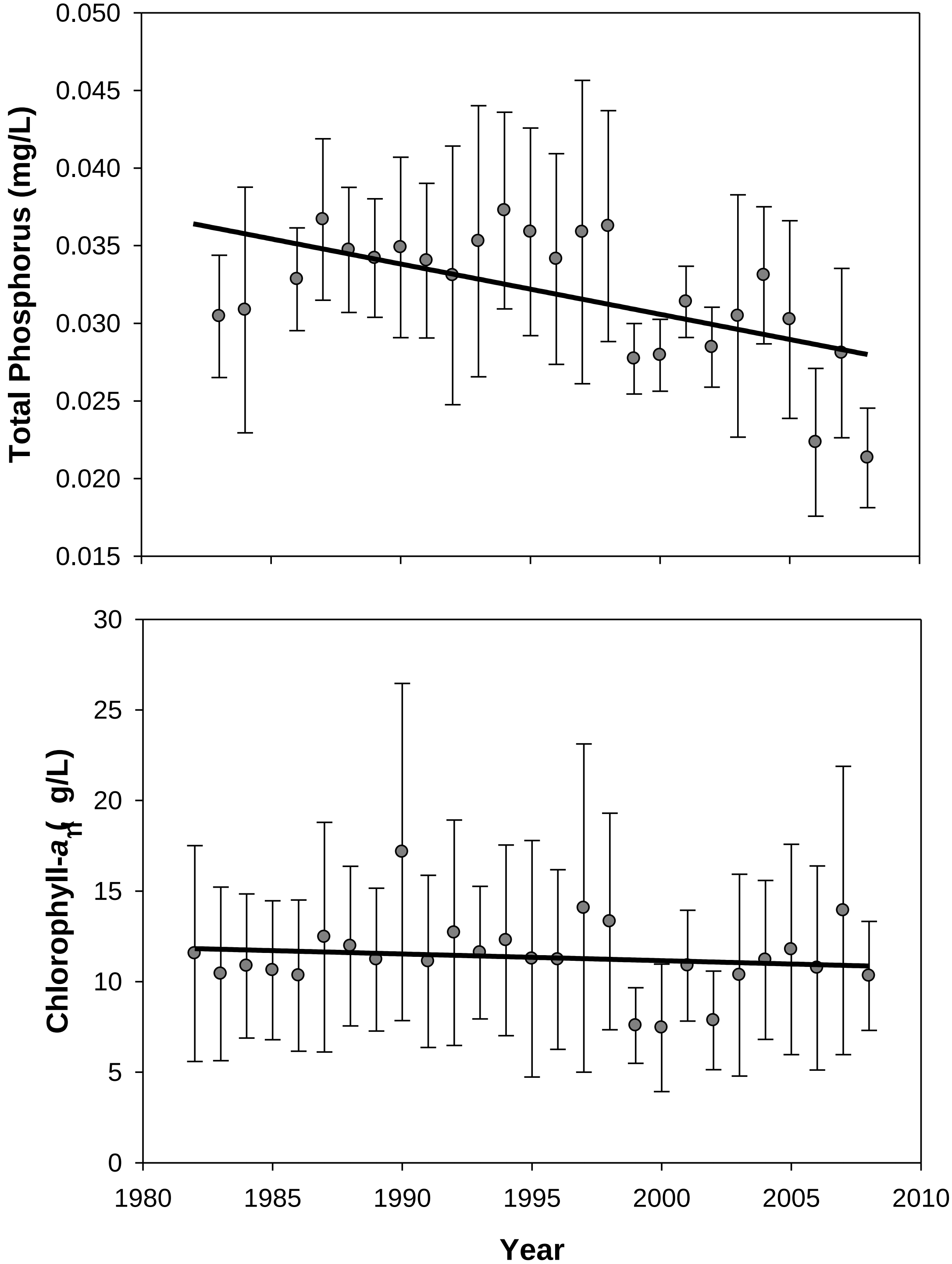

Figure 5 Annual open-water total phosphorus (upper) and chlorophyll-*a* (lower) concentrations at Wabamun Lake from 1982-2008. Error bars denote one standard deviation from the mean and the dark lines denote a fitted linear regression curve.

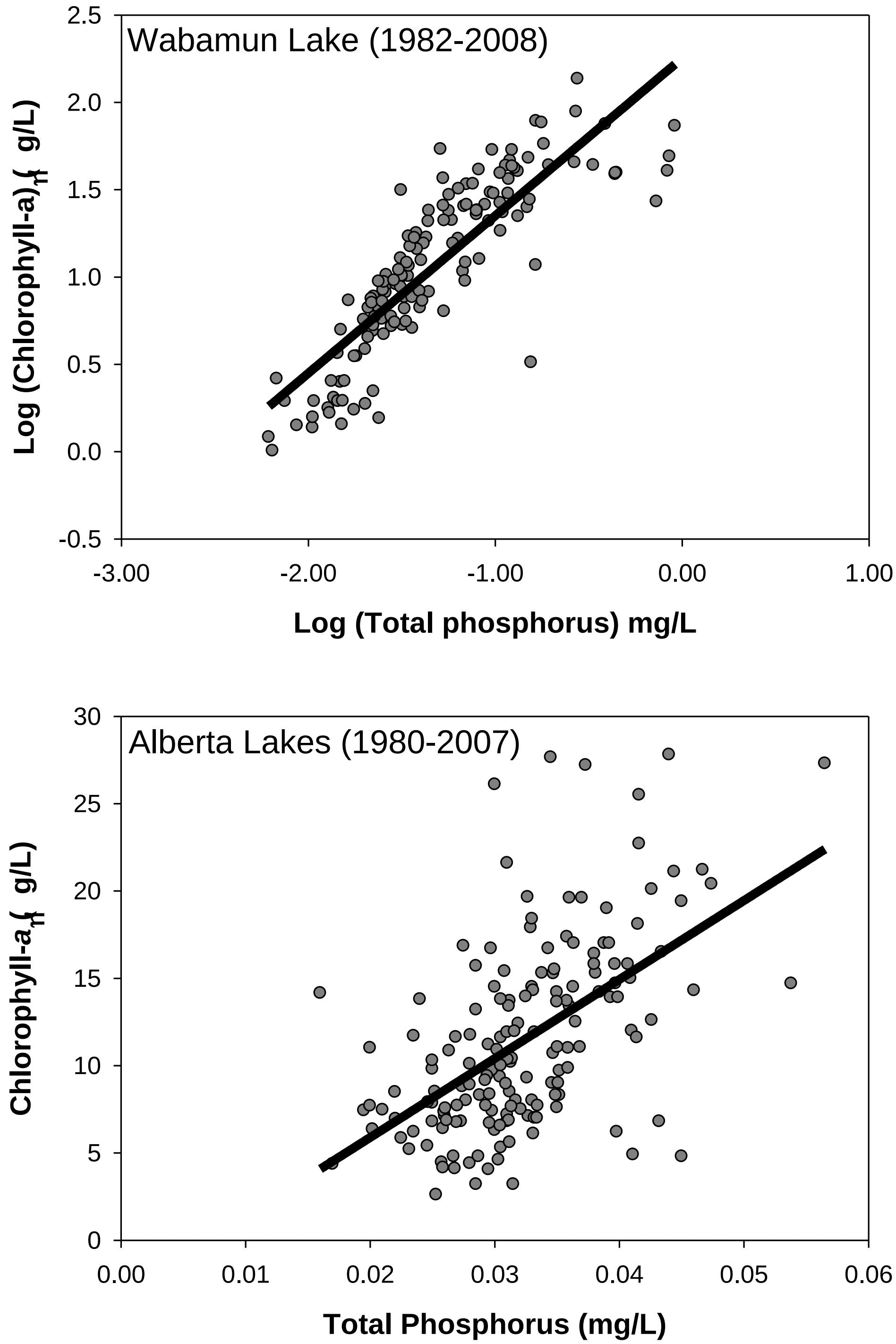

Figure 6 Chlorophyll-*a* and total phosphorus relationships from Wabamun Lake ($p<0.01$, linear regression, n=178) and from lakes and reservoirs across Alberta (data from Alberta Environment; $p<0.01$, linear regression, n=134). Note: log scale on upper chart.

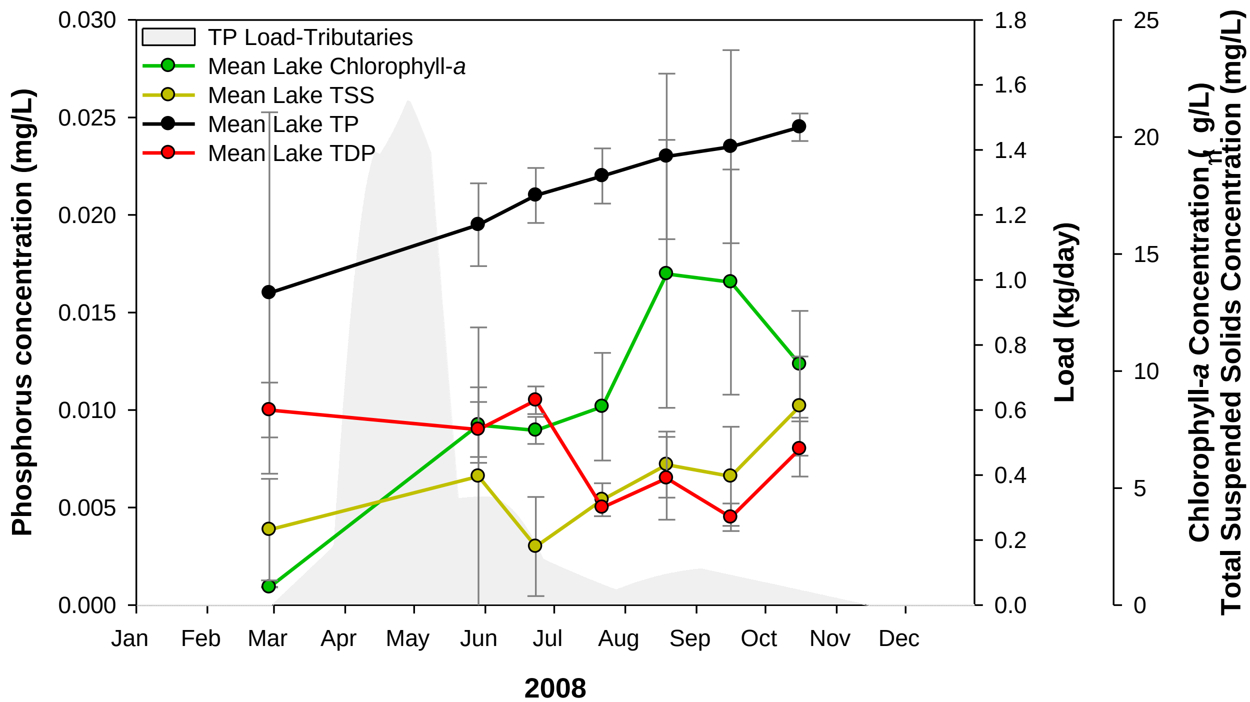

Figure 7 Mean lake phosphorus chemistry, chlorophyll-*a* and suspended sediment concentrations during the 2008 open-water season at Wabamun Lake. Tributary total phosphorus load is displayed in background as an area-fill. Error bars denote one standard deviation from the mean.

10. Appendix

Table A1 Percent land cover in subwatersheds of Wabamun Lake.

Subwatershed	Area (km2)	%Watershed	%Forested	%Agriculture/ Exposed Soil	%Urban	%Wetlands	%Grassland/ Shrubs
Primary Streams	**124.8**	**45.7**	**15.2**	**16.5**	**0.7**	**6.5**	**6.8**
Ascot_09	2.5	0.9	47.5	13.9	4.6	15.3	18.7
Coal_12	11.9	4.4	37.0	35.7	2.1	10.1	15.2
Fallis_13	5.4	2.0	16.8	44.2	5.2	7.3	26.5
Freeman_05	3.3	1.2	40.4	33.0	2.0	7.0	17.7
Rosewood_26- 27	39.6	14.5	38.5	27.5	0.2	20.4	13.3
Seba_20	8.1	3.0	47.6	19.6	6.2	11.9	14.6
Seba_22-23	54.0	19.8	27.0	45.4	1.3	11.9	14.4
Secondary Streams	**25.0**	**9.2**	**3.4**	**2.4**	**0.4**	**1.0**	**2.0**
Diffuse Areas	**39.5**	**14.5**	**6.1**	**1.3**	**0.2**	**3.4**	**3.4**
Mine-affected & Industrial	**83.8**	**30.7**	**4.6**	**12.2**	**0.2**	**10.0**	**3.7**
Watershed Total	**273.2**	**100.1**	**29.2**	**32.4**	**1.6**	**20.9**	**15.8**

Table A2 Mean stream and bulk deposition chemistry measurements during 2008 from the Wabamun Lake watershed.

	Tributaries							Outlet	Precip.	Industrial		Lake
	Ascot_09	**Coal_12**	**Fallis_13**	**Freeman_05**	**Rosewood_26-27**	**Seba_20**	**Seba_22-23**	**Wabamun_Outlet**	**Highvale_01**	**Flyash_04**	**Wabamunn_WTP**	**Wabamun Lake**
Field Measurements												
Water Temperature	5.7	5.0	6.9	5.7	15.0	7.3	5.2	16.5	-	12.3	-	13.9
pH	7.8	7.9	8.0	8.0	7.8	7.8	7.7	7.9	5.3	8.8	8.1	8.5
Discharge	0.014	0.008	0.002	0.003	0.011	0.002	0.027	0.015	-	0.139	0.366	-
Dissolved Oxygen	9.6	10.2	10.3	11.1	7.5	10.1	9.9	6.7	-	9.8	-	8.7
Specific Conductance	645	596	761	723	577	604	437	571	16	606	573	583
Major Ions & Related												
Calcium	76.5	84.9	90.6	92.8	37.5	56.5	43.8	28.4	1.0	22.1	51.4	26.8
Sodium	29.9	20.4	35.2	37.9	78.1	62.8	37.8	68.1	L1	82.9	42.6	70.3
Magnesium	27.8	23.8	29.6	27.4	10.5	13.7	11.5	20.3	0.2	16.4	19.4	19.6
Potassium	3.6	3.9	2.2	3.8	5.3	2.4	6.7	9.0	L1	8.4	2.5	9.5
Bicarbonate	409	416	480	436	318	355	264	264	L5	173	170	245
Carbonate	L5	L5	L5	L5	L5	L5	L5	L5	L5	19.2	L0.5	8.5
Sulphate	27.1	8.6	13.2	50.3	43.0	18.4	19.4	73.4	3.4	84.1	128.7	78.5
Chloride	10.5	13.2	23.6	10.6	2.6	23.8	8.0	11.0	L1	37.6	16.9	11.8
Alkalinity	336	341	395	357	264	292	216	217	L5	174	139	214
Hardness	305	310	348	344	137	197	157	154	3	123	208	146
Total Dissolved Solids	377	360	432	441	335	354	257	341	6	356	351	349

	Tributaries							Outlet	Precip.	Industrial		Lake
	Ascot_09	Coal_12	Fallis_13	Freeman_05	Rosewood_26-27	Seba_20	Seba_22-23	Wabamun_Outlet	Highvale_01	Flyash_04	Wabamunn_WTP	Wabamun Lake
Nutrients												
Total Phosphorus	0.101	0.094	0.021	0.052	0.153	0.102	0.124	0.033	0.069	0.017	0.006	0.021
Total Diss Phosphorus	0.042	0.042	0.011	0.042	0.069	0.056	0.060	0.012	0.054	0.009	0.005	0.008
Total Nitrogen	1.131	0.911	0.260	2.185	1.283	1.298	1.153	1.178	0.944	0.686	0.316	0.946
Total Kjdl. Nitrogen	1.119	0.828	0.221	1.498	1.275	1.078	1.146	1.172	0.684	0.680	0.309	0.919
Ammonia	0.071	0.135	0.026	0.020	0.016	0.122	0.029	0.020	0.313	0.007	0.081	0.059
Nitrate+Nitrite	0.011	0.082	0.039	0.687	L0.006	0.220	0.007	L0.006	0.260	L0.006	0.007	L0.006
Nitrate	0.009	0.077	0.038	0.680	L0.006	0.214	L0.006	L0.006	-	L0.006	0.005	L0.006
Nitrite	0.003	0.006	L0.002	0.006	L0.002	0.006	L0.002	L0.002	-	L0.002	L0.003	L0.003
Silica	16.2	14.1	15.6	14.9	6.8	10.3	7.7	0.5	0.3	3.2	4.0	1.7
Others												
Total Susp. Solids	6.4	7.8	L3	L3	11.4	5.9	8.1	L3	26.5	L3	4.1	5.0
Iron	L0.05	0.06	0.05	L0.05	0.07	0.15	0.39	L0.05	L0.05	L0.05	L0.06	L0.004
Manganese	0.27	0.59	0.09	L0.01	L0.01	0.27	0.15	0.04	0.01	L0.01	L0.004	0.006
Hydroxide	L5	L5	L5	L5	L5	L5	L5	L5	L5	L5	L0.5	L0.5
Fluoride	0.118	0.109	0.165	0.149	0.213	0.107	0.137	0.380	0.090	0.366	0.381	0.404

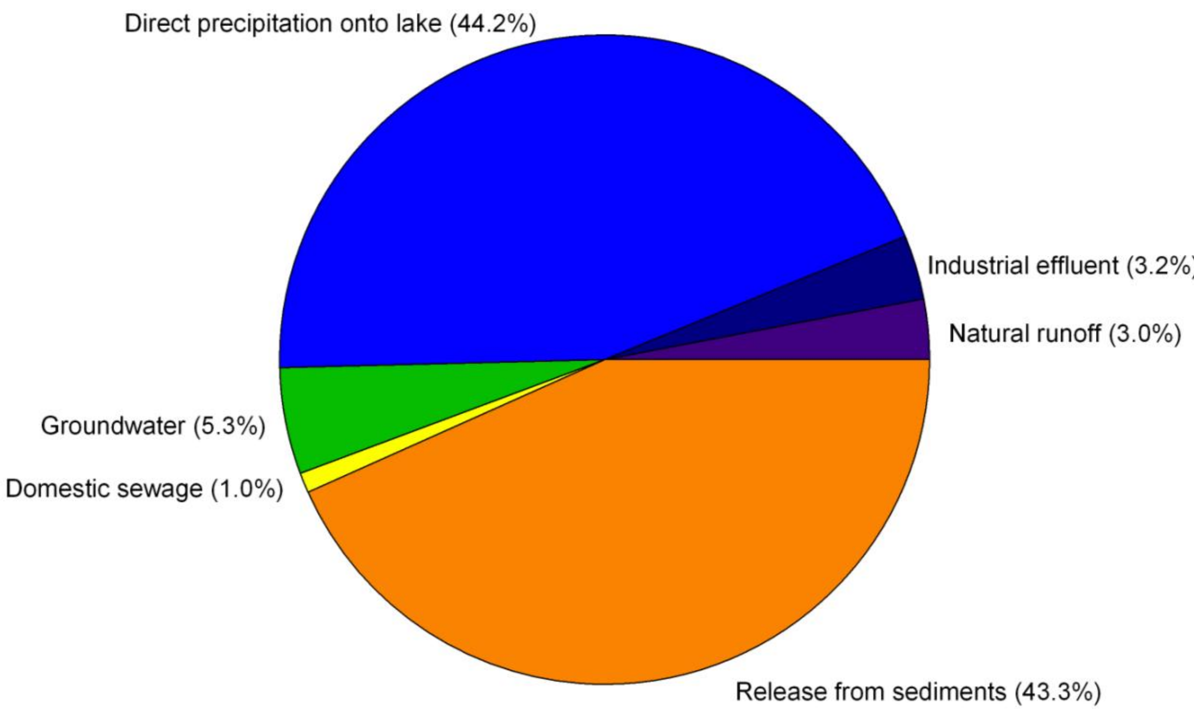

Figure A3 Total phosphorus loading as a percentage to Wabamun Lake water during the open water season of 2008.