

Manitoba Prairie Lakes: Mass balance budget for nutrient management at Pelican Lake, Manitoba



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Review and Advisory: Dr. Nora Casson and Dr. Scott Higgins

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The authors also wish to express their gratitude to several individuals for their insight, guidance and support in the development of this report. Thank you to Dr. Nora Casson and Dr. Scott Higgins for their peer review, and Assiniboine Hills Conservation District, Neil Zalluski and Devon Baete, for their collaborative effort in continuing and coordinating sampling and monitoring at Pelican Lake. We are also grateful to Dr. Casson for providing the much-needed hydrologic field equipment.

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Executive Summary

Eutrophication is a well-documented phenomenon in many freshwater ecosystems in Manitoba and is a pervasive water quality issue affecting surface waters across Canada and internationally. Lake eutrophication is a natural process resulting from the gradual accumulation of nutrients, increased productivity and slow filling in of the basin with accumulated sediments, silt and organic matter from the watershed. Many lakes in Manitoba are susceptible to these natural eutrophication processes, irrespective of land use, due to high soil fertility, runoff patterns and geology (Environment Canada & Manitoba Water Stewardship, 2011; Lewtas, Paterson, Venema, & Roy, 2015). However, human-induced cultural eutrophication occurs when nutrient, soil or organic matter loads to the lake dramatically increase, significantly shortening a lake's lifespan. Cultural eutrophication is a significant problem in Manitoba, for Lake Winnipeg, and for many surface waters across the province—many lakes are experiencing algal blooms, degradation of water quality including, in some cases, elevated algal toxin concentrations, and reduction of the ecological services (e.g., recreation, irrigation, fisheries) they provide to local communities and economies.

While the water quality of many prairie lakes is monitored and the extent of the eutrophication—and associated negative consequences—generally understood, information on the specific nutrient sources and in-lake processes is often insufficient to identify specific management options.

This study sought to conduct a water and nutrient mass balance, identifying the variance and relative importance of different nutrient sources and internal lake processes for a lake that could be used as a general model for other prairie lakes. As with many other shallow prairie lakes, the eutrophication of Pelican Lake has become increasingly pronounced over recent years. Our results identified:

1. That external nutrient fluxes into the lake were strongly linked to surface hydrology, suggesting that increased rainfall associated with climate variability or climate change has strongly contributed to nutrient inputs to prairie lakes in recent years.
2. Variation in nutrient concentrations was high between the tributaries that drained the lakes sub-catchments, suggesting the potential for management of land use or morphology (e.g., hill slope stabilization) to reduce external nutrient loads.
3. Biological processes (i.e., N_2 fixation), driven by elevated phosphorus (P) concentrations, appeared to be a significant component of the nitrogen (N) budget and causing the lake to become a net source of N to the surrounding environment (including groundwater).
4. Internal recycling (i.e., internal loading from the lake sediments) represented ~10 per cent of external P loads, and the sediments were a net source of P to the water column during the study period.
5. The lake was a net sink for P, retaining ~70 per cent of external inputs.

**Table ES1. Summary of TP and TN budget components for Pelican Lake for the study period.**

Budget component	TP	TN
Lake concentration (mean, mg L ⁻¹)	0.305	1.7
Inputs		
Stream inflow (kg)	6,101	20,253
Diverted inflow (PLO8A) (kg)	4,863	23,376
Precipitation (kg)	808	9,788
Outputs		
Groundwater (net, kg)	1,180	103,007
Diverted outflow (PLO8C) (kg)	1,698	7,667
Internal recycling processes (kg)	1,156	53,883
Δ water column	10,051	-3,374

In determining a lake's nutrient budget at a sub-catchment scale, a mass balance approach was critical to identify source areas. The budget in this report identified temporal and spatial patterns in external loading of P and N to the lake, highlighting several sub-catchments as critical source areas; the highest loads of nutrients come not from the largest catchment by area, but rather from the catchment with the highest percentage of agricultural area. The results from our study demonstrate that Pelican Lake is a net sink of P (accumulation was primarily in the water column) and a net source of N to the surrounding environment. Internal recycling and biological processes played significant roles in the mass balance.



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1.0 Introduction

Eutrophication has become the primary water quality issue for many freshwater ecosystems around the world. Lake eutrophication is a natural process resulting from the gradual accumulation of nutrients, increased productivity and slow filling in of the basin with accumulated sediments, silt and organic matter from the watershed (Schauser, Lewandowski, & Hupfer, 2003; Waters & Webster-Brown, 2016). Many lakes in Manitoba would likely be categorized as eutrophic even without development in the watershed, due to the province's regional soil fertility, runoff patterns and geology, which encourage natural eutrophic conditions (Environment Canada & Manitoba Water Stewardship, 2011; Lewtas et al., 2015). However, human-induced cultural eutrophication—where human activities greatly accelerate nutrient loading—can dramatically increase the rates at which natural eutrophication occurs and exacerbate problems in lakes even when considered naturally eutrophic. High loading of nutrients from anthropogenic sources can result in hypoxic or anoxic conditions in stratified rivers, lakes, reservoirs, estuaries and coastal regions (Smith, 2003; Smith, Joye, & Howarth, 2006; Smith & Schindler, 2009). Of increasing concern are the symptoms of eutrophication, particularly algal blooms and the development of blooms that may include toxic algal species of cyanobacteria (Schindler et al., 2008).

Lake ecosystems represent a complex set of physical, chemical and biological factors and interactions that influence their responsiveness to remediation and management efforts. These factors vary with lake origin, the regional setting and the watershed, and include hydrology, climate, watershed geology, soil fertility, hydraulic residence time, biological factors (such as the presence of fish taxa that increase rates of sediment and nutrient resuspension, or the presence of effective algal grazers), the presence or absence of thermal stratification, and external and internal nutrient sources and rates. Solutions to eutrophication can be approached on different paths, and the success of a remediation management strategy varies greatly from lake to lake; however, it is generally agreed that these treatments are usually not worth considering unless external nutrient loads can also be reduced and controlled (Lewtas et al., 2015).

Water quality parameters, such as nutrient concentration, have complex relationships with external nutrient loads and in lake processes. Shallow eutrophic lakes can display complex nutrient dynamics, with processes such as sediment-water exchanges, playing a much greater role than in deep, dimictic lakes (Ishikawa & Tanaka, 1993; Goda & Matsukoa, 1986; Søndergaard Kristensen, & Jeppesen, 1992). With site-specific lake and catchment hydrological characteristics, some lakes may also be relatively unresponsive to watershed nutrient management (Welch & Cooke, 1995).

Primary productivity in lake systems is strongly limited by nutrient availability, and the role of macronutrients nitrogen (N) and phosphorus (P) in controlling phytoplankton biomass is well established in the literature (Schindler et al., 2008). Phosphorus is considered to be the foremost nutrient in the limitation of primary productivity in most lakes, as it exists predominantly in forms that are not bioavailable (Schindler et al., 2008). Limiting primary production, attempts are often made to decrease the external P load (Schauser et al., 2003; Schindler et al., 2008). Phosphorus control is also more feasible than to of nitrogen because, unlike nitrogen, there is no atmospheric source of phosphorus that is bioavailable (Zamparas & Zacharias, 2014).

With awareness growing on the role that shallow inland lakes and wetlands play in water quality mitigation, an expanding number of policy interventions are being implemented to restore those ecosystems that have been affected by eutrophication. There is a need to share lessons in best practices and overarching principles for framing lake restoration and nutrient management projects due to growing uncertainties regarding in-lake remediation, and for enhancing overall efficiency and effectiveness in watershed management to alleviate growing water quality and security concerns.

Eutrophication is marked by many different symptoms, and it is essential to determine management goals at the onset of any remediation strategy. The successful implementation of a lake nutrient management plan requires



a site-specific study of a range of parameters affecting viability of the treatment applied, in connection with an assessment of the potential adverse effects on biotic and abiotic factors, and ecosystem and human health. In-lake remediation treatments are not a panacea, and their implementation should consist of a management approach as part of an integrated watershed management plan. The effectiveness and longevity of in-lake remediation treatments is reduced if managing external nutrient loads is not given the necessary importance in lake restoration (Zamparas & Zacharias, 2014).

Eutrophication is a well-documented phenomenon in many freshwater ecosystems in Manitoba and a pervasive water quality issue affecting surface waters in many jurisdictions across Canada. The economic impact to society is significant (Dodds et al., 2009) and continual efforts are being made to prevent, manage and reverse eutrophication to waterbodies already affected (European Commission, 2000; Waters & Webster-Brown, 2016). In Manitoba, water quality issues are particularly contentious due to wetland loss resulting from the intensification of agriculture.

The recurring water quality problems of Pelican Lake, which include annual algal blooms that persist over much of the summer period, have a major impact on biodiversity and recreational use. The growing concerns about the health of the Pelican Lake, along with several other waterbodies in the region, involve complex, site-specific nutrient loading dynamics and requires management strategies to be lake-specific and long-term in nature (Effler & Matthews, 2008). The current research on Pelican Lake is a pilot project to examine the relative importance of different nutrient sources to small prairie lakes and the importance of internal recycling processes. The purpose of this report is to inform lake management decisions and remediation intervention strategies by identifying and understanding the behaviour of critical nutrients, phosphorus and nitrogen, through load sources, sinks and transformation processes specific to small prairie lake systems. A sub-catchment scale, mass balance model approach was designed for Pelican Lake to illustrate how nutrient budgets can inform the development of integrated catchment management plans and guide cost-effective remediation interventions and monitoring programs.



2.0 Methods

2.1 Lake and Catchment Characteristics

The Pelican Lake watershed is located in the southern region of Manitoba, and is one of several smaller, shallow lakes along the Pembina River. The Pembina River is a major watercourse located in south-central Manitoba, and is part of the larger Lake Winnipeg Basin (MAFRI, 2009). The calculated area of the Pelican Lake watershed is 1169 km². The Pelican Lake watershed is located in the northwestern portion of the Pembina River basin (Figure 1).

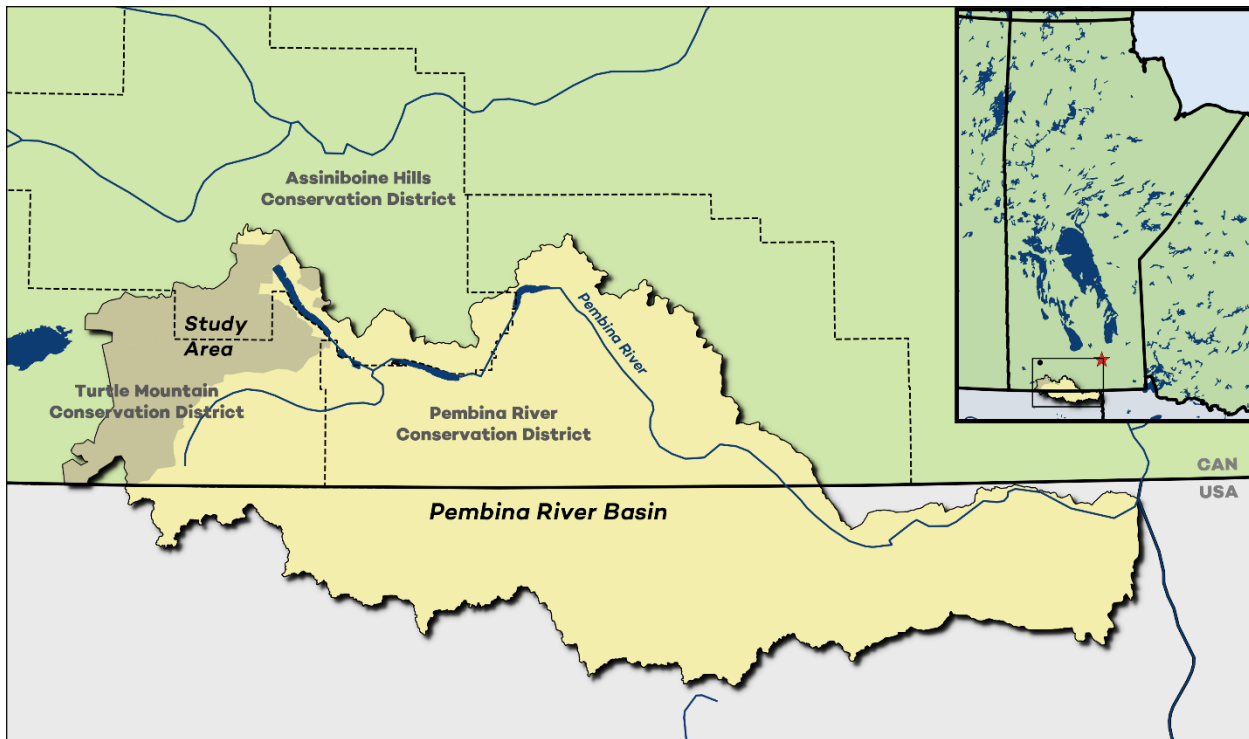


Figure 1. Map and location of the study site, Pelican Lake, within Manitoba.

Source: Created by IISD (Geoffrey Gunn) for this research. Land use GIS data obtained from the Government of Manitoba land use cover, 2006.

Pelican Lake is a turbid, eutrophic lake, with a surface area of 27.7 km² that has experienced regular algal blooms. The lake's mean depth is 3.88 metres and its average volume is 108,084,000 m³ (Province of Manitoba, 2015). The lake refresh rates were calculated by the lake volume obtained from volume frequency curve, and refresh rates for return period of two and 10 years are illustrated below (Table 1). Pelican Lake is fully regulated, and inflow data from the Pembina River and outflow data are recorded by a provincial hydrometric station at the southern shoreline of the lake.

**Table 1. Summary of Pelican Lake physical and hydrological characteristics**

Watershed area (km ²)	1169
Surface area (km ²)	27.7
Length (km)	16
Width (km)	1.6
Mean depth (m)	3.88
Average volume (m ³)	108,084,000
Volume of 1 in 10 years event (m ³)	28,600,000
Refresh rate for 1 in 10 years event (occurrences/year)	0.26
Volume of 1 in 2 years event (m ³)	6,400,000
Refresh rate for 1 in 2 years event (occurrences/year)	0.06

Source: Pellissier, Oliver, & Lowdon, 2014; Province of Manitoba, 2015.

The lake catchment is primarily flat and the predominant land use is agricultural, both crop production and livestock grazing. The area directly surrounding the shoreline is steep, and combined with forest and wetland loss in the region, the erosion of naturally phosphorus-rich soils has contributed to the lake's water quality issues. A bathymetric survey conducted in 2014 indicated the presence of three main substrate classes in Pelican Lake (Pellissier et al., 2014):

- Soft clay comprised 51.2 per cent of bottom substrate, and was most abundant in deeper regions away from the shoreline.
- Silt or clay-silt mixtures comprised 44.5 per cent of bottom substrate and was mostly near shore and within the lake's southern basin.
- The remaining 4.3 per cent of the bottom substrate consisted of sand or loose shale.

An aquatic vegetation survey was also conducted, where estimates of plant coverage and biovolume were determined for the summer and fall of 2014 (Table 2). Submerged plant height and coverage were combined into a single measure of plant biovolume.

Table 2. Summary of submerged aquatic vegetation for Pelican Lake

	June 2014 survey	September 2014 survey
Mean biovolume (%)	0.13	0.13
Maximum biovolume (%)	24.2	19.0
Mean plant height (cm)	13.3	12.6
Maximum plant height (cm)	70.6	75.3
Whole lake plant coverage (%)	16.8	14.4

Source: Pellissier et al., 2014.

Determining the lake's nutrient budget requires derivation of phosphorus and nitrogen from contributing sub-catchments and from different land-use types. Agricultural land use and associated land cover can influence watershed processes and affect issues like water quality and hydrological flow within the watershed. Agriculture is the predominant land use in the Pelican Lake watershed—an estimated 667 km² (or 58 per cent) of the total drainage area (Table 3; Figure 2). For the individual monitored sub-catchments, agricultural land use percentage ranged from 45 per cent (PL10) to 82 per cent (PL05).

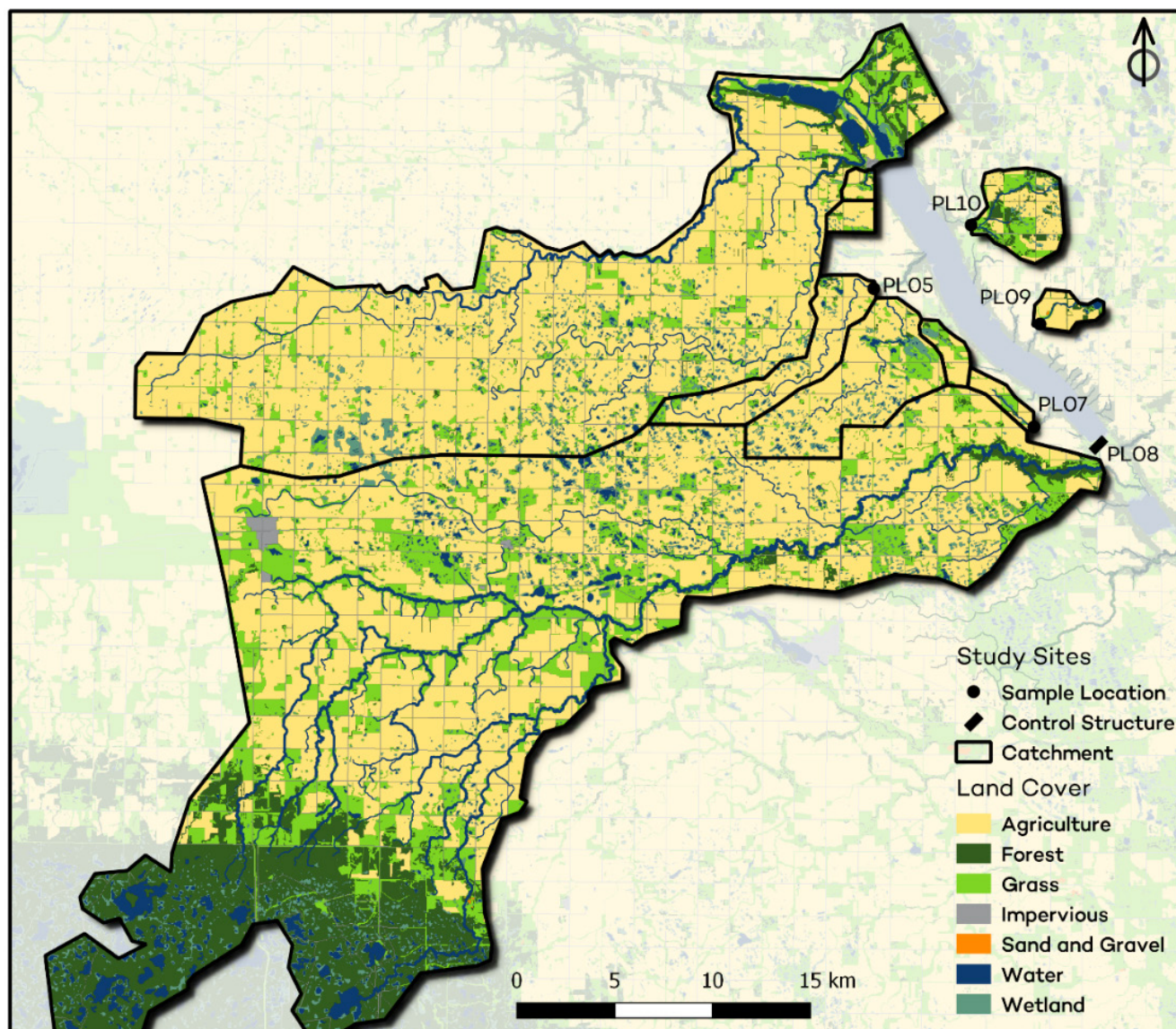


Figure 2. Land use for the load-contributing sub-catchments in the Pelican Lake watershed.

Source: Created by IISD (Geoffrey Gunn) for this research. Land use GIS data obtained from the Government of Manitoba land use cover, 2006.

**Table 3. Land use distribution for monitored sub-catchments of the Pelican Lake watershed**

Sub-catchment	Land use, in km ² and percentage (%) of drainage area							Total drainage area
	Forest	Grass	Impervious	Sand and gravel	Water	Wetland	Agriculture	
PL01	12.0	47.7	11.1	0.0	8.3	20.1	267.4	367 km ²
	3.3%	13%	3%	0%	2.3%	5.5%	72.9%	32%
PL02	0.2	0.5	0.2	0.0	0.0	0.0	1.5	2.4 km ²
	9.1%	21%	6.6%	0%	0.6%	1.7%	61%	0.2%
PL03	0.1	0.6	0.1	0.0	0.0	0.2	2.7	3.7 km ²
	3.1%	17%	2.1%	0%	0%	6.4%	72%	0.3%
PL05	0.3	1.6	0.5	0.0	0.4	1.7	20.5	25 km ²
	1.4%	6.4%	2.1%	0%	1.5%	6.7%	82%	2.1%
PL05B	0.3	4.9	0.5	0.0	0.9	4.9	29.1	41 km ²
	0.8%	12%	1.2%	0%	2.2%	12.1%	72%	3.5%
PL06	0.2	1.2	0.1	0.0	0.0	0.4	2.7	4.7 km ²
	5.2%	26.4%	2.2%	0%	0.1%	8.3%	57.8%	0.4%
PO7	0.1	0.8	0.1	0.0	0.0	0.1	2.6	3.8 km ²
	3.9%	22.3%	2.4%	0%	0%	3%	68.5%	0.3%
PL08	124	150	194	0.1	27.1	39.4	339	700 km ²
	17.8%	21.5%	2.8%	0%	3.9%	5.6%	48.5%	60%
PL09	0.7	0.4	0.1	0.0	0.2	0.2	3.7	5.2 km ²
	13.2%	7.3%	1.2%	0.4%	3.5%	3.4%	70.9%	0.5%
PL10	3.1	4.7	0.4	0.0	0.1	1.1	7.5	16.9 km ²
	18.5%	27.5%	2.2%	0.1%	0.5%	6.6%	44.6%	1.5%
Total watershed	142	213	32.3	0.1	36.9	68.2	677	1,169 km ²
	12%	18%	2.8%	0%	3.2%	5.8%	58%	

*Sub-catchment land use area estimates calculated from the Government of Manitoba GIS land cover data, 2006.

Note: Figure 3 (next page) illustrates the location of all monitored sub-catchments in the Pelican Lake watershed.

2.2 Sampling Method

To create a mass balance P and N budget for Pelican Lake, hydrological inflows and outflows to and from the lake over a discrete period of time were measured, as were the nutrient concentrations of those flows. Inflows to the lake are predominantly from the Pembina River (contributes from the south end of the lake through a regulated dam) and stream flow through Grasse Lake wetland on the north end of the lake. However, significant areas of hillslope drain to the lake via smaller streams, and runoff through ditch and culverts. The lake has one natural inlet through Grasse Lake and its wetland, and one artificial inlet, a dam that regulates input from the Pembina River to manage flooding in the catchment and lake levels.

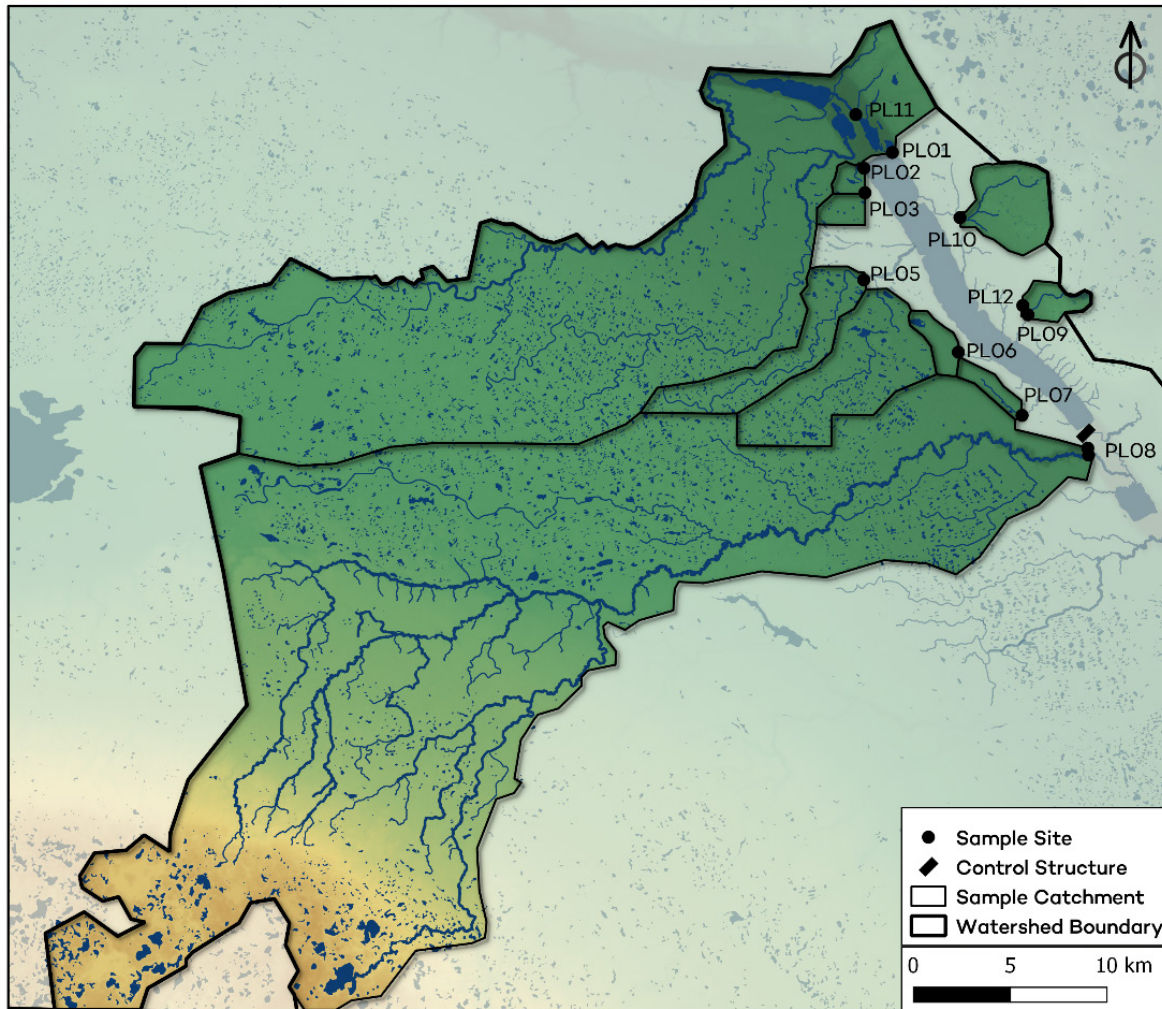


Figure 3. Water quality and stream flow velocity monitoring sites at Pelican Lake and their contributing catchment drainage area.

Source: Created by IISD (Geoffrey Gunn) for this research. Land use GIS data obtained from the Government of Manitoba land use cover, 2006.

Sampling at Pelican Lake involved two components:

1. **Stream flow sampling:** These sites are referred to as PL01 – PL12, and at each site:
 - a. Water sample was collected for water quality laboratory analysis.
 - b. Flow velocity measurements, using a hand-held flow meter, were recorded.
2. **In-lake sampling:** Monthly in-lake water quality parameters were measured from May to October 2016 as part of the Province of Manitoba water quality monitoring program.

Sampling was designed to span across seasons, flows and differing parts of the hydrograph to illustrate variability in nutrient concentrations. The area surrounding Pelican Lake was surveyed prior to spring melt runoff in March 2016 to determine potential inflow and loading sites. Tributaries, streams and ditch-culvert systems that directly flowed into the lake were then monitored during spring melt and at moderate-to-high rainfall events: 12 stream monitoring sites were identified and monitored from March to November 2016 (Figure 3).



Figure 4. Stream sampling at Pelican Lake during March (spring melt runoff, top) and July (bottom) at site PL05 (outlet of culvert).



Figure 5. Stream sampling at Pelican Lake during March (spring melt runoff, left) and July (right) at site PL05 (inlet of culvert).



Figure 6. Stream sampling at Pelican Lake during March spring melt runoff.

At stream sampling sites, a water sample was collected in polypropylene containers and analyzed at ALS Laboratories in Winnipeg, Manitoba. Flow velocity parameters were recorded with a hand-held Solinst levelogger flow meter. In-lake water quality samples were collected mid-lake and monthly, whereas stream inflow site sampling was dependent on precipitation events and was variable between months.

2.3 Hydrology and Water Budgets

2.3.1 Lake Volume

The total lake volume of Pelican Lake is approx. 108,084,000 m³, at a lake water level of 412.09 m (Pellissier et al., 2014). The water volume and height of Pelican Lake are controlled by an inlet-outlet structure (dam) that limits the range of fluctuation in water table height. Changes in level (and hence volume) during dam opening events were used in this research to quantify the volume lost during opening. For the period of this study (March to October 2016), the difference between the maximum and minimum water level was 35.5 cm. The assumption has been made that the relationship between the water level (WL) and lake volume (V) is linear:

$$V = 108084000 - (412.09 - WL) * Area_{lake} \quad (1)$$

The lake's water budget balance is the difference between the hydrological inputs and outputs of any water system during a period of time and can be represented as equation (2).

$$inflows - outflows = \frac{dV}{dt} \quad (2)$$

where $\frac{dV}{dt}$ is the change in volume or storage over time

The components of the *inflows* (dV/dt) typically include precipitation ($Precip$), surface runoff (Q_{in}) and groundwater inflow (G_{in}). The components of the outflows are represented by evaporation and evapotranspiration (E), surface outflows (Q_{out}) and groundwater seepage (G_{out}). Therefore, equation (2) can be derived as:

$$GW_{net} = G_{in} - G_{out} = \frac{dV}{dt} - Precip + E - Q_{in} + Q_{out} \quad (4)$$

In general, precipitation, surface runoffs and change in volume can be measured directly, while groundwater and evaporation are more complex. However, there are various methods to quantify evaporation from open water, such as Penman Montith (Food and Agriculture Organization of the United Nations [FAO], 1998; Blaney & Criddle 1962). In many water budget studies, the net groundwater flow (GW_{net} - the deficit between G_{in} and G_{out}) is calculated as the residual term of the water balance equation (Swancar, Lee, & O'Hare, 2000):



2.3.2 Stream Flows and Direct Runoff

To estimate the sub-catchment runoff component in Pelican Lake's water budget, the Soil Conservation Service Curve Number (SCS-CN) method was used. The SCS-CN method was originally developed by the U.S. Department of Agriculture to estimate direct runoff from rainfall events on agricultural fields (Soulis & Valiantzas, 2012). The SCS-CN method is widely used in many hydrologic applications, such as water budgets models and flood designs. The SCS-CN method is based on the following empirical equation (Mockus, 2010):

$$\begin{aligned} Q &= \frac{(P-I_a)^2}{P-I_a+S} & \text{for } P > I_a \\ Q &= 0 & \text{for } P \leq I_a \end{aligned} \quad (5)$$

Where:

Q = depth of runoff, mm

P = depth of total rainfall, mm

I_a = initial abstraction, mm

S = maximum potential retention, mm

The initial abstraction (I_a) and maximum potential retention (S) are calculated using:

$$S = \frac{25400}{CN} - 254 \quad (6)$$

$$I_a = \lambda S \quad (7)$$

CN value is a representation for the soil types and land cover and its value ranges from 40 to 100 (impermeable surface). The value for CN can be determined by using the National Engineering Handbook (Land Cover Table 9-1, Part 360, Hydrology) by Mockus and Hjelmfelt (2004). The SCS-CN values commonly used in hydrologic practice assume that the initial abstraction rate is set constant at $\lambda=0.2$, in order that S (its transformation CN) remains the only free unknown parameter of the model (Soulis & Valiantzas, 2012). In the context of this study, the initial values for CN and λ were 75 and 0.2, respectively. However, these initial values were adjusted to 78 and 0.18 after the water balance model was calibrated using a chloride (a conservative element) mass budget.

The runoff depth is calculated based on daily time step and then is summed to a monthly time step using Matlab (MATLAB 6.1, The MathWorks Inc., Natick, MA, 2000). To calculate the monthly volume of water that enters the lake from each stream, the following equation is used:

$$V_{Stream(i)} = Q * Area_i \quad (8)$$

$Area_i$ is the sub-catchment area that corresponds to tributary _(i). Watersheds were delineated manually on ArcGIS using topographic vector data, near infrared satellite imagery, and provincial aerial photography (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute).

2.3.3 Groundwater

Groundwater exchange between lakes and aquifers can be a significant component in the water budget for individual months; therefore, it can play a great role in the chemical regulation of lakes (Gurrieri & Furniss, 2004; Swancar et al., 2000). Given that there was no available data to describe the groundwater interaction between Pelican Lake and the regional aquifer (such as groundwater tables and hydraulic conductivities) the net groundwater flow to the lake (GW_{net}) was estimated as the residual term by using Equation 4 (water balance



equation). This approach to estimating net groundwater component in lakes' water balance is widely used in the literature when it is difficult to make independent estimates (Hood Roy, & Hayashi, 2006; Swancar et al., 2000; Sacks, Lee, & Swancar, 2014; Phelps & German, 1996). However, the limitation of the approach is that inflow and outflow cannot be separated, and it incorporates other budget components errors in the GW_{net} .

Winter (1981) estimates the overall uncertainty as the square root of the sum of the individual uncertainties squares as in the following equation:

$$e_{net\ GW} = ((e_{\Delta V})^2 + (e_{Precip})^2 + (e_E)^2 + (e_Q)^2)^{1/2} \quad (9)$$

Uncertainties in monthly water balance components are assumed as follows: precipitation (e_{Precip}) 5 per cent, evaporation (e_E) 15 per cent, diverted flows ($e_{\Delta V}$) 10 per cent and tributary flows (e_Q) 100 per cent.

2.3.4 Precipitation

The precipitation and temperature data used in this study were measured at Belmont weather station, which is located at 2.2 km east of Pelican Lake. The total volume of precipitation (P) that falls directly on Pelican Lake—measured in cubic meters—is calculated by the following equation,

$$Precip = Area_{lake} * R \quad (10)$$

where $Area_{lake}$ is the surface area (m^2) of Pelican Lake as per the bathymetric survey report by Pellissier et al. (2014). R is total rainfall depth for each month measured in meters.

2.3.5 Evaporation

The evaporation rates from Pelican Lake were calculated on daily basis using Matlab coding based on Penman Montieith method (Equation 11) as described in FAO (1998) and Zotarelli et al., (2015). The required data for calculation were obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program.

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (11)$$

where:

ET_o = evaporation rate ($mm\ day^{-1}$)

Δ = slope of the saturated vapour pressure;

R_n = net radiation flux ($MJ\ m^{-2}\ d^{-1}$);

G = sensible heat flux into the soil ($MJ\ m^{-2}\ d^{-1}$);

u_2 = wind speed, at 2 m above the ground ($m\ s^{-1}$);

T = mean air temperature ($^{\circ}C$);

e_s = saturation vapour pressure, kPa;

e_a = actual vapour pressure, kPa;

γ = psychrometric constant, $kPa\ ^{\circ}C^{-1}$

The monthly volumes (m^3) of water that evaporate (E) from Pelican Lake were then calculated using the following relationship:

$$E = Area_{lake} * \sum ET_o \quad (12)$$



2.4 Chemical Analyses

Water quality parameters analyzed were based on nutrient model requirements and in lake-remediation treatments' monitoring needs that would complement the provincial surface water monitoring program. Multiple nutrient species were monitored and analyzed to estimate their respective contributions from unmeasured stream inflows in the development of the nutrient budgets. These nutrient subspecies include:

- Phosphorus: Total P, total particulate P and total dissolved P
- Nitrogen: Total-N, nitrate, nitrite and total kjeldahl-N (TKN) and ammonia

Chloride (Cl) concentration was also analyzed to validate the water budget as a conservative tracer. Chloride concentration acts as a marker and by comparing the changes in mass of chloride within a water body to the net loads, the accuracy of the water budget can be determined (James, 2014).

2.5 Phosphorus and Nitrogen Mass Loads

2.5.1 Stream Inflow and Outflow

Stream nutrients loads are calculated on a daily basis and then aggregated for each month. The following steps were followed in calculating the stream nutrients loads from each sub-catchment:

1. The relationship between the nutrient concentration and stream discharge was defined. Matlab Statistical Toolbox was used for the regression analysis. In the cases of relationships between the nutrient concentration and stream discharge weren't statistically significant, the median values of concentration were used.
2. The daily loads from each stream were then calculated using the following equation:

$$M_{Stream(i)} = Q_i * Con_i \quad (13)$$

3. The total tributary monthly loading is then calculated by summing all daily loads from the contributing sub-catchments.

2.5.2 Groundwater

The groundwater loading is based on the calculated groundwater flow component from the water budget. The assumption made here is if the groundwater is leaving the lake (negative value) then the nutrient concentration values given to calculate the mass is the concentration of the lake. Where the groundwater term is positive, then average concentration values for the nutrients from the regional aquifer were used in the calculations:

$$\begin{aligned} M_{GW} &= GW_{net} * Con_{Lake} && \text{for } GW_{net} < 0 \\ M_{GW} &= GW_{net} * Con_{GW} && \text{for } GW_{net} > 0 \end{aligned} \quad (14)$$

2.5.3 Precipitation

Monthly nutrient loading (M_{atm}) from precipitation for each month was calculated as the percentage of the total precipitation during each month to the total annual precipitation, multiplied by the annual loading and Pelican Lake surface area.

$$= Annual\ Loading * \frac{Precip_{month(i)}}{\sum_{i=1}^{12} Precip_{month(i)}} * Area_{lake} \quad (15)$$

Monthly loading for total phosphorus (TP) and total nitrogen (TN) was estimated from annual loading values reported in the literature, 20 mg/m²/ha and 424 mg/m²/ha for TP and TN, respectively (Shaw et al., 1989).



2.5.4 Internal Loading Processes: Sediment and macrophyte reservoir

The internal processes component of the budget includes an estimate of the combined nutrient reservoirs from sediment and lake macrophyte. To derive TP concentrations in the sediment, the summation of all fraction concentrations during sequential extractions and sediment density figures obtained from sediment cores, and lake area, would be needed to calculate the nutrient reservoir in the sediment. Sediment cores were not collected, and although a macrophyte survey was conducted in 2014, nutrient concentrations in that biomass were not measured; therefore, a net internal nutrient load was determined by the difference between external nutrient inputs, output and the lake's water column nutrient mass (nutrient mass retained in the water column; Equation 16).

$$\Delta S = (M_{inputs} + M_{internal}) - M_{outputs} \quad (16)$$

2.5.5 Nutrient Retained in the Lake: Water column reservoir

The mass of P and N contained in the lake water column was derived from lake volume and the TP and TN concentrations observed in the lake. Nutrient concentrations were derived from samples collected and analyzed from the Government of Manitoba water monitoring data. Changes between sampling dates in the calculated mass of P and N, net inflow and outflow nutrient loads, were used to indicate fluxes between sediment and macrophyte (internal processes), and the water column. The following mass balance equation is used to calculate the nutrient retention (S) in the lake.

$$M_{atm} + M_{trib} + M_{inflow} + M_{GW} - M_{out} + M_{internal} = S \quad (17)$$



3.0 Results

3.1 Hydrology and Water Balance

Nutrient mass (load) transported to the lake by stream flows, and the other contributing sources, was calculated by multiplying the volume of water inflows by nutrient concentrations. For stream nutrient concentrations, all loads were derived from relationships established between sampled stream water nutrient concentrations and simultaneous discharge. The modelled water balance for each potentially contributing input to the lake (streams, diverted inflow, precipitation and groundwater) and then output from the lake (evaporation, diverted outflow and groundwater) was used to calculate loading mass is illustrated in Table 4.

Table 4. Pelican Lake modelled water balance (million m³) presented by stream flows, diverted inflow, groundwater, precipitation, evaporation and diverted outflow over the eight-month research period

Month	Input			Output		GW	Δ volume
	Stream flows	Diverted inflow (PL08-Inlet)	Precipitation	Evaporation	Outflow (PL08-Outlet)		
March	0.757	4.97	0.222	1.17	0.0	-2.35	2.43
April	0.489	1.54	1.43	2.12	0.0	0.94	2.24
May	2.194	0.11	1.10	3.09	0.0	3.72	3.90
June	8.263	2.16	5.82	2.47	0.731	-15.8	-3.28
July	2.352	0.0	5.73	1.25	6.23	1.14	1.41
August	0.004	0.0	1.16	0.37	0.0	-1.39	-0.582
September	0.256	0.0	2.21	0.62	0.0	-2.43	-0.562
October	0.165	0.0	0.84	0.68	0.148	-0.502	-0.310

Note: GW = groundwater; Δ volume = changes in lake volume.

Diverted inflow (PL08A-Inlet) and diverted outflow (PL08C-Outlet) is the volume of water entering or leaving the lake through a regulated dam at the south end of Pelican Lake. The dam's inlet, allowing water from the Pembina River into Pelican Lake, was opened for 18 days (March 10–14 and 19–20, April 18–22 and May 31–June 5). The dam's outlet was opened for three days at the end of June (28–30 June) and then for 29 days during July (July 1–29; Tables 4 and 11).

The water budget for Pelican Lake indicated that in the month of June, a significant amount of water left the lake, the change in lake volume was -3.28 million m³, and transferred to surrounding aquifers, -15.8 million m³. This month also corresponds to the highest lake level recorded during the study period.

3.2 Phosphorus Budget: Load transported to and from the lake

3.2.1 Streams

Table 5 presents the results of P loads transported to the lake from streams as calculated from the load estimation model, including P loads delivered by high rainfall events during this period. The highest concentrations of TP recorded were both at PL05; 2.36 mg L⁻¹ (March) and then again in August at 2.37 mg L⁻¹. PL05 had significantly higher TP concentration than any other load-contributing stream inflow site. For all contributing streams, TP concentrations measured in March were higher relative to other months. The lowest recorded TP concentration was measured in April at 0.093 mg L⁻¹ (PL10). Mean stream concentrations are presented in Appendix A, organized by nutrient, site and month.

**Table 5. Phosphorus load delivered to Pelican Lake by stream flow over the eight-month period.**

Stream Inflow	Total Dissolved P	Total Particulate P	Total Phosphorus (TP)
PL05	5041	252	5271
PL08A-Inlet	2680	2183	4863
PL09	252	58	310
PL10	439	82	520

Approximately 11,000 kg of P was transported into the lake from the stream inlets sampled over the eight-month research period (6,101 kg was transported from tributary stream sites and 4,863 kg was transport from diverted inflow [PL08C-inlet] [Tables 6 and 7]). Table 5 presents the P loads delivered as TP, particulate- P and dissolved P. Specifically, 77 per cent of the phosphorus load transported to the lake by streams in dissolved forms and the 23 per cent was in particulate forms.

Table 6. Phosphorus load (kg) presented by stream sites that contributed to the lake nutrient budget.

Load (kg)		March	April	May	June	July	August	September	October
PL05	Dissolved Total P	920	62.9	124.1	2,979	954	0.0	0.0	0.1
	Total Particulate P	31.0	6.3	31.7	157	25.6	0.0	0.0	0.0
	Total P	937	66.3	156	3,136	976	0.0	0.0	0.1
PL08 Inlet	Dissolved Total P	2,166	222	154	139	0.0	0.0	0.0	0.0
	Total Particulate P	1,330	788	21.6	43.1	0.0	0.0	0.0	0.0
	Total P	3,495	1,010	176	182	0.0	0.0	0.0	0.0
PL09	Dissolved Total P	61.5	3.9	13.3	124	499	0.0	0.0	0.0
	Total Particulate P	14.5	1.3	3.2	31.9	6.8	0.0	0.0	0.0
	Total P	76.0	5.2	16.5	155	56.6	0.0	0.0	0.0
PL10	Dissolved Total P	52.3	8.1	37.8	270	70.8	0.0	0.0	0.0
	Total Particulate P	20.1	3.2	4.1	43.4	10.9	0.0	0.0	0.0
	Total P	72.4	11.3	41.3	313	81.7	0.0	0.0	0.0
PL08C Outlet	Dissolved Total P	0.0	0.0	0.0	0.0	1292	0.0	0.0	0.0
	Total Particulate P	0.0	0.0	0.0	0.0	405	0.0	0.0	0.0
	Total P	0.0	0.0	0.0	0.0	1,698	0.0	0.0	0.0

Only four sites of the 11 sites sampled primarily contributed loading to the lake: PL05, PL08-Inlet, PL09 and PL10. Inflow site PL05, runoff through a ditch during moderate-to-high rainfall events on the west side of the lake, delivered the greatest amount of TP to the lake (Table 6). However, when the inlet (PL08A) to the lake was open (inflow from the Pembina River occurred over 40 days during the study period) the waters from the Pembina River contributed a significant percentage of the phosphorus load to the lake (Tables 5 and 6). Stream flows and diverted inflow (PL08C) represent the largest input component or contribution of loading to Pelican Lake's nutrient budget.

The research period (March to November 2016) experienced unusually low precipitation for the region and possibly underestimates the load contribution that could occur during normal to high-precipitation years. Due to low precipitation and low water nutrient concentrations from August and October, it was determined that streamflow during these months contributed no or insignificant nutrient loading to the lake.



3.2.2 Precipitation

Precipitation was estimated to have delivered 808 kg of P to the lake over the eight-month study period (Table 7). The precipitation component of Pelican Lake's nutrient budget is the smallest contributing load input.

3.2.3 Groundwater

The calculated load groundwater transported to the lake is -1,180 kg (Table 7); therefore, 1,180 kg of TP moved from the lake to groundwater aquifers, presented as a negative value. Due to the negative value from the model, groundwater was determined as an output budget component, rather than an input to Pelican Lake's nutrient budget. Phosphorus load transported from the lake to groundwater aquifers accounted for 41 per cent of the total outflow P load.

3.2.4 Diverted Outflow

A total phosphorus load of 1,698 kg was calculated to have been transported out of the lake during the dam opening events (diverted outflow) that occurred over the eight-month period. The dam at the south end of Pelican Lake was opened for 3 days at the end of June (28-30 June) and then for 29 days during July (July 1-29; Tables 4 and 7). Phosphorus load transported from the lake via the dam connecting the Pembina River to Pelican Lake (PL08C) accounted for 59 per cent of the total outflow P load.

3.2.5 Internal Recycling Processes

The internal loading processes, including lake sediment and macrophyte, was estimated to contribute 1,156 kg of P to the lake over the eight-month study period (Table 7). Apparent increase in TP mass was observed, indicating Pelican Lake sediment and macrophyte were a source of phosphorus. Further research is required to more fully understand the dynamics of P in the sediment reservoir, and flux between sediment pore water and macrophyte.

3.2.6 Lake Water Column

Inflow and outflow P loads over the eight-month research period show that approximately 10,051 kg of P was retained in the lake water column.

3.2.6 Phosphorus Budget

Pelican Lake was a strong net sink of P; retaining ~70 per cent of P external inflows, with accumulation primarily in the water column. Internal recycling and processes (i.e., internal loading from the lake sediments and macrophytes) represented ~10 per cent of external P loads, and the sediments were a net source of P to the water column during the study period (Table 7).



Table 7. Pelican Lake phosphorus budget (TP, kg) by month for the eight-month study period.

Month	Input			Output	GW	Δ water column	Δ internal processes
	Stream inflow	Diverted inflow	Precipitation	Diverted outflow			
March	1,086	3,495	9.7	0.0	-259	16,267	11,934
April	82.8	1,010	62.4	0.0	197	-11,198	-12,549
May	213.6	176	47.9	0.0	751	202	-987
June	3,604	182	254	0.0	-1,730	5,135	2,825
July	1,114	0.0	250	1,698	336	4,442	4,439
August	0.0	0.0	50.6	0.0	-152	8,288	8,390
September	0.0	0.0	96.5	0.0	-267	-3,337	-3,167
October	0.12	0.0	36.5	0.0	-55.1	-9,749	-9,730
Study period	6,101	4,863	808	1,698	-1,180	10,051	1,156
	10,964						

Note: GW = groundwater. Internal processes = change load (kg) due to the change in lake volume within the month.

Δ internal processes: Positive values indicate internal processes as a source of nutrients to the lake; negative values indicate nutrient sink. GW: Negative (-) value represents water leaving the lake; positive (+) values represents water entering the lake.

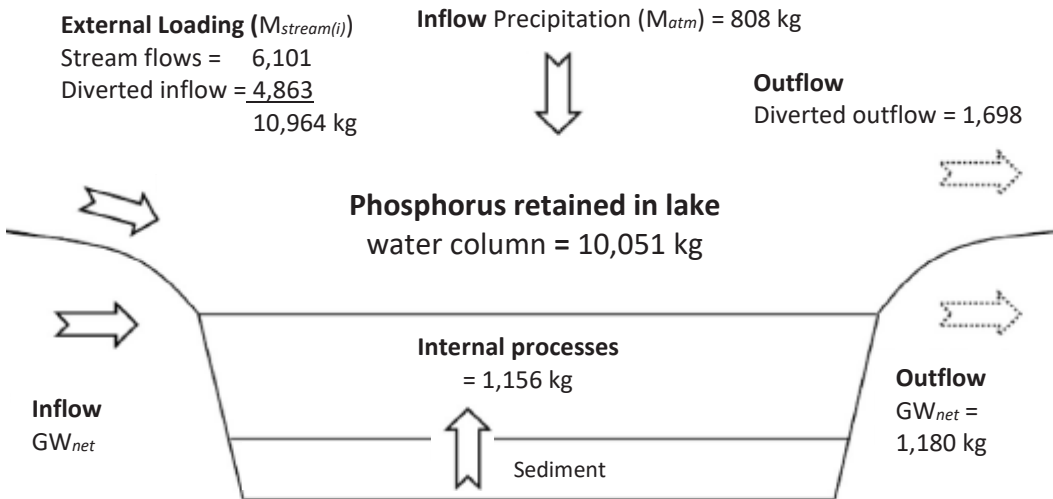


Figure 7. Pelican Lake phosphorus budget (TP, kg) for the eight-month study period.

External loading inputs = stream flows, diverted inflows and precipitation. Outputs = diverted outflow, groundwater.

The highest and lowest concentrations of TP recorded in the lake during the study period were 0.376 mg·L⁻¹ (early August) and 0.253 mg·L⁻¹ (early October), respectively. Temporal variability in ambient phosphorus concentrations is not significant over the sample period; however, mean lake TP concentration of 0.305 mg·L⁻¹ classifies the lake as eutrophic, according to the OECD boundary values for open trophic classification system (OECD, 1982). Maximum TP lake mass was observed in August at 39,295 kg, and minimum TP mass was observed in April at 21,228 kg.

**Table 8. Pelican Lake phosphorus mass (kg) for the eight-month study period, presented by month**

	March	April	May	June	July	August	Sept	Oct
Total Dissolved P	16,502	11,941	18,884	23,361	26,593	35,115	29,827	21,755
Total Particulate P	12,751	9,287	2,599	3,101	4,415	4,180	6,132	4,455
Total Phosphorus	32,426	21,228	21,430	26,565	31,007	39,295	35,958	26,210

3.3 Nitrogen Budget: Load transported to and from the lake

3.3.1 Streams

Tables 9 and 10 present the results of N loads transported to the lake from streams as calculated from the load estimation model, including N loads delivered by high rainfall events during this period. The highest concentration of TN recorded was 10.3 mg L⁻¹ at PL05 in March. Similar to TP stream concentration, PL05 had significantly higher TN concentrations than any other load-contributing stream inflow site. For all contributing streams, TN concentrations measured in March were also higher relative to other months. The lowest recorded TN concentration was measured in April at 0.87 mg L⁻¹ (PL10). Mean stream concentrations are presented in Appendix A, organized by nutrient (TKN, TN, ammonium, nitrite, nitrate, P-dissolved, P-particulate, TP), site and month.

Table 9. Nitrogen load (kg) delivered to Pelican Lake by stream flow over the eight-month research period.

Nitrogen Load (Kg)	PL05	PL05B	PL07	PL08A (Inlet)	PL08C (Outlet)	PL09	PL10
Ammonium	423	2.40	6.54	2,992	185	89.2	146
Nitrate and Nitrite	3,491	6.26	11.9	5,430	291	604	265
Nitrate	3,290	1.79	4.84	5,203	135	582	147
Nitrite	282	0.89	1.70	202	62.3	31.4	27.7
Total Kjeldahl Nitrogen	12,179	140	222	18,007	7,667	1,180	3,228
Total Nitrogen	15,143	140	222	23,376	7,667	1,785	3,325

Approximately 43,600 kg of N was transported into the lakes from the stream inlets sampled over the eight-month research period (20,253 kg was transported from tributary stream sites and 23,376 kg was transported from diverted inflow from the dam at site PL08). Tables 9 and 10 present the N loads delivered as ammonia, nitrate, nitrite, TKN and TN. Unlike phosphorous loads to Pelican Lake, the majority of the nitrogen load came from site PL08 (diverted inlet) and accounted for 45 per cent of TN load from streams. Site PL05 accounted for 30 per cent of TN load transported to the lake by streams.

Primarily, four sampling sites contributed external loading to the lake: PL05, PL08-Inlet, PL09 and PL10. Inflow site PL05 (runoff through a ditch during moderate-to-high rainfall events on the west side of the lake) delivered the greatest amount of TP to the lake (Table 10). However, when the inlet (PL08A) to the lake was open (inflow from the Pembina River occurred over 40 days during the study period) the waters from the Pembina River contributed a significant percentage of the phosphorus load to the lake (Tables 5 and 6). Stream flows and diverted inflow (PL08C) represent the largest input component or contribution of loading to Pelican Lake's nutrient budget.

**Table 10. Nitrogen load (kg) presented by stream sites that contributed to the lake nutrient budget**

Nitrogen load (kg)		March	April	May	June	July	August	September	October
PLO5	Ammonium	130	2.6	29.2	222	39.0	0.0	0.0	0.0
	Nitrate and Nitrite as N	2,675	293	137	325	61.2	0.0	0.0	0.0
	Nitrate	2,597	293	124	252	23.3	0.0	0.0	0.0
	Nitrite	78.1	4.4	62.1	126	11.7	0.0	0.0	0.0
	Total Kjeldahl Nitrogen	1,398	233	1,272	7,718	1,559	0.0	0.0	0.3
	Total Nitrogen	4,068	526	1,272	7,718	1,559	0.0	0.0	0.3
PLO8 Inlet	Ammonium	1,446	198	1,327	20.5	0.0	0.0	0.0	0.0
	Nitrate and Nitrite as N	4,393	597	12.5	428	0.0	0.0	0.0	0.0
	Nitrate	4,242	543	11.3	407	0.0	0.0	0.0	0.0
	Nitrite	151	23.2	5.7	20.5	0.0	0.0	0.0	0.0
	Total Kjeldahl Nitrogen	10,395	4,532	1,690	1,390	0.0	0.0	0.0	0.0
	Total Nitrogen	14,791	5,073	1,690	1,821	0.0	0.0	0.0	0.0
PLO9	Ammonium	37.2	3.6	3.3	34.0	11.1	0.0	0.0	0.0
	Nitrate and Nitrite as N	426	39.5	8.8	97.7	31.6	0.0	0.0	0.0
	Nitrate	414	38.6	8.8	90.8	29.9	0.0	0.0	0.0
	Nitrite	12.3	1.1	2.1	13.8	2.1	0.0	0.0	0.0
	Total Kjeldahl Nitrogen	233	27.3	110	628	183	0.0	0.0	0.0
	Total Nitrogen	659	66.9	118	727	215	0.0	0.0	0.0
PL10	Ammonium	83.8	8.3	9.1	37.5	7.4	0.0	0.0	0.0
	Nitrate and Nitrite as N	76.2	20.7	20.5	119	28.9	0.0	0.0	0.0
	Nitrate	73.4	20.1	5.9	38.3	9.6	0.0	0.0	0.0
	Nitrite	2.7	0.9	2.9	17.0	4.1	0.0	0.0	0.0
	Total Kjeldahl Nitrogen	325	182	346	1,933	442	0.0	0.0	0.1
	Total Nitrogen	402	203	346	1,933	442	0.0	0.0	0.1
PLO8 Outlet	Ammonium	0.0	0.0	0.0	0.0	185	0.0	0.0	0.0
	Nitrate and Nitrite as N	0.0	0.0	0.0	0.0	291	0.0	0.0	0.0
	Nitrate	0.0	0.0	0.0	0.0	135	0.0	0.0	0.0
	Nitrite	0.0	0.0	0.0	0.0	62.3	0.0	0.0	0.0
	Total Kjeldahl Nitrogen	0.0	0.0	0.0	0.0	7,667	0.0	0.0	0.0
	Total Nitrogen	0.0	0.0	0.0	0.0	7,667	0.0	0.0	0.0

3.3.2 Precipitation

Precipitation was estimated to have delivered 9,788 kg of N to the lake over the eight-month study period (Table 11). The precipitation component of Pelican Lake's nutrient budget is the smallest external load source and contributor to the lake's budget.

3.3.3 Groundwater

Groundwater load transported to the lake was -103,007 kg (Table 11); it was determined that 103,007 kg of TN moved from the lake to aquifers. Due to the negative value from the model, groundwater was presented as an output budget component. Nitrogen load transported from the lake to groundwater aquifers accounted for 93 per cent of the total outflow N load.



3.3.4 Diverted Outflow

A total nitrogen load of 7,667 kg was calculated to have been transported out of the lake during the artificial (dam) opening events (diverted outflow) that occurred over the eight-month period. The dam at the south end of Pelican Lake was opened for three days at the end of June (June 29–30) and then for 29 days during July (July 1–29; Tables 4 and 11). Nitrogen load transported from the lake via the dam connecting the Pembina River to Pelican Lake by a dam accounted for 6.9 per cent of the total outflow N load.

3.3.5 Internal Recycling Processes

The internal loading processes, including lake sediment and macrophyte, constitutes a large reservoir of N relative to the water column and was estimated at -53,883 kg of N over the eight-month study period (Table 11). Apparent increase (i.e., negative retention) in TN mass was observed, indicating Pelican Lake sediment and macrophyte were a source of nitrogen.

3.3.6 Lake Water Column

Inflow and outflow nitrogen loads over the eight-month study period show that -3,374 kg of N was associated to the lake's water column over this period (Table 11). The negative value expressed in Table 11 (-3,374 kg) indicates Pelican Lake may be a source of TN to downstream systems. The highest and lowest concentration of TN recorded in the lake during the period of research were 1.77 mg L⁻¹ (early September) and 1.64 mg L⁻¹ (early October), respectively. Mean TN concentration over the study period was approximately 1.7 mg L⁻¹.

3.3.7 Nitrogen Budget

Biological processes, such as N₂ fixation, driven by elevated P concentrations, appeared to be a significant component of the lake's nitrogen budget and causing the lake to become a net source of N to the surrounding environment (including groundwater, see Table 11).

Table 11. Pelican Lake nitrogen budget (TN, kg) by month for the eight-month study period.

Month	Input			Output	GW	Δ water column	Δ internal processes
	Stream inflow	Diverted inflow	Precipitation	Diverted outflow			
March	5,128	14,791	118	0.0	-11,772	91,372	83,107
April	796	5,073	756	0.0	1,455	-107,475	-115,554
May	1,736	1,690	580	0.0	5,838	9,391	-454
June	10,378	1,821	3,079	0.0	-78,796	7,611	71,130
July	2,215	0.0	3,032	7,667	1,855	-2,845	-2,279
August	0.0	0.0	613	0.0	-6,942	7,381	13,710
September	0.0	0.0	1,169	0.0	-12,137	5,241	16,209
October	0.38	0.0	442	0.0	-2,508	-14,051	-11,986
Study period	20,253	23,376	9,788	7,667	-103,007	-3,374	53,883
	10,964						

Note: GW = groundwater. Internal processes = change load (kg) due to the change in lake volume within the month.

Δ internal processes: Positive values indicate internal processes as a source of nutrients to the lake; negative values indicate nutrient sink. GW: Negative (-) value represents water leaving the lake; positive (+) values represents water entering the lake.

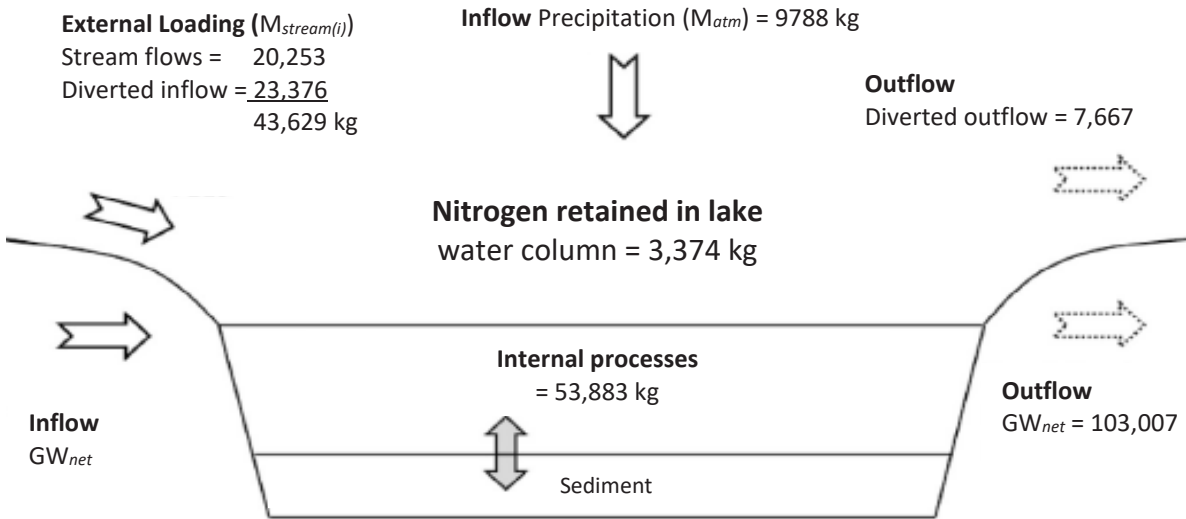


Figure 8. Pelican Lake nitrogen budget (TN, kg) for the eight-month study period.

External loading inputs = stream flows, diverted inflows, precipitation and delta volume (change in lake storage).

Outputs = diverted output and groundwater. Note: Nitrogen retention includes fluxes to and from sediment and biological processes, such as N fixation and nitrification/denitrification.

Table 12. Pelican Lake’s in-lake nutrient mass (kg) for the eight-month study period by month.

Nitrogen mass (kg)	March	April	May	June	July	August	Sept	Oct
Ammonia	4,210	2,245	3,978	1,137	4,625	3,867	2,286	2,072
Nitrate and Nitrite	-	-	-	-	3,153	-	-	-
Nitrate	-	-	-	-	-	-	-	-
Nitrite	-	-	-	-	-	-	-	-
Total Kjeldahl Nitrogen	247,234	157,170	173,456	176,757	171,328	178,709	183,949	169,898
Total Nitrogen	264,645	157,170	166,561	174,173	171,328	178,709	183,949	169,898

3.4 Summary: TP and TN Budgets

A majority of the load inputs and outputs for Pelican Lake are captured in the mass budgets based on measurements from major stream inflow, precipitation, groundwater, and diverted inflow and outflow (Figures 8 and 9; Table 13). Diverted inflow and outflow through the dam, connecting the Pembina River and Pelican Lake, accounted for the majority of variation in lake volume and nutrient retention. However, stream inflow, particularly from PL05, contributed significant loading to the lake. Internal recycling processes, which included fluxes to/from the sediments (both N and P), losses to the atmosphere (N), and biological processes (i.e., N fixation), were also important in some cases. For phosphorus, net fluxes from the sediments to the lake were approximately 10 per cent of external loading. For nitrogen, the retention term was nearly equivalent to external loading. Given the low N:P ratio of external inputs (<4 by mass), the large retention value for N most likely indicates high rates of biological N₂ fixation.



Pelican Lake's large external TP and TN loads and the limited outflows have resulted in high P and N retention in the lake (Table 13). Our results identified:

1. External nutrient fluxes into the lake were strongly linked to surface hydrology, suggesting that increased rainfall associated with climate variability or climate change has strongly contributed to nutrient inputs to prairie lakes in recent years.
2. Variation in nutrient concentrations was high between the tributaries that drained the lakes sub-catchments.
3. Biological processes (i.e., N₂ fixation), driven by elevated P concentrations, appeared to be a significant component of the N budget and causing the lake to become a net source of N to the surrounding environment (including groundwater).
4. Internal recycling (i.e., internal loading from the lake sediments) represented ~10 per cent of external P loads, and the sediments were a net source of P to the water column.
5. The lake was a net sink for P, retaining ~70 per cent of external inputs. Internal recycling and biological processes played significant roles in the mass balance.

Table 13. Summary of TP and TN budget components for Pelican Lake for the study period.

Budget component	TP	TN
Lake concentration (mean, mg L ⁻¹)	0.305	1.7
<i>Inputs</i>		
Stream inflow (kg)	6,101	20,253
Diverted inflow (PLO8A) (kg)	4,863	23,376
Precipitation (kg)	808	9,788
<i>Outputs</i>		
Groundwater (net, kg)	1,180	103,007
Diverted outflow (PLO8C) (kg)	1,698	7,667
Internal recycling processes (kg)	1,156	53,883
	<i>Source</i>	<i>Source</i>
Δ water column	10,051	-3,374
Δ water column	10,051	-3,374



4.0 Discussion

4.1 External Loads, Catchment Land Use Variation and the Importance of Sub-Catchment Scale Budget

This study's goal was to conduct a water and nutrient mass balance, identifying the variance and relative importance of different nutrient sources and internal lake processes. For the purpose of this study, Pelican Lake's watershed was separated into multiple sub-catchments based on drainage and loading sources to the lake. The results identified that external nutrient fluxes into the lake were strongly linked to surface hydrology, and that variation in nutrient concentrations was high between the tributaries that drained the lake's sub-catchments. Eleven sub-catchments were identified as possible loading sources, and Table 16 presents an estimate of contributing catchment yields over the eight-month study period.

Catchment	Area (km ²)	Percentage of Pelican Lake watershed	TP	TN
			Catchment yield (kg-km ²)	Catchment yield (kg-km ²)
PL05	25	2.1	211	606
PL08	700	60	81	34
PL09	5.2	0.5	60	343
PL10	16.9	1.5	31	197

Note: Catchment yield include stream inflow, diverted inflow and groundwater inputs.

Identifying critical source areas (CSAs) as a tool is important for addressing the management of phosphorus eutrophication and nutrient enrichment water quality issues, and is well documented in the literature (Daniel, Sharley, & Lemunyon, 1998; McDowell, Biggs, Sharpley, & Nguyen, 2004; Waters & Webster-Brown, 2016). Sample site PL05 (and its catchment) was clearly the most significant contributor of external P load to Pelican Lake from March to October 2016, in both contributing load and yield (Table 14). Surprisingly, PL05 has a relatively small catchment area, 25 km², compared to the other sites. For example, PL01 and PL08 have the largest catchment areas, 367 km² and 700 km², respectively. Input from PL08 is regulated by a dam, which would account for a lesser contribution; however, site PL01 flow contributions were insignificant to the lake's mass balance, which could be explained by unusually low precipitation observed in the region during 2016. The reasons for the high yield at PL05 are likely to include both source factors such as soil types and artificial P sources (fertilizer and agricultural practices), and transport factors such as runoff intensity due to ditch-culvert patterns, hillslope morphology, and erosion of hill slopes and stream banks (Waters & Webster-Brown, 2016). PL05, despite its relative smaller catchment area size (25 km²), has the largest percentage of agricultural land use (82 per cent; Table 3). In comparison to PL09 and PL10, agricultural land use accounts for approximately 71 per cent and 45 per cent, respectively.

Pelican Lake's phosphorous budget clearly indicated that targeted measures to control P transport should focus on high-percentage agricultural land use catchment (PL05, PL09 and PL10) and flood-associated transported at PL08-dam. The budget also illustrates that catchment area is not necessarily the strongest precursor to load contribution and yield. The natural P-rich soils of the catchment and high agricultural land use suggest lake management should reduce stream and hill slope erosion, such as changes in soil, crop and stock management (Ekholm & Lehtoranta, 2012). A more detailed understanding of specific agricultural land use practices would increase the efficiency of targeting these transport processes.

Catchment yields were also estimated for the eight-month study period (March to October 2016). Due to unusually low precipitation in 2016, it was assumed that the streams did not run or contribute significant flow to the lake from November to February (precipitation as snow accumulated in ditches as snowpack); therefore, the catchment yields



estimated for this study period are extrapolated as annual yields for comparison purposes to annual catchment yields found in the literature. Yields from North American mixed agricultural lands reported by Young et al. (1996) estimate 50–150 kg per km² per year and 10–70 kg per km² per year for south-east Australian pastures. Catchment yields are reported by Waters & Webster-Brown (2016) at 68–81 kg per km² per year. Catchment yields for Pelican Lake are high, but several of the sites, such as PL09 and PL10, are not unusual for agricultural watersheds based on the literature.

In Pelican Lake, as in many prairie systems, the external loads of phosphorus and nitrogen are high and come mostly via tributaries. The highest loads of nutrients come not from the largest catchment by area, but rather from the catchment with the highest percentage of agricultural area. This research found that surface flow dominated phosphorus inputs, and external influx from each sub-catchment is strongly related to flow. This result demonstrates the importance of variation in precipitation-related flow associated with climate change variability and future climate scenarios. Highly variable flow regimes affect waterbodies in many ways, including impacts on stratification, turbidity, and P load, and potentially affecting rates of internal loading (North et al., 2015).

4.2 Flood Events on the Prairie Landscape and the Importance of Monitoring Spring Runoff Event

In the Canadian prairies, flooding is most common in the spring as the snowfall accumulated during the winter begins to melt and runoff. One major factor that affects spring runoff potential is the soil moisture at the time of freeze-up, and is largely determined by the accumulated summer and fall precipitation (Government of Manitoba, 2016).

Monitoring and modelling of nutrient sources in Pelican Lake indicate a trend in the temporal distribution of phosphorus and nitrogen transport in the sub-catchments, as well as the entire watershed. The peak flow velocity and majority of nutrient transport to the lake was associated with high-precipitation events and diverted inflow at PL08 during spring runoff. Approximately 45 per cent of the phosphorus load during the eight-month research period was delivered to the lake when PL08A-inlet dam was opened in March. Furthermore, the majority of P was transported to the lake as particulate associated March PL08A-inlet dam opening, allowing nutrient-rich spring runoff water from the Pembina River to flow into Pelican Lake (Table 5).

Peak flow and modelled water balance-determined stream inflow and precipitation contribution was highest in June (8.26 million m³ and 5.82 million m³, respectively). The water budget for Pelican Lake indicated that in the month of June, a significant amount of water left the lake: the change in lake volume was -3.28 million m³, and transferred to surrounding aquifers, -15.8 million m³. This month also corresponds to the highest lake level recorded during the study period. The majority of the P and N load to Pelican Lake is also associated with transport during high-precipitation events. In comparison to the literature, a review of small Wisconsin catchment determined that 50–76 per cent of annual TP loads were associated with storm flows and a small number of storms dominating the load (Danz, Corsi, Graczyk, & Bannerman, 2010).

Furthermore, the majority of P and N retained in the water column was dissolved, which is commonly found in prairie streams (Table 8). Strong affinity for particulate and dissolved material, and the erosive influence of surface flow associated with low-frequency, high-intensity rainfall events explains the flood sensitivity of nutrient transport in contributing catchments of Pelican Lake (McDowell et al., 2004; Waters & Webster-Brown, 2016).

4.3 Internal Phosphorus Loading

Management of internal and external nutrient loading must both be examined when considering lake management and remediation strategies. While changes in lake water column P concentration are driven largely by internal loading processes, these nutrients are a legacy of decades of high external loading to the lake from the catchment (Schindler et al., 2008, 2012). Internal loading and recycling, commonly phrased as legacy issues, are well



documented in the literature and have been linked to poor responses to phosphorus management interventions and remediation treatments (Waters & Webster-Brown, 2016).

Efforts to manage eutrophication include the reduction of external nutrient loading with a focus on phosphorus (P), due to its control on primary producers (Schindler, 1977; 2012; Schindler et al., 2012; North et al., 2015). However, the historical catchment nutrient loading in a waterbody is retained in bottom sediment, and mobilization of this legacy P often causes significant delays in the recovery of lakes (Jeppesen et al., 2005). Since sedimentary P mobilization can lead to the production of algal toxins, it is important to better quantify sedimentary P cycling. This is particularly important—although understudied—in the Canadian prairies, because reported internal P loads into prairie lakes are often higher than other locations in North America, and this fact has been attributed to their hardwater characteristics (high sulphur and low iron content) (Loh et al., 2013; North et al., 2015).

For Pelican Lake, internal recycling (i.e., internal loading from the sediments) represented ~10 per cent of external phosphorus loads, and the sediments were a net source of P to the water column during the study period. What appears to be occurring is that rates of internal recycling are high (at least during the summer months) leading to the retention of P in the water column, fueling algal blooms. Biological processes (i.e., N₂ fixation), were also driven by elevated phosphorus concentrations, and appeared to be a significant component of the nitrogen budget, causing the lake to become a net source of N to the surrounding environment (including groundwater). However, uncertainties in Pelican Lake's nutrient budget include P reservoirs involved in the internal loading processes, such as the pore water reservoir, sediment reservoir and macrophyte reservoir. Knowledge on the role internal nutrient loading and nutrient resuspension have in Pelican Lake and other small, shallow, eutrophic prairie lakes is limited, with little information on the duration, frequency, magnitude and extent of these events. The internal loading component is likely to be of considerable importance to the nutrient balance given the potential for nutrient release during hypoxic condition, and the potential for resuspension of nutrients in shallow waters (Environment Canada & Manitoba Water Stewardship, 2011). Internal P loading from the sediment reservoir could be a dominant factor during low flow summer months, and during significant changes in lake P conc. associated with cyanobacterial blooms (Waters & Webster-Brown, 2016).

The reflux of phosphorus from the sediments represents a pathway that becomes increasingly important in these prairie ecosystem lakes. The estimate retained mass of phosphorus in the lake represents the collective external inputs; however, mechanisms of internal nutrient loading and recycling and the associated role of sediment characteristic was not examined in this research. The likelihood of substantial P fluxes from the sediment has been discussed in the literature but this hypothesis has yet to be examined in the field.

Internal P loading is common in lakes with significant sediment P reservoirs (Søndergaard et al., 1992) and accurate estimation of the internal loading rates, sediment P mass and mobility, of Pelican Lake could account for short-term fluctuations in water column P concentrations. With the current data, it is impossible to separate the role of sediment resuspension. Appropriate in-lake remediation treatments should reflect the lake-specific dynamics that drive P release from the lake sediments. Added complexities, such as more biotic model components and chemical dynamics, can strengthen a realistic representation of the causal connection among exogenous nutrient loading, ambient nutrient concentrations and lower food web dynamics associated with eutrophication issues (Zhang et al., 2013).

4.4 Management Implications

Visible effects of accelerated nutrient enrichment in waterbodies include an increase in phytoplankton biomass (Dillon & Rigler, 1974; McCauly et al., 1989), which has the potential to manifest as algal blooms and a shift in community composition toward the dominance of cyanobacteria (Environment Canada & Government of Manitoba, 2011). While algal blooms occur naturally, particularly in naturally eutrophic prairie lakes where soils are rich in nutrients, blooms become more frequent with cultural eutrophication. In the case of Pelican Lake, external



nutrient fluxes into the lake were strongly linked to surface hydrology, suggesting that increased rainfall associated with climate variability or climate change has strongly contributed to nutrient inputs to prairie lakes in recent years. The management of nutrient inputs to the lakes has the potential to significantly reduce eutrophication and cyanobacteria blooms due to nutrient over-enrichment (Waters & Webster-Brown, 2016); however, in-lake restoration has had mixed success in the literature (Lewtas et al., 2015).

For any particular lake, there may be several options for reducing algal blooms, and using more than one remediation treatment can improve the prospects of getting to below the critical threshold (Hickey & Gibbs, 2009). The success of a remediation management strategy varies greatly from lake to lake, where it is generally agreed that these treatments are usually not worth considering unless external nutrient loads can also be reduced and controlled.

Identifying lake-specific sources and processes that result in phosphorus loading will likely improve remediation results by providing guidance for more targeted interventions. The results of a simple mass balance phosphorus and nitrogen budget, such as that established in this study for Pelican Lake, provide clear guidance for catchment management. The management of Pelican Lake and its watershed should consider responding to the following nutrient loading issues:

- The transport of P from the Pembina River and regulation of the control structure-dam at the south shoreline of the lake. Regulation should consider not just lake level height and flood mitigation, but also the Pembina River nutrient load contribution potential.
- The transport of nutrients from sub-catchments, particularly agricultural fields on the east side of the lake, during high-intensity and low-frequency rain or flood events. Flood events that occur during the spring thaw/runoff are of particular concern in the Manitoba agricultural landscape. The variation in nutrient concentration was high between the tributaries that drained the lake's sub-catchments, suggesting the potential for management of land use or morphology (e.g., hill slope stabilization) to reduce external nutrient loads.
- The release of P from the large reservoir of P-binding lake sediment that can be recycled into the water column. Pelican Lake's large external TP and TN loads and the limited outflows have resulted in very high P and N retention in the lake's water column (Table 13).

Due to the high percentage of agricultural land use in the source catchments and entire watershed (58 per cent), a more detailed understanding of land-use practices, such as fertilizer application, would inform lake management strategies. If fertilizer applications are resulting in excess loading to the catchment, over and above crop requirements, addressing transport mechanisms may result in a shift in the P legacy from the lake to the catchment soil (Waters & Webster-Brown, 2016).

The quantification of Pelican Lake's water and load budget also associated P load from flood-related events at PL08: during high rainfall events, specifically spring runoff on 2016, the dam at the south end of Pelican Lake opens to divert water from the Pembina River into the lake. Remediation treatments such as constructed wetlands, are a suitable option for nutrient stripping and a sedimentation basin (Waters & Webster-Brown, 2016). However, the capacity of constructed wetlands is limited because the highest flood flows into the lake are usually diverted directly to the lake at PL08. Analysis of the efficacy of this management option for the smaller, high-yield catchments, such as PL05, could account for the large amounts of P transported during peak flows at uncontrolled inflow sources.

Lake restoration failure can occur when decision makers have little knowledge about how to select appropriate lake remediation treatments. Understanding the physical, biological and chemical drivers of lake eutrophication through modelling and monitoring opportunities requires an integrated approach consisting of both external and internal nutrient loads. From a hydrological standpoint, stream flow velocity and water balance measurement must



be conducted over a long enough timeframe to capture representative flow variations and must include high-precipitation, runoff events. The accuracy of a nutrient budget will be affected by sampling frequency: continuous monitoring enables stronger results by increasing the confidence in load estimations (Cassidy & Jordan, 2011). Uncertainties in P reservoirs present in Pelican Lake's budget were a result of our inability to collect sediment core samples to determine P recycling and flux rates. Detailed analysis of chemical P fractions by examining sediment pore water can indicate the possible results of management strategies on internal loading, such as sediment capping.

Successful remediation and management actions aimed at reducing eutrophication symptoms require a pre-implementation impact assessment of the lake—the research at Pelican Lake illustrates the morphological, hydrological and chemical data necessary to establish a simple mass balance nutrient budget and the importance of determining loading sources for suitable remediation strategies. Determining the pre-implementation (i.e., pre-impact of remediation treatment) state of the lake enables necessary monitoring of the remediation treatment effect on water quality and ecosystem health, as well as identifying any unintended, adverse consequences.



5.0 Conclusion

Freshwater ecosystems are complex and interconnected with the landscape, particularly in regions of agricultural priority, such as in Manitoba. An integrated approach will ultimately prove most effective in influencing the eutrophication of freshwater in the province. The eutrophication of Pelican Lake has become increasingly pronounced over recent years and is the main concern regarding the health of the lake.

The report demonstrates that for Pelican Lake, and most likely, many other shallow prairie systems, external nutrient fluxes are high, primarily driven by surface flow (tributaries) and there is significant variation in loads from different sub-catchments. External phosphorus was largely retained within the lake, primarily accumulating in the water column, suggesting that internal processes are particularly important in this system, and any remediation efforts at controlling eutrophication must consider these processes. This information demonstrates the sensitivity of these shallow lakes to variations in precipitation and runoff associated with climatic variability and climate change, and that changes in land use could be effective in reducing nutrient loads.

The goal of this report was to assess the nutrient fluxes and pools in Pelican Lake to inform future management decisions. The methodology and findings provide important information in the particular case of Pelican Lake, but are also more widely applicable to shallow prairie lakes in general. Each lake and its watershed will have somewhat varying characteristics, but also share many similarities to Pelican Lake and other prairie systems. The approach used for Pelican Lake can be replicated for other prairie lakes as well; the linkages to surface hydrology and flooding are likely to be shared. The report provides several insights into the differences in phosphorus and nitrogen cycling through prairie lakes and their watersheds including: that high external P loads and low N:P ratios of inputs appear to drive high rates of biological N fixation within lakes, leading to significant losses of N from the lake to groundwater; that prairie lakes are net sinks of P (in the case of Pelican Lake retaining ~70 per cent of external loads); and that internal recycling of P within the lakes is likely of high importance to managing eutrophication.

This research, identifying the sources and fluxes of nutrients, also sets the stage for considering how different management scenarios and future climate change may influence the eutrophication of shallow prairie lakes and potential next steps for addressing knowledge gaps. Climate forecasts for this region estimate equivalent or increased rainfall, suggesting the problems associated with external loads will remain unless more effectively managed. While the study demonstrates the role of P recycling within shallow prairie lakes, an important gap is to improve our understanding of mechanisms and logistics to reduce internal loading. This research represents an important step in identifying both the nutrient sources and potential solutions to the eutrophication of prairie lakes in Manitoba.



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APPENDIX

A.1 Stream water chemistry data by site and month

Table A1. Nutrient concentration (mg L⁻¹) at PLO5 over the eight-month study period.

PLO5		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	0.250	0.021	0.047	0.041	0.045	0.111	-	0.026
	Nitrate and Nitrite	5.15	1.59	<0.22	<0.11	<	<	-	<0.07
	Nitrate	5.0	1.59	<0.20	<0.10	<	<	-	<0.02
	Nitrite	0.185	<0.05	<0.10	<0.05	<	<	-	<0.01
	TKN	2.69	2.21	2.05	2.32	1.78	2.17	-	1.55
	Total Nitrogen	7.83	3.8	2.05	2.32	1.78	2.17	-	1.55
Phosphorus Load (kg)	Total Dissolved P	1.77	0.332	0.200	0.412	1.09	1.12	-	0.09
	Total P	1.80	0.405	0.251	0.449	1.12	1.18	-	0.107
	Total Particulate P	0.090	0.073	0.051	0.449	0.037	0.064	-	0.017
Chloride (Cl)		6.45	26.7	39.7	37.9	5.99	8.67	-	7.75

Table A2. Nutrient concentration (mg L⁻¹) at PLO8A-inlet over the eight-month study period.

PLO8		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	0.334	0.016	3.915	-	-	-	-	-
	Nitrate and Nitrite	0.879	<0.070	<0.070	-	-	-	-	-
	Nitrate	0.848	<0.020	<0.030	-	-	-	-	-
	Nitrite	0.032	<0.010	<0.010	-	-	-	-	-
	TKN	2.863	1.42	5.797	-	-	-	-	-
	Total Nitrogen	3.743	1.42	5.797	-	-	-	-	-
Phosphorus Load (kg)	Total Dissolved P	0.422	0.033	0.538	-	-	-	-	-
	Total P	10.5	0.188	0.609	-	-	-	-	-
	Total Particulate P	10.1	0.155	0.104	-	-	-	-	-
Chloride (Cl)		7.72	9.42	15.0	-	-	-	-	-

Table A3. Nutrient concentration (mg L⁻¹) at PLO9 over the eight-month study period.

PLO9		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	0.37	0.077	0.032	0.033	0.076	0.050	-	0.089
	Nitrate and Nitrite	4.26	0.62	0.085	0.189	0.217	0.311	-	0.793
	Nitrate	4.14	0.62	0.085	0.189	0.205	0.305	-	0.793
	Nitrite	0.12	<0.010	<0.020	<0.10	0.017	0.013	-	<0.020
	TKN	2.33	0.88	1.06	1.01	1.253	1.535	-	0.89
	Total Nitrogen	6.59	1.5	1.14	1.2	1.473	1.85	-	1.69
Phosphorus Load (kg)	Total Dissolved P	0.62	0.079	0.129	0.132	0.343	0.420	-	0.137
	Total P	0.76	0.113	0.160	0.156	0.388	0.511	-	0.199
	Total Particulate P	0.15	0.034	0.031	0.156	0.063	0.081	-	0.062
Chloride (Cl)		5.27	6.26	5.0	5.0	3.52	5.315	-	6.8

**Table A4. Nutrient concentration (mg L⁻¹) at PL10 over the eight-month study period.**

PL10		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	0.61	0.013	0.031	0.025	0.018	0.031	-	0.025
	Nitrate and Nitrite	0.56	0.185	<0.070	<0.070	<0.070	<0.070	-	<0.070
	Nitrate	0.54	0.185	<0.020	<0.020	0.025	0.041	-	0.033
	Nitrite	0.02	<0.010	<0.010	<0.10	<0.010	<0.010	-	<0.010
	TKN	2.37	0.88	1.18	1.23	1.07	1.095	-	0.87
	Total Nitrogen	2.93	1.07	1.18	1.23	1.07	1.095	-	0.87
Phosphorus Load (kg)	Total Dissolved P	0.38	0.074	0.129	0.122	0.172	0.202	-	0.078
	Total P	0.53	0.093	0.141	0.143	0.198	0.246	-	0.101
	Total Particulate P	0.15	0.019	<0.014	0.143	0.026	0.044	-	0.023
Chloride (Cl)		4.94	4.22	4.87	3.68	2.537	3.045	-	4.14

Table A5. Nutrient concentration (mg L⁻¹) at PLO8C-outlet over the eight-month study period.

PLO8C-outlet		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	-	-	-	-	0.034	-	-	-
	Nitrate and Nitrite	-	-	-	-	<0.070	-	-	-
	Nitrate	-	-	-	-	<0.040	-	-	-
	Nitrite	-	-	-	-	<0.020	-	-	-
	TKN	-	-	-	-	1.627	-	-	-
	Total Nitrogen	-	-	-	-	1.627	-	-	-
Phosphorus Load (kg)	Total Dissolved P	-	-	-	-	0.323	-	-	-
	Total P	-	-	-	-	0.405	-	-	-
	Total Particulate P	-	-	-	-	0.082	-	-	-
Chloride (Cl)		-	-	-	-	14.1	-	-	-



B.1 Nutrient load summarized by stream site and month

Table B1. Nutrient load at PLO5 over the eight-month study period.

PLO5		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	130.02	2.61	29.17	221.79	39.04	0.00	0.00	0.01
	Nitrate and Nitrite	2,675.25	293.18	136.53	324.57	61.18	0.00	0.00	0.02
	Nitrate	2,597.30	293.18	124.12	252.44	23.30	0.00	0.00	0.02
	Nitrite	78.05	4.35	62.06	126.22	11.65	0.00	0.00	0.00
	TKN	1,397.91	232.95	1,272.24	7,717.47	1,558.52	0.00	0.00	0.27
	Total Nitrogen	4,067.96	526.12	1,272.24	7,717.47	1,558.52	0.00	0.00	0.29
Phosphorus Load (kg)	Total Dissolved P	920.33	62.92	124.12	2,978.80	954.34	0.00	0.00	0.11
	Total P	937.38	66.33	155.77	3,135.67	975.89	0.00	0.00	0.11
	Total Particulate P	30.97	6.31	31.65	156.87	25.64	0.00	0.00	0.00
Chloride (Cl)		3,349.78	2,294.62	24,637.93	83,846.33	5,231.96	0.00	0.00	2.37

Table B2. Nutrient load at PLO8A-inlet over the eight-month study period.

PLO8A		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	1,446.32	197.66	1,327.20	20.48	0.00	0.00	0.00	0.00
	Nitrate and Nitrite	4,392.66	596.84	12.48	427.82	0.00	0.00	0.00	0.00
	Nitrate	4,241.47	542.79	11.34	407.35	0.00	0.00	0.00	0.00
	Nitrite	151.20	23.16	5.67	20.48	0.00	0.00	0.00	0.00
	TKN	10,394.78	4,532.30	1,690.19	1,390.15	0.00	0.00	0.00	0.00
	Total Nitrogen	14,791.42	5,072.77	1,690.19	1,821.21	0.00	0.00	0.00	0.00
Phosphorus Load (kg)	Total Dissolved P	2,165.50	221.60	154.27	139.02	0.00	0.00	0.00	0.00
	Total P	3,495.43	1,009.92	175.83	182.12	0.00	0.00	0.00	0.00
	Total Particulate P	1,329.93	788.33	21.55	43.11	0.00	0.00	0.00	0.00
Chloride (Cl)		32,457.57	12,492.77	1,327.20	16,380.11	0.00	0.00	0.00	0.00

Table B3. Nutrient load at PLO9 over the eight-month study period.

PLO9		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	37.19	3.60	3.31	33.96	11.12	0.00	0	0.00
	Nitrate and Nitrite	425.90	39.55	8.79	97.67	31.56	0.00	0	0.02
	Nitrate	413.91	38.58	8.79	90.76	29.91	0.00	0	0.02
	Nitrite	12.26	1.09	2.07	13.82	2.14	0.00	0	0.00
	TKN	232.69	27.33	109.64	628.10	182.56	0.00	0	0.02
	Total Nitrogen	658.59	66.88	117.91	727.27	214.60	0.00	0	0.04
Phosphorus Load (kg)	Total Dissolved P	61.54	3.87	13.34	123.52	49.91	0.00	0	0.00
	Total P	76.04	5.18	16.55	155.37	56.56	0.00	0	0.00
	Total Particulate P	14.49	1.31	3.21	31.86	6.80	0.00	0	0.00
Chloride (Cl)		526.84	124.33	517.17	2,389.17	513.19	0.00	0	0.14



Table B4. Nutrient load at PL10 over the eight-month study period.

PL10		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	83.85	8.29	9.08	37.47	7.43	0	0	0
	Nitrate and Nitrite	76.16	20.66	20.51	119.21	28.89	0	0	0
	Nitrate	73.45	20.12	5.86	38.32	9.63	0	0	0
	Nitrite	2.72	0.89	2.93	17.03	4.13	0	0	0
	TKN	325.24	182.31	345.81	1,932.87	441.58	0	0	0.05
	Total Nitrogen	401.54	203.21	345.81	1,932.87	441.58	0	0	0.05
Phosphorus Load (kg)	Total Dissolved P	52.26	8.09	37.81	269.92	70.85	0	0	0
	Total P	72.40	11.31	41.32	313.35	81.71	0	0	0.01
	Total Particulate P	20.15	3.22	4.10	43.43	10.87	0	0	0
Chloride (Cl)		678.19	280.32	1,427.21	6,743.77	1,046.86	0	0	0.24

Table B5. Nutrient load at PLO8C-outlet over the eight-month study period.

PLO8C		March	April	May	June	July	August	Sept	October
Nitrogen Load (kg)	Ammonia, Total	0	0	0	0	184.93	0	0	0
	Nitrate and Nitrite	0	0	0	0	290.90	0	0	0
	Nitrate	0	0	0	0	135.06	0	0	0
	Nitrite	0	0	0	0	62.34	0	0	0
	TKN	0	0	0	0	7,667.27	0	0	0
	Total Nitrogen	0	0	0	0	7,667.27	0	0	0
Phosphorus Load (kg)	Total Dissolved P	0	0	0	0	1,292.42	0	0	0
	Total P	0	0	0	0	1,697.60	0	0	0
	Total Particulate P	0	0	0	0	405.18	0	0	0
Chloride (Cl)		0	0	0	0	72,309.19	0	0	0

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