Pigeon Lake Phosphorus Budget

March 2014

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EXECUTIVE SUMMARY

Pigeon Lake is a large recreational lake located southwest of Edmonton. Recent occurrences of significant blue-green algae (cyanobacteria) blooms have resulted in stakeholders at Pigeon Lake seeking management options to assist with reducing the frequency and intensity of such events. Management of blooms has focused primarily on reducing phosphorus concentrations in the lake. To more effectively target activities, a nutrient budget was developed to identify phosphorus entering the lake from external and internal (sediment release) sources.

Approximately 57% (7,510 kg) of phosphorus during the open water season comes from sediment release, the remaining 43% (5,755 kg) from external sources. Of these external sources, diffuse runoff (48%; 2,913 kg) and dustfall/precipitation (43%, 2,596 kg) comprise the majority of phosphorus loads to the lake. Groundwater, stream inflows and sewage comprise the remaining 9% (587 kg) of phosphorus inputs to Pigeon Lake. These numbers are based on longer term averages where possible, as it was noted that significant inter-annual variability exists in most Alberta Lake data.

The phosphorus budget for Pigeon Lake should be used as an educational and planning tool. The relative partitioning of phosphorus to the various sources emphasizes where significant sources of phosphorus are coming from. However, it must be kept in mind that while some sources may have a relatively small contribution, management of these sources may be relatively straightforward and should be pursued. The relatively even split of external and internal sources indicates that while watershed management efforts must be pursued, there may be merit in exploring in-lake options for controlling phosphorus release to achieve a more timely reduction of nuisance blooms in the future.

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ACKNOWLEDGEMENTS

This report represents the culmination of several years of planning and monitoring and hence numerous people were involved. I would like to first thank the residents and stakeholders at Pigeon Lake. This includes the Pigeon Lake Watershed Association (PLWA) who first identified the need for a phosphorus budget to support work on the integrated watershed management plan, local municipalities for providing required watershed data, and local residents for providing volunteer support which included weekly boating trips on Pigeon Lake for field staff to collect samples.

Collection of data was carried out by ESRD field staff (McIntyre Centre) and Alberta Lake Management Society (ALMS). I would like to specifically thank Elynne Murray (ALMS) who conducted the majority of stream and lake sampling in 2013 and acted as the primary day-to-day contact with Pigeon Lake residents. ESRD data management staff ensured that all of the data was managed and organized in a logical and easily accessibly manner while also ensuring errors and omissions were addressed in a timely manner. My thanks to Lisa Reinbolt (ESRD) for taking the lead on data management and accommodating project drift.

Richard Casey (ESRD) and David Trew (North Saskatchewan Watershed Alliance) provided much appreciated insight and critical reviews of the report. Terry Chamaluk (ESRD) developed the 20-year water balance for Pigeon Lake and provided necessary hydrological data and input to support the development of the nutrient budget. Greg Nelson (ESRD) provided watershed maps and land cover statistics. Mary Raven (ESRD) assisted greatly with formatting and moving this report through the production process.

1.0 INTRODUCTION

Eutrophication of recreational lakes is an important management issue across much of the settled areas of Alberta. During the summer, many lakes experience significant growth of planktonic algae which often include nuisance blooms of cyanobacteria. While nutrient rich soils, shallow depths and high alkalinity mean that many of Alberta's lakes are naturally productive, paleolimnological studies have indicated that eutrophication of lakes has been exacerbated in recent decades by activities such as land clearing and agricultural and residential development (Blais *et al*. 2000, Köster *et al.* 2008). Aside from aesthetic effects, blooms of cyanobacteria have been linked to human health risk factors, primarily production of toxins such as microcystins (Zurawell 2010).

Phosphorus is often identified as the limiting nutrient to nutrient growth in temperate lakes (Smith and Schindler 2009), and the majority of Alberta lakes, with the exception of truly saline lakes, show a strong relationship between algal biomass (as chlorophyll *a*) and total phosphorus concentration (Casey 2011). Phosphorus in lakes comes from a number of different sources including runoff, precipitation (atmospheric deposition), groundwater, sewage and lake sediments. With respect to lake management, it is important to understand the proportional contribution of these sources in order to prepare effective long-term management plans and to target effective measures for controlling these nutrient sources.

Pigeon Lake is a large recreational lake located approximately 60km southwest of Edmonton. Due to its proximity to this large urban centre, the ease of access to the lake, and available amenities and recreational opportunities within the region, Pigeon Lake is one of Alberta's most popular recreational lakes. Land-uses within the Pigeon Lake watershed include undisturbed natural areas, agriculture, and urban residential (both seasonal and permanent). From a management perspective, there are 10 summer villages surrounding the lake, two provincial parks and one first nations reserve (Mitchell and Prepas 1990). Also, Pigeon Lake falls within two county boundaries; Leduc County on the northwest side, and the County of Wetaskiwin for the remainder of the watershed (Figure 1-1).

Pigeon Lake is in the dry mixedwood sub-region of the boreal region of Alberta (Natural Regions Committee 2006) and forms part of the Battle River watershed. While the surface area of Pigeon Lake is quite large at $97km^2$, its watershed is relatively small at only $187km^2$, resulting in a long water residence time (exceeding 100 years; Mitchell and Prepas 1990). This long water residence time combined with shallow overall depth (maximum = 9m, average = 6m) and a well mixed, non-stratified water column means that nutrients entering the lake tend to remain available within the lake for extended periods of time. This results in Pigeon Lake being relatively productive (fertile) as measured by chlorophyll-*a* (a common photosynthetic plant/bacteria pigment) and total phosphorus (an essential nutrient required for plant growth). Average concentrations of chlorophyll-a and total phosphorus in Pigeon Lake are $17.2mg/m^3$ and 0.035mg/L respectively (Casey 2011) placing it in a mesotrophic to eutrophic category of lake productivity, typical of many central Alberta lakes.

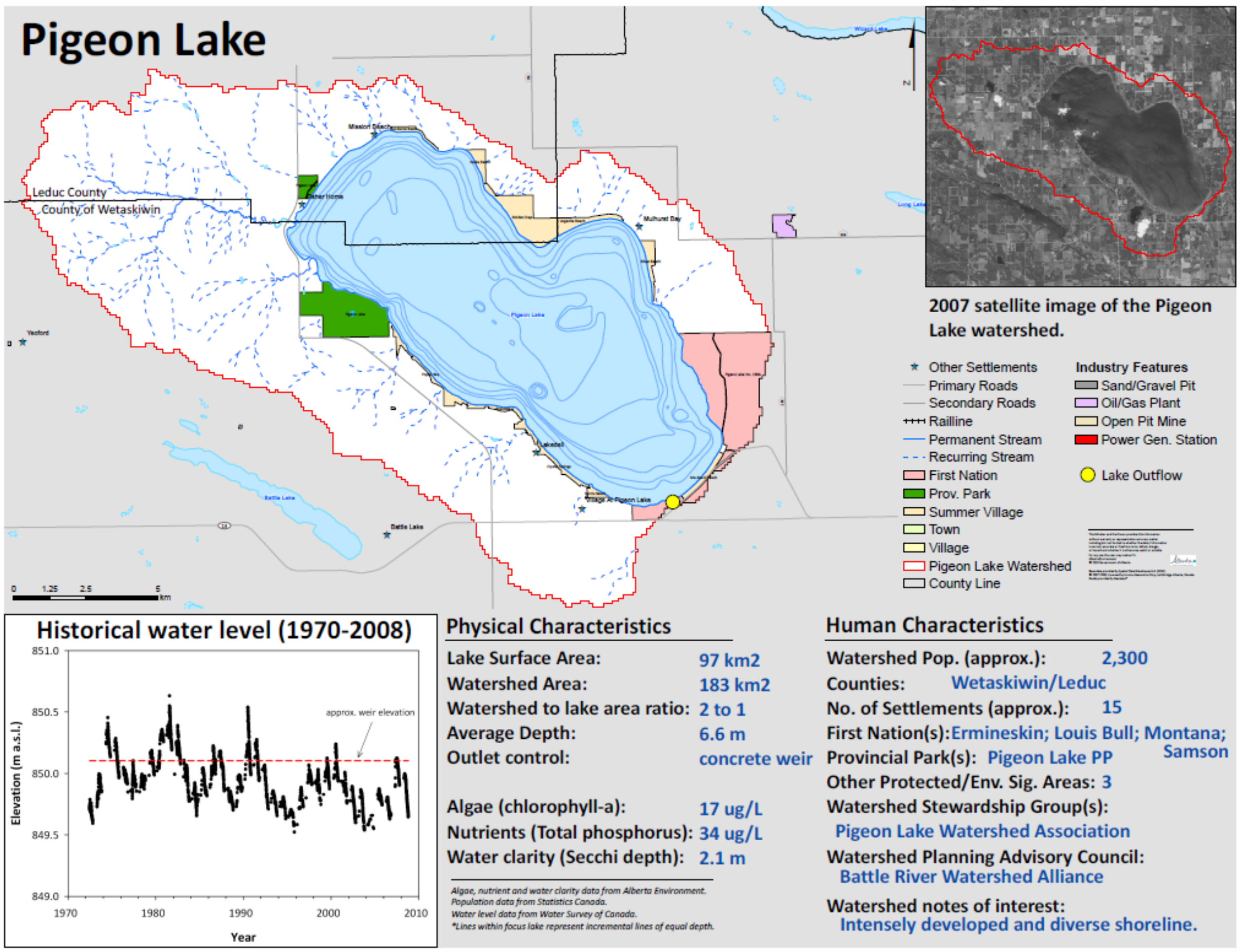

Figure 1-1 Overview of Pigeon Lake Watershed

Pigeon Lake is susceptible to nuisance blooms of algae and cyanobacteria (blue-green algae) due to relatively high phosphorus concentrations. Significant blooms have occurred in recent years, most notably in 2006 when Pigeon Lake experienced a severe *Gloeotrichia* and *Lyngbya* dominated bloom (Ron Zurawell, Alberta Environment and Water, pers. comm.). Observations have shown other nuisance bloom-forming cyanobacteria genera such as *Aphanizomenon* and *Anabaena* to be present in Pigeon Lake.

As a result of nuisance blooms, there has been a demand from users at Pigeon Lake to examine methods to reduce the frequency and intensity of cyanobacterial blooms. In 2012, a report summarizing potential options for watershed and in-lake management of blooms was produced (Teichreb 2012). Further discussions highlighted the need to identify relative proportions of phosphorus entering the watershed both from external and internal (sediment loading) sources. This report summarizes the results of the 2013 nutrient budget study at Pigeon Lake and provides an overview of relative proportions of phosphorus in Pigeon Lake.

The following sections present an overview of the 2013 Pigeon Lake nutrient budget monitoring program, followed by methods utilized to calculate water and phosphorus budgets. Results are presented as both inputs and outputs along with a summary phosphorus budget for Pigeon Lake. Finally, discussion of implications of the phosphorus budget for nutrient management and general conclusions and recommendations are presented.

2.0 OVERVIEW OF 2013 SURVEY AND NUTRIENT BUDGET

The following section presents an overview of data collected in 2013 in support of developing a phosphorus budget for Pigeon Lake. This supports equations presented in Section 3.0 and the results calculated in Section 4.0.

2.1 2013 Pigeon Lake Water Quality Sampling Program

A more comprehensive water quality sampling program of Pigeon Lake was implemented in 2013 to collect appropriate data for the nutrient budget as well as to gain a better understanding of changes in lake water quality and ecology. These results, including raw data, are in Teichreb *et al.* (*in press*).

The lake was sampled 15 times from June through September (Table 2-1). Water quality samples were taken at depth profile and composite sites. Composite samples are made up of 10 predetermined sites around the lake (including the profile site). For the purposes of the lake phosphorus budget, only composite sample results were utilized as this provides a better representation of overall water quality condition for the lake.

Table 2-1 Pigeon Lake Sample Dates, 2013

Month	Dates Sampled
June	5, 16, 18, 26
July	4, 10, 17, 24, 29
August	8, 14, 22, 28
September	5, 19

A total of eight streams, including the outflow of Pigeon Lake were sampled in 2013 (Figure 2-1, Table 2-2). While a subset of streams was sampled in 2012 as part of an initial exploratory program, 2013 remains the only year in which more complete detailed stream water quality and instantaneous discharge data were collected. Streams at Pigeon Lake represent a directly measurable source of runoff of nutrients and other water quality variables to the lake, as opposed to diffuse runoff.

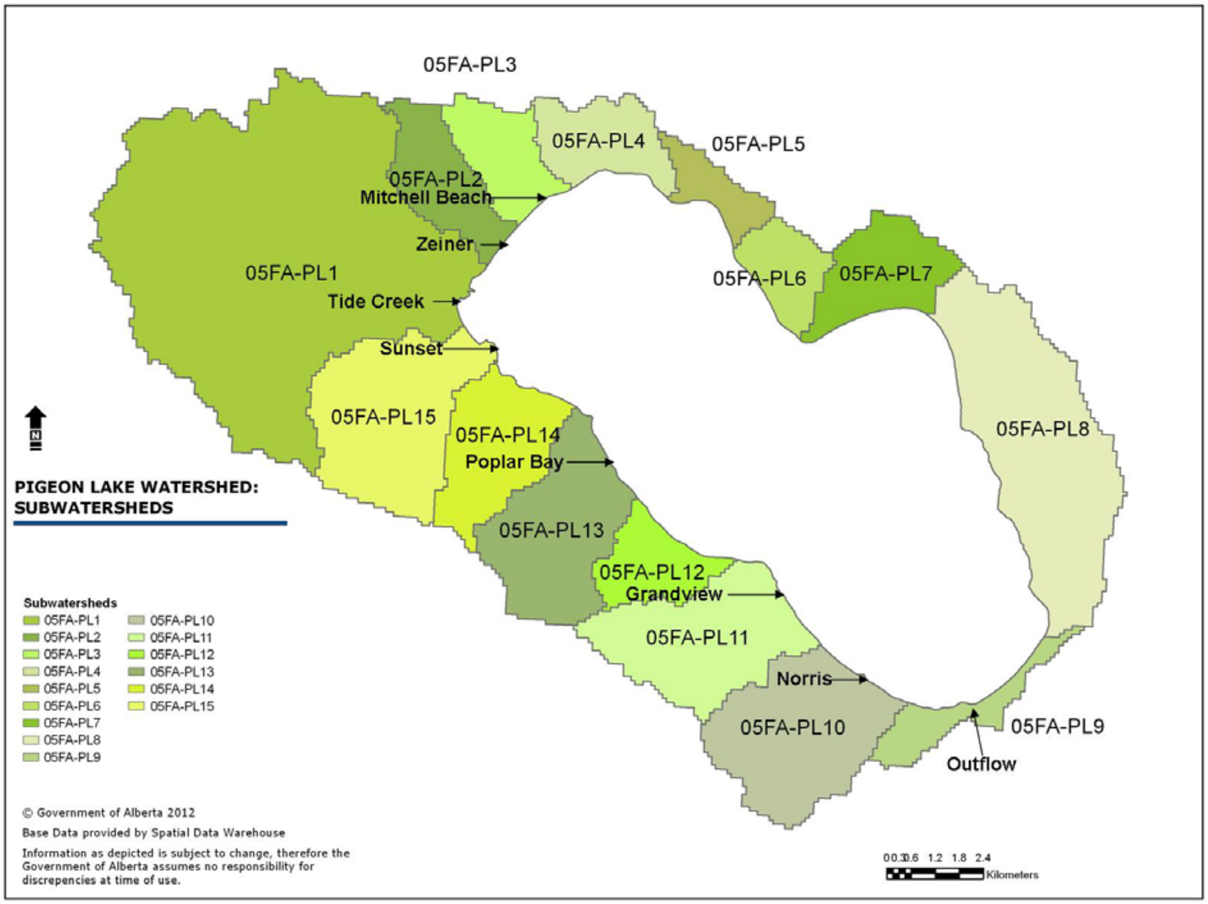

Figure 2-1 Pigeon Lake Stream Water Quality Sample Locations, 2013

Table 2-2 Pigeon Lake Stream Sample Dates, 2013

Location	Date ('X' indicates sample was collected)															
	4/25	4/26	4/30	5/2	5/6	5/13	5/27	6/10	6/24	7/8	7/16	7/22	8/6	8/20	9/3	9/17
Grandview		X														
Mitchell	X			X	X	X	X	X	X	X	X	X				
Norris		X		X												
Outflow				X	X	X	X	X	X	X	X	X	X	X	X	X
Poplar Bay	X			X	X		X				X					
Sunset	X			X	X	X	X	X	X	X	X	X		X		
Tide			X								X					
Zeiner		X		X	X	X	X	X	X	X	X	X				

Note: Highlighted cells correspond to samples collected after significant rainfall events.

Very little groundwater data within the Pigeon Lake watershed was available prior to 2013. To address this, a total of twelve domestic groundwater wells within the watershed were sampled in October 2013 for basic nutrients, dissolved solids and bacteriological parameters. Locations were limited to areas where volunteers agreed to have water samples collected from their wells and were primarily located within summer villages surrounding the lake and varied in depth from 7 to 53 m. Complete results and discussion can be found in Teichreb *et. al.* (*in press*). Summary locations and sampling dates are shown in Figure 2-2 and Table 2-3.

Table 2-3 Pigeon Lake Groundwater Sampling Locations and Dates, 2013

Sample ID	Location	Date
13GWE01506	Crystal Keys	22-Oct-13
13GWE01500	Ma-Me-O	22-Oct-13
13GWE01501	Rundle's Mission	22-Oct-13
13GWE01502	Itaska Beach	22-Oct-13
13GWE01503	Golden Day's Beach	22-Oct-13
13GWE01504	Grandview Beach 1	22-Oct-13
13GWE01505	Crystal Springs	22-Oct-13
13GWE01510	Grandview Beach 2	23-Oct-13
13GWE01509	Leduc County @ Hwy 616 RR 11	23-Oct-13
13GWE01511	Sunset Harbour	23-Oct-13
13GWE01508	Silver Beach	23-Oct-13
13GWE01507	Johnsonia Beach	23-Oct-13

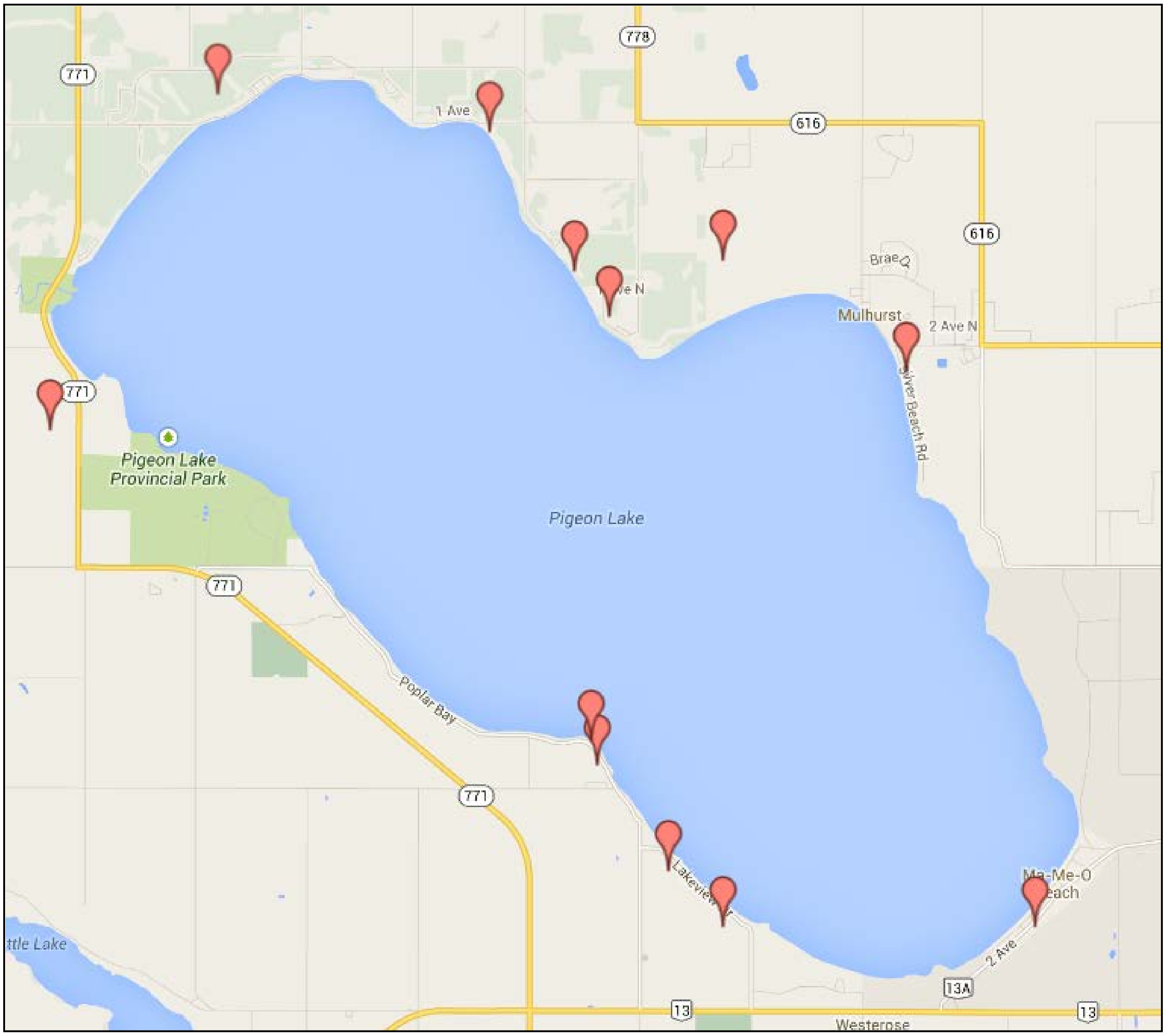

Figure 2-2 Pigeon Lake Groundwater Sampling Locations, 2013

Atmospheric deposition of nutrients on Pigeon Lake was not measured in 2013 and instead relied upon literature values for Alberta lakes (see Section 4.1.2). However, precipitation amounts were available from the nearby Battle River Headwaters and Breton weather stations maintained by Environment Canada (Figure 2-3).

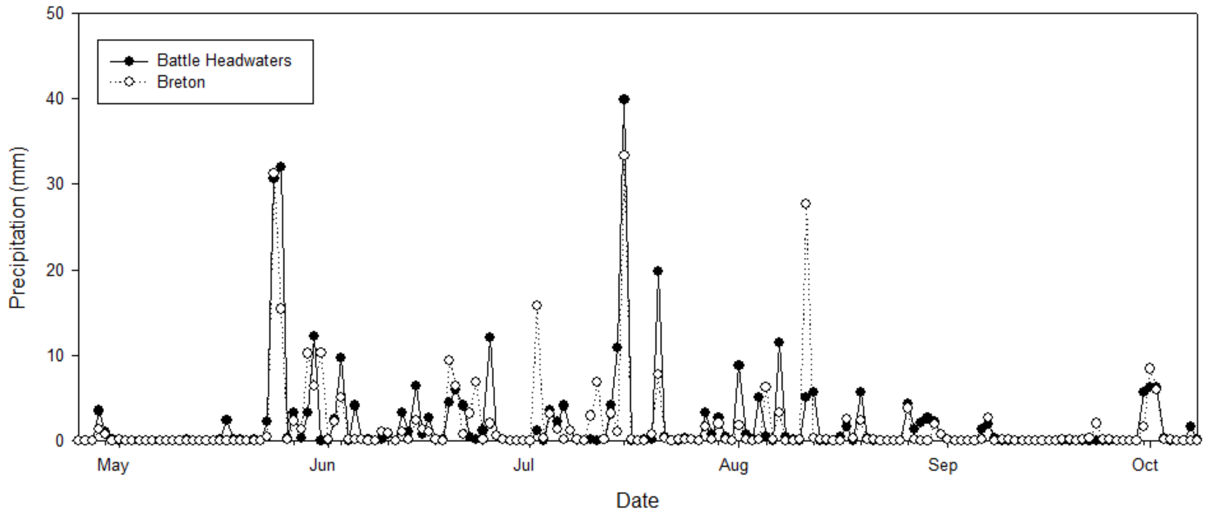

Figure 2-3 Precipitation Data for Battle Headwaters and Breton Weather Stations, 2013

Data for diffuse runoff and nutrients in sewage were not available or easily obtained. Instead, calculation of these nutrient sources relied on literature values obtained from other Alberta lakes.

Water volume calculations for the lake water balance relied primarily upon the 20-year water balance with monthly time-steps developed by Alberta Environment and Sustainable Resource Development for Pigeon Lake. For lake volumes, a capacity curve was used to estimate volumes at given elevations (see section 4.3). Lake elevation readings at times of lake sampling were obtained from the Water Survey of Canada website.

2.2 Pigeon Lake Nutrient Budget

Within a given lake, there can be a great deal of intra and inter annual variability for nutrients (for examples, see Casey 2011). For example, a year with relatively high amounts of precipitation may result in increased nutrient loads to a lake, while external loads may be relatively low in dry years. As the intent of this nutrient budget was to obtain "average" partitioning of nutrients for external and internal sources, a decision to utilize longer-term data where feasible was made. This involved relying primarily on long-term water quality data and the 20-year water balance for the typical open water season (April to October) to obtain estimates of phosphorus loads to Pigeon Lake.

In some cases, such as inputs from streams, longer-term water quality and quantity data is not available and relative contributions are calculated on the current data only. However, as the relative contribution of streams to the overall nutrient budget is typically small, the lack of encompassing inter-annual variability is likely not to be as important as would be the case for larger components of the nutrient budget.

Ultimately, the phosphorus budget is a planning and educational tool. It provides a relative estimate of the proportional contributions of phosphorus sources to Pigeon Lake thus providing information on the relative impact of activities in the watershed and in-lake may have.

3.0 WATER AND PHOSPHORUS BUDGET CALCULATIONS

Lake phosphorus budgets require hydrological water balances which provide long-term estimates of water volumes entering and leaving a lake. For Pigeon Lake, a 20-year monthly water balance extending from 1986 to 2006 was previously developed by ESRD regional hydrologists and utilized for this report. The general water balance model can be expressed as:

$$\Delta S = (R+P+G_{in}) - (G_{out}+D+O+E) \qquad \text{[eq. 1]}$$

Where:

- ΔS is the change in lake volume;
- R, P, and G_{in} are water volumes flowing into the lake from runoff, direct atmospheric precipitation and groundwater respectively; and
- G_{out}, D, O and E are water volumes out of the lake from groundwater, diversions, surface outflow and evaporation respectively.

For the Pigeon Lake model, the groundwater term is simplified to a net groundwater influx (G_{in} – G_{out}). Overall, a good relationship between modeled and recorded results was obtained (r^2=0.75, Figure 3-1).

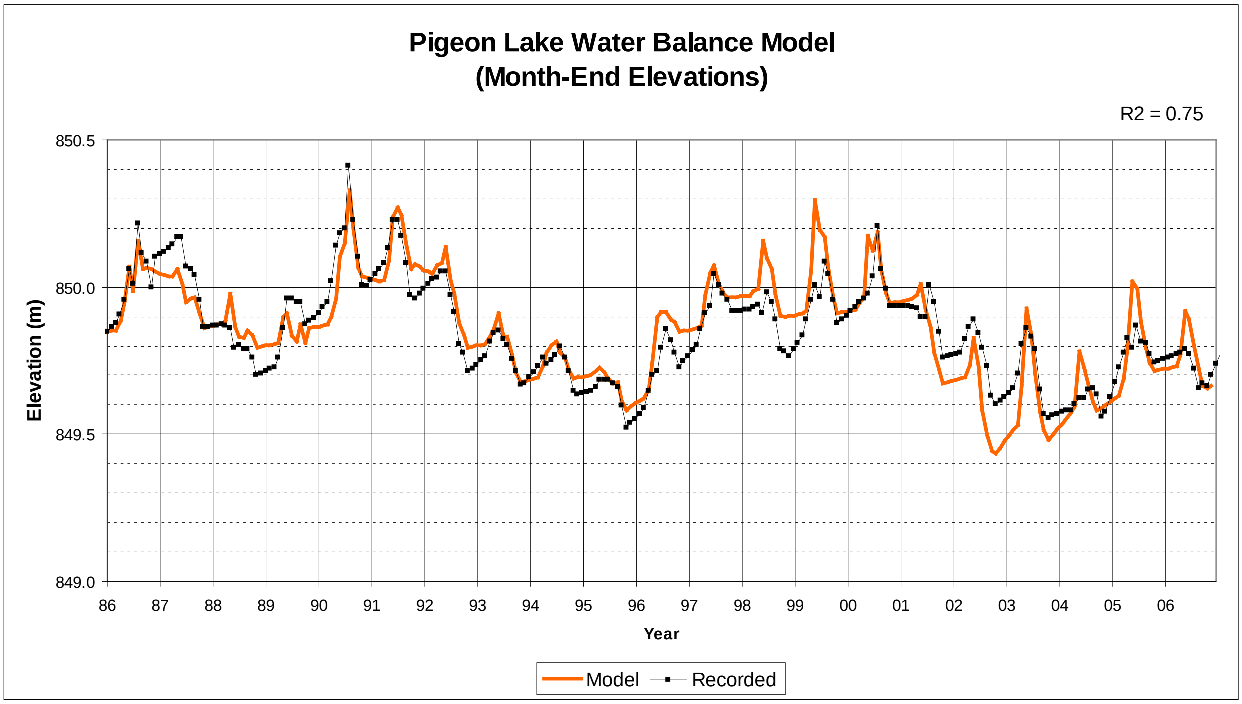

Figure 3-1 Pigeon Lake Water Balance - Modeled and Recorded Elevations.

The lake phosphorus budget utilized water balance data to calculate terms in a mass budget equation. For Pigeon Lake, a modified mass budget equation from Vollenweider and Kerekes (1980) was used and can be expressed as:

$$\Delta M = (I_R + I_P + I_G + I_A) - (O_G + O_D + O_O) - (LS) \qquad \text{[eq. 2]}$$

Where:

- ΔM is the change in lake mass of total phosphorus;
- $I_{R,P,G,A}$ are TP mass fluxes into the lake from runoff (point source and diffuse), atmospheric deposition, groundwater and sewage respectively;
- $O_{G,D,O}$ are TP mass fluxes out of the lake from groundwater, diversions and surface outflow respectively; and
- LS is TP mass flux either into (+) or out of (-) the lake sediments.

As with the water balance, the groundwater portion of the mass budget equation was simplified to I_G-O_G for Pigeon Lake.

4.0 RESULTS

The following sections present results of calculated phosphorus inputs (Section 4.1) and outputs (Section 4.2) utilizing the data collected and formula described in Sections 2.0 and 3.0.

4.1 Phosphorus Inputs

4.1.1 Runoff

4.1.1.1 Direct Runoff

$$I_R = 377 \text{ kg}$$

Figures 4-1 and 4-2 presents a summary of instantaneous and total cumulative (open-water) discharge measurements at all streams (including the outflow) in 2013. Figure 4-3 presents total phosphorus concentrations observed at all streams in 2013. Typical of a relatively small watershed, the Pigeon Lake streams had low flows characterized by peaks primarily during the spring melt and after major rainfall events.

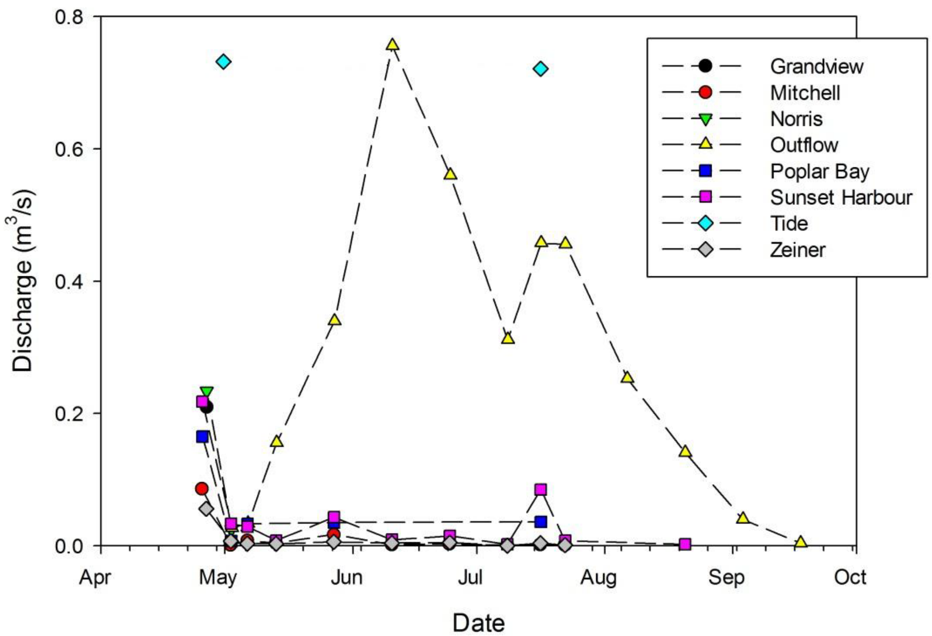

Figure 4-1 Pigeon Lake Stream Discharge, 2013

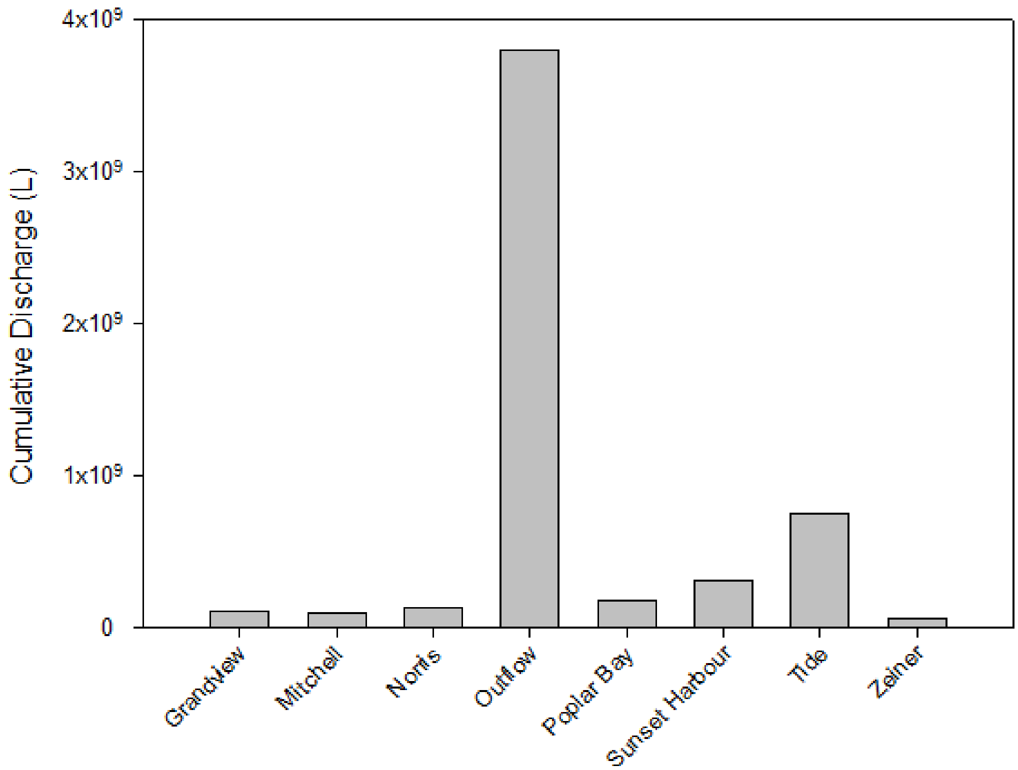

Figure 4-2 Pigeon Lake Stream Cumulative Discharge, 2013

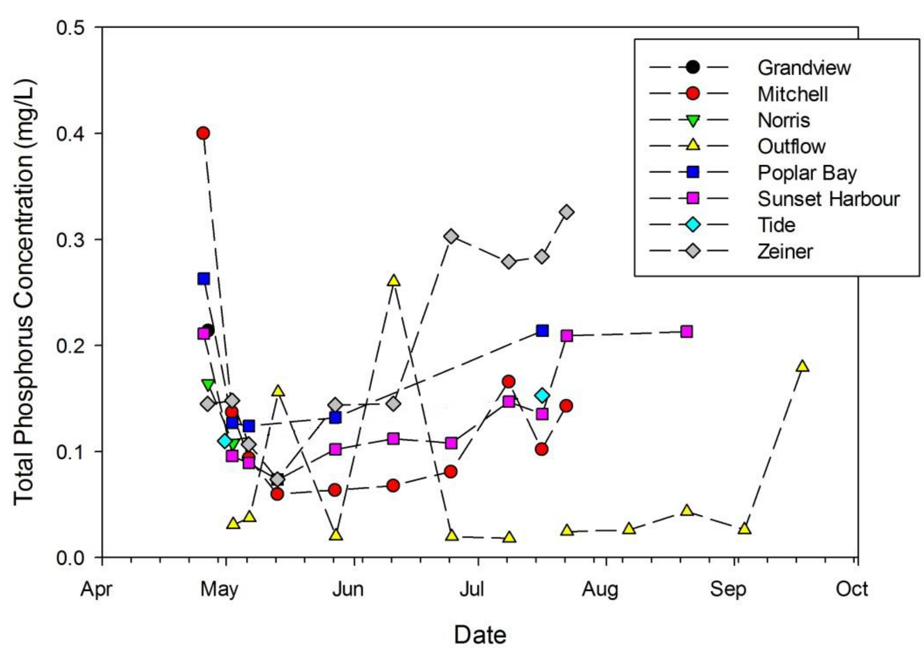

Figure 4-3 Pigeon Lake Streams Total Phosphorus Concentrations, 2013

To calculate daily stream loads to Pigeon Lake, total phosphorus concentrations were multiplied by instantaneous discharge measurements collected on each sampling date. To obtain cumulative loads for the season, the daily load was multiplied by the number of days to the next sampling event and summed to the final sampling event. Using equations 3 through 7, an example using Mitchell Beach is provided in Table 4-1.

Daily discharge (L/day) = Instantaneous discharge (m^3/s) x 1000L/m^3 x 86,400s/day [eq. 3]

Daily load (kg/day) = Concentration (mg/L) x Daily Discharge (L/day) x 1,000,000mg/kg [eq. 4]

Days to next sampling event (days) = Next sampling date - Current sampling date [eq. 5]

Total Load (kg) = Daily Load (kg/day) x Days to next sampling event (days) [eq. 6]

Total Discharge (L) = Daily Discharge (L/day) x Days to next sampling event (days) [eq. 7]

Table 4-1 Cumulative Phosphorus Loads for Mitchell Beach Inflow

Date	Conc. (mg/L)[1]	Daily Discharge (L/day)	Daily Load (kg/day)	Days to next sampling event	Total Load (kg)	Total Discharge (L)
25-Apr-13	0.400	7,430,400	2.972	6.92	20.56	51,393,600
2-May-13	0.137	86,400	0.012	4.00	0.05	345,300
6-May-13	0.094	691,200	0.065	6.96	0.45	4,809,600
13-May-13	0.060	345,600	0.021	14.00	0.29	4,838,400
27-May-13	0.064	1,468,800	0.094	14.05	1.31	20,629,500
10-Jun-13	0.068	172,800	0.012	13.99	0.16	2,417,400
24-Jun-13	0.081	259,200	0.021	13.99	0.29	3,627,000
8-Jul-13	0.166	86,400	0.014	8.03	0.12	693,900
16-Jul-13	0.102	172,800	0.018	5.97	0.11	1,030,800
22-Jul-13	0.143	86,400	0.012	15.16	0.19	1,309,500
6-Aug-13	-	0	-	-	-	-
Total					**23.52**	**91,095,000**

1. Measured total phosphorus concentration.
Note: Numbers have been rounded off for presentation and may result in some discrepancies in calculated values.

It was assumed that flow and concentrations were constant from one sampling event to the next, although flows would have changed between sampling events, making this method a general approximation suitable for the low flows. As sampling was flow biased (i.e. more samples collected during higher flow periods), any large variations in flows were likely accounted for. Gauged stream inflows total phosphorus mass was calculated to be 262 kg. Estimated loads in 2012 were 121 kg (unpub. data) highlighting variability in stream discharge volumes and concentrations and emphasizing the need for longer-term data.

In addition to measured inflows, it was assumed sub-watersheds which were not sampled (Figure 2-1) each had an inflowing stream. To estimate phosphorus loads for these streams, cumulative discharge for sub-watersheds not sampled in 2013 was first calculated by taking the cumulative discharge for measured inflowing streams (in liters) and dividing by the measured sub-watershed area (in hectares) to give a water yield (in l/ha). This water yield was then multiplied by the area of the unmeasured sub-watersheds (in hectares) to estimate cumulative discharge (in liters).

TP mass flux from unmeasured sub-watersheds was estimated by regressing discharge and TP concentrations from measured inflows (best fit shown in equation 3). Estimated discharge volumes from unmeasured sub-watersheds were used to estimate TP loads (kg).

$$\ln(TP) = -15.811 + (1.001 * \ln(\text{discharge})) \quad [\text{eq. } 3]$$

Using equation 3, TP loads from unmeasured sub-watersheds was estimated to be 115 kg. Total TP load from the unmeasured streams entering Pigeon Lake was estimated to be 377 kg.

4.1.1.2 Diffuse Runoff

$$I_R = 2913 \text{ kg}$$

Diffuse or non-point runoff includes overland water flow not entering Pigeon Lake via streams. This includes overland flow from agricultural and residential areas which could include nutrients from stormwater, fertilizers, livestock manure, wildlife/pet faeces and soil particles. Measuring contributions of diffuse runoff loads to a lake is commonly done through the use of export coefficients with a compilation of methods and estimates utilized in Alberta recently completed (Donahue 2013). Two methods were utilized to estimate diffuse runoff contributions of total phosphorus to Pigeon Lake, the first based on the Pigeon Lake water balance, and the second using export coefficients from the scientific literature. Both are described below.

The water balance method utilized average 20-year inflow volumes to Pigeon Lake for April to September. The total estimated water volume entering the lake via direct runoff was removed from this number and the result multiplied by the flow weighted mean total phosphorus concentration for all inflowing streams. This provided an estimate of 2,722 kg TP entering Pigeon Lake for the year via diffuse inflow.

The second method utilized export coefficients determined for forested/natural and mixed/light agricultural areas at Baptiste and Wabamun lakes (Mitchell and Trew 1982). These were applied to detailed land cover for each sub-watershed at Pigeon Lake was obtained using ArcGIS (Figure 4-4 and Table 4-2). Total coverage of forested/natural and mixed/light agricultural areas was calculated and multiplied by average export coefficients. For exposed/developed, the same runoff coefficient as was used for mixed/light agricultural areas was assumed. This method resulted in an estimate of 3,103 kg TP entering Pigeon Lake per year.

As can be seen, the two methods used to estimate diffuse inflow contributions of total phosphorus to Pigeon Lake were relatively close. For the purposes of the annual phosphorus budget, an average of the two estimates, 2,913 kg TP, was used.

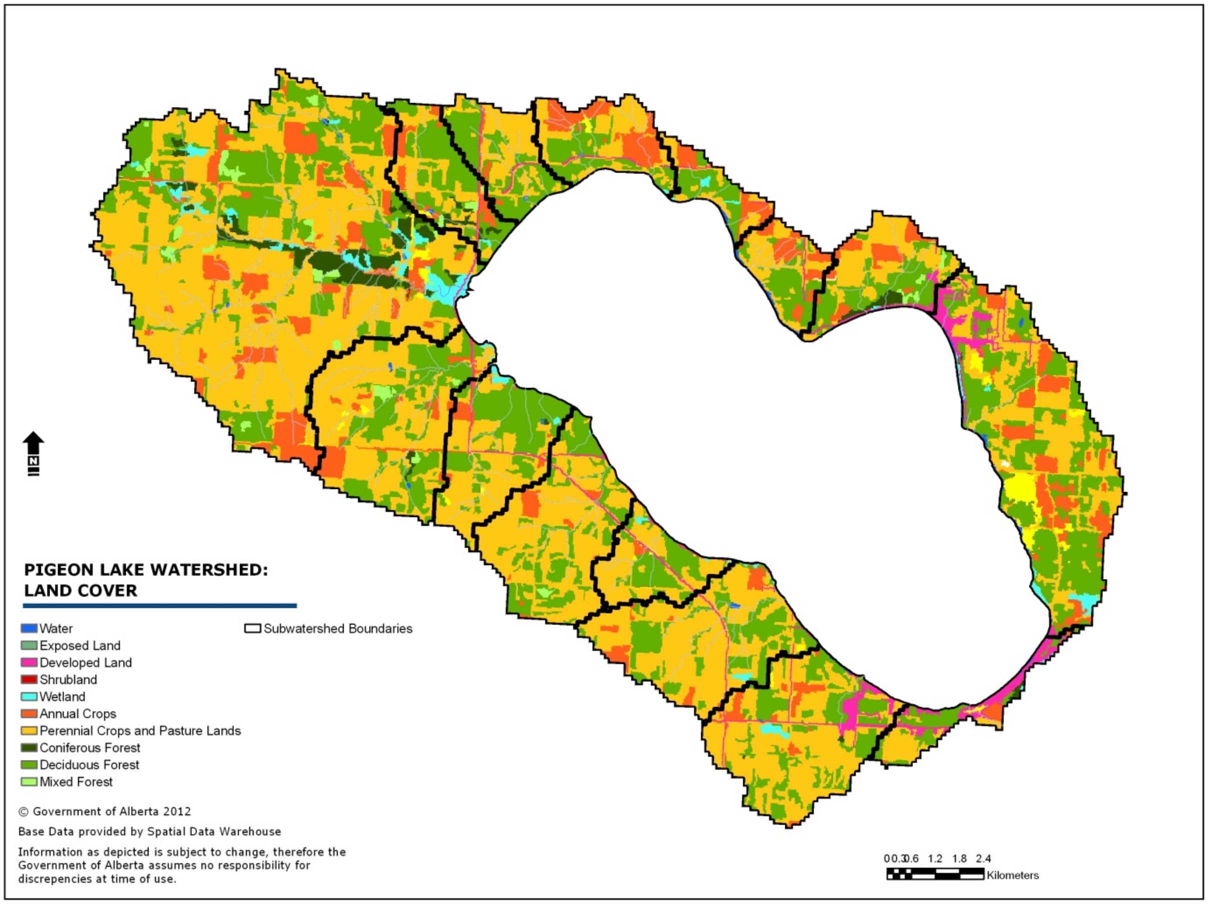

Figure 4-4 Pigeon Lake Watershed Land Cover

Table 4-2 Pigeon Lake Watershed Land Cover

	05FA-PL1	05FA-PL2	05FA-PL3	05FA-PL4	05FA-PL5	05FA-PL6	05FA-PL7	05FA-PL8
LANDCOVER TYPE[1]								
Water	33.2	4.0	5.6	10.1	14.8	23.3	7.8	51.9
Exposed Land	0	0	0	0	0	0.8	1.17	2.25
Developed	7.74	5.4	10.8	8.1	5.9	5.1	28.5	107.6
Shrubland	29.2	4.95	3.51	6.5	0	0	0	111.9
Wetland	142.5	3.51	0	2.1	8.6	0	3.3	41.2
Annual Crops	610.9	76.9	17.4	162	70	94.5	82.2	302.9
Perrenial Crops/Pasture	3022.1	177.4	214.0	234.2	87.7	147.1	279.4	673.7
Coniferous	294.6	29.4	0.4	0	0	0	28.8	1.6
Deciduous	1297	309.9	273.9	172.6	119.9	140.5	234	906.6
Mixed Forest	90.6	12.9	0.8	0	0	0	16.6	0
Ecological lands	1887.2	364.7	284.2	191.2	143.3	163.8	290.5	1113.2
Built-Up/Urban lands	3641	259.7	242.2	404.3	163.6	247.5	391.2	1087
Total Area	**5528.0**	**624.4**	**526.4**	**595.5**	**306.8**	**411.3**	**681.7**	**2199.8**

	05FA-PL9	05FA-PL10	05FA-PL11	05FA-PL12	05FA-PL13	05FA-PL14	05FA-PL15
LANDCOVER TYPE[1]							
Water	7.0	10.3	7.1	9.9	5.0	17.1	9.6
Exposed Land	0	0	0	0.9	0	0	0.5
Developed	80.3	25.5	20	12.6	19.7	101.5	4.3
Shrubland	6.48	3.96	5.4	4.86	0	4.7	8.6
Wetland	13.41	12.3	5.7	14.6	1.62	5.3	7.3
Annual Crops	72.4	71.7	7.6	39.4	46.4	24.6	107
Perrenial Crops/Pasture	751.4	769.1	176.7	413.2	751.7	91.3	816.4
Coniferous	2.8	0	0	1.71	0	9.4	8.2
Deciduous	410.7	361.4	180.4	385	364.5	117.9	467.9
Mixed Forest	0	0	0	0	5.94	0	22
Ecological lands	440.4	388.0	198.5	416.1	377.0	154.4	523.5
Built-Up/Urban lands	904.1	866.3	204.3	466.2	817.9	217.5	928.3
Total Area	**1344.5**	**1254.2**	**402.8**	**882.2**	**1194.9**	**371.9**	**1451.8**

1. All areas in hectares. White highlighted cells represent natural areas while grey highlighted cells represent exposed, developed or agricultural areas.
Note: Numbers have been rounded off for presentation and may result in some discrepancies in calculated values.

4.1.2 Atmospheric Deposition

$$I_P = 2{,}596 \text{ kg}$$

Atmospheric deposition (expressed as I_P in the mass budget equation) was not directly measured at Pigeon Lake in 2013 or other previous years. Three methods were used to estimate contributions of total phosphorus to Pigeon Lake as described below. It should be noted that the methods estimate atmospheric contribution directly to the lake surface only. Total phosphorus associated with precipitation and dustfall which falls on the watershed is accounted for in estimates of direct and indirect runoff into Pigeon Lake (I_R).

Method 1 utilizes an average TP deposition rate of 20 mg/m^2/year determined for several Alberta lakes (Shaw *et. al.* 1989). This rate was multiplied by the lake surface area (96.7 km^2) to give an estimate of 1,934 kg TP/year for I_P. As the deposition rate is annual, utilizing this rate assumes that all snow and associated nutrients that fall on the lake surface during the winter enter into the lake in the spring.

Method 2 utilized the average TP concentration of 0.069 mg/L determined from direct measurements of precipitation at Wabamun Lake in 2008 (Emmerton 2011). Long-term average precipitation amounts from the Battle River Headwaters and Breton weather stations for April to September were obtained from Alberta Agriculture (http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp) and multiplied by the surface area to determine precipitation volumes directly falling on the lake surface for the year (37×10^9 L and 38×10^9 L for the Battle and Breton stations respectively). These volumes were then multiplied by the flow weighted TP concentration to give estimates of 2,547 and 2,645 kg TP for the two stations.

Method 3 utilized the 20-year phosphorus precipitation volumes (P from equation 1) from April to September. An average input volume was calculated (55×10^9 L) and multiplied by the average TP concentration from Method 2 giving an estimated TP mass of 3,821 kg. While this method uses April to September data, the April estimates in the water balance include all snow melt inputs, so naturally would be higher than Method 2 which only includes only average rainfall from April to September.

Previous estimates for TP input (Mitchell and Prepas 1990) estimated TP input from atmospheric deposition for Pigeon Lake at 2,127 kg. Method 1, while similar to this value, appears to underestimate atmospheric deposition. Method 2 utilizes more recently collected water quality data from nearby Wabamun Lake watershed and uses local precipitation data. Method 2 also corresponds well with the long-term 20-year water balance used in the calculation of several other phosphorus budget components. Hence, for consistency, an average of the two values calculated using Method 2 was utilized. The uncertainty does, however, point to the need for local monitoring of atmospheric deposition within the Pigeon Lake watershed.

4.1.3 Groundwater

$$I_G - O_G = 90 \text{ kg}$$

Average total phosphorus concentration from the 12 wells was 0.03 mg/L. This value was multiplied by the estimated net groundwater inflow into Pigeon Lake based on the 20-year water balance, specifically limiting data to the period of sampling (April to September) to provide an estimated TP load of 90 kg.

4.1.4 Sewage

$$I_A = 120 \text{ kg}$$

Several types of sewage or septic systems are utilized throughout the Pigeon Lake watershed reflecting changing development strategies and technology over the years. Older systems, such as pit toilets or field systems are less common, but still utilized. Individual pump-out tank systems are relatively more common and rely upon contracted haulers to occasional remove accumulated material. Regional wastewater lines have been installed for some portions of Pigeon Lake and are being expanded to service other areas surrounding the lake.

Total phosphorus contributions from sewage are difficult to measure directly owing to the diffuse nature by which they enter a lake and reluctance of residents to allow sampling to determine potential faulty septic systems. Previous surveys have looked for other indicators of sewage contamination in Pigeon Lake such as caffeine (White 2003) or fluorescence and conductivity signatures specific to sewage (Mitchell 1982). While White (2003) did not find direct evidence of elevated caffeine levels, Mitchell's use of a "septic snooper" did point to potential sewage contamination in Pigeon Lake (Mitchell 1982). With the exception of communal pump-out tanks or wastewater lines, traditional single-residence wastewater systems should be assumed to have a failure rate which will result in some sewage entering Pigeon Lake.

To estimate sewage input, municipal census data was gathered on the number of dwellings in each summer village (Alberta Municipal Affairs 2014). This was supplemented by additional data obtained from the Association of Pigeon Lake Municipalities for other near lake residential areas not included in the municipal affairs census data (Brian Waterhouse, President, Association of Pigeon Lake Municipalities, pers. comm.). The total number of dwellings (2,386) was multiplied by a factor of 2.5 (assumed number of users per dwelling during the open-water season).

To estimate sewage input, first communities and the associated residents which are currently serviced by the North East Pigeon Line wastewater line were removed (assumes 0% failure rate for the wastewater line). The remaining total number of users (3,863) was multiplied by 10%. This assumes that there is a 10% failure rate of existing sewage systems. This value was then multiplied by the phosphorus export coefficient of 0.93 kg TP/person/year as determined for other Alberta lakes (Mitchell 1998) to give an annual estimate (360 kg). As most users are seasonal utilizing the lake only from May to September, the annual estimate was divided by four to produce an estimated TP sewage load to the lake for the open water season.

While it may be argued that the above overestimates length of seasonal use of a given dwelling or the number of users per dwelling, this method underestimates potential contributions from year-round residents. As well, it does not account for day use visitors to Pigeon Lake which may also add to nutrient loads to the lake.

4.2 Phosphorus Outputs

4.2.1 Groundwater

$$I_G - O_G = 90 \text{ kg}$$

Outputs of total phosphorus via groundwater outflow were not calculated for Pigeon Lake as this number was not estimated as part of the 20-year water balance as this requires extensive sampling, monitoring and modelling. Net groundwater input was utilized instead to calculate a net input of total phosphorus from groundwater into Pigeon Lake (*i.e*. $I_G - O_G$).

4.2.2 Diversions

$$O_D = 10 \text{ kg}$$

Diversions are all known legal water withdrawals from Pigeon Lake. This overall volume is small, as most users utilize groundwater or flowing water sources rather than the lake. Total phosphorus diverted from Pigeon Lake was calculated as the average volume of diversions on a monthly basis (in the water balance) multiplied by average lake TP concentration for that month. This was done for June to September and provided an estimate of 10 kg TP diverted from Pigeon Lake.

4.2.3 Surface Outflow

$$O_O = 331 \text{ kg}$$

Total phosphorus loads associated with the outflow of Pigeon Lake were calculated in the same way as surface inputs to the lake (see Surface Inflows). As the outflow is highly channelized and therefore does not drain a significant portion of the surrounding land, a diffuse outflow fraction was not calculated.

4.3 Change in Lake Mass

$$\Delta M = 13{,}265 \text{ kg}$$

The change in lake mass is calculated by multiplying lake phosphorus concentration collected on the individual sample dates (Figure 4-5) by estimated volumes as determined by a lake volume capacity curve (Figure 4-6). This capacity curve allows conversion of known lake elevation to lake volume based on a specific date.

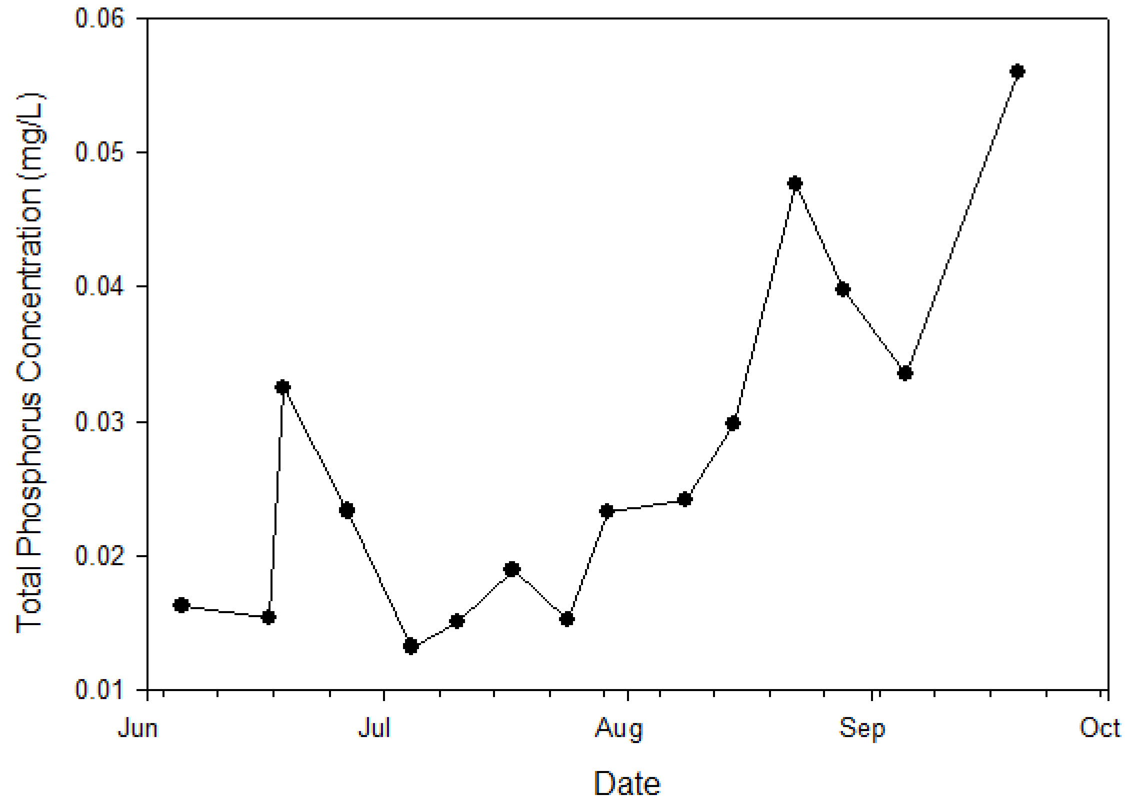

Figure 4-5 Pigeon Lake Total Phosphorus Concentration, 2013

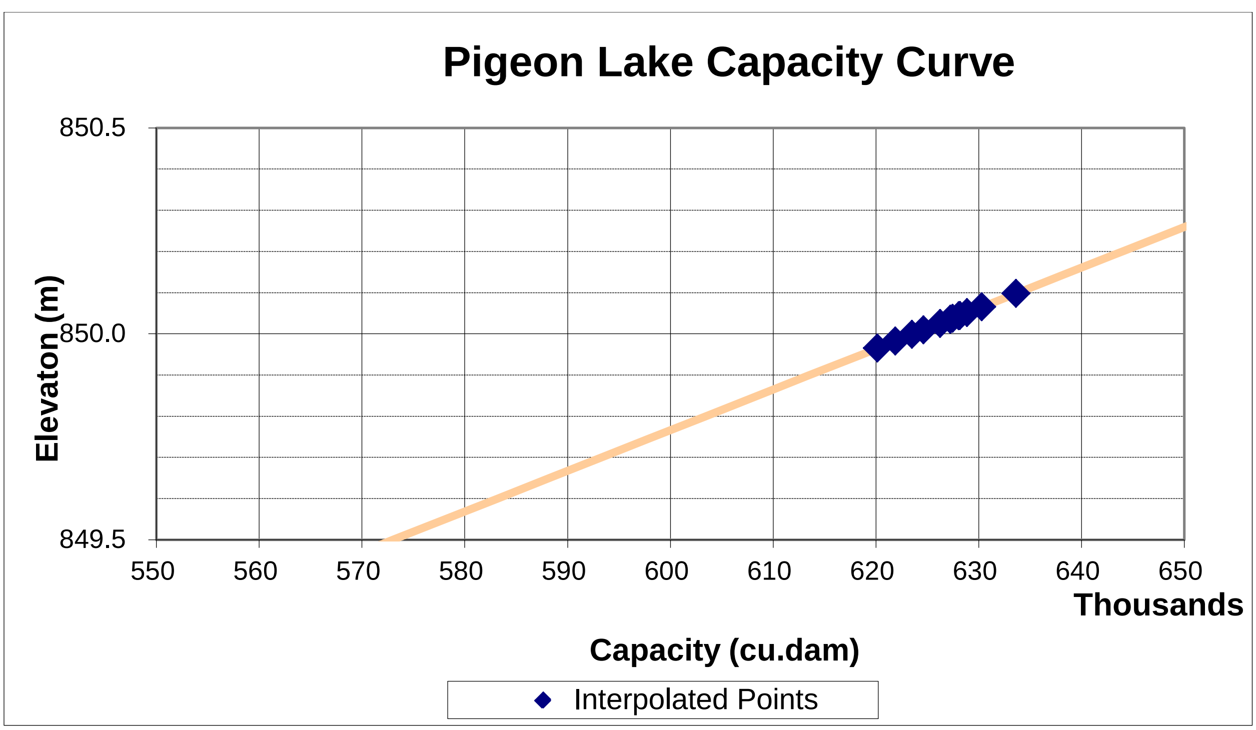

Figure 4-6 Pigeon Lake Capacity Curve

One of the primary difficulties with calculating total phosphorus mass changes in Pigeon Lake is the very large size of the lake in terms of water volume. Very minor fluctuations in total phosphorus concentrations can result in large changes in estimated TP lake mass as a result of the large estimated volumes by which those concentrations are being multiplied by. For example, in 1988 samples were collected from Pigeon Lake on a daily basis during two periods (July and August). Estimated daily change in lake TP mass ranged from 567 to 1,638 kg (Table 4-3). As can be seen, total phosphorus concentrations only varied by a few micrograms or parts per billion, while lake volume changed by over 600 million liters through changes of less than 1 cm of lake elevation.

Table 4-3 Daily Change in Lake Total Phosphorus Mass

Date	[TP] (mg/L)	Lake elevation (masl)	Lake volume (dam^3)	Lake volume (L)	Lake TP mass (kg)	Change in lake TP mass (kg)
27-Jul-88	0.0403	849.806	604049.5	6.04×10^{11}	24,343.19	
28-Jul-88	0.0394	849.8	603441.4	6.03×10^{11}	23,775.59	-567.601
27-Aug-88	0.0515	849.798	603238.8	6.03×10^{11}	31,066.8	
28-Aug-88	0.0534	849.796	603036.1	6.03×10^{11}	32,202.13	1,135.331
29-Aug-88	0.0507	849.794	602833.4	6.03×10^{11}	30,563.65	-1,638.47

The above example serves to illustrate that due to its sheer size, very small differences in phosphorus concentration or lake elevation can result in large estimated changes in lake mass. While more frequent sampling may help, the reality is that changes are within typical field and laboratory variations and precise changes in total phosphorus lake mass will never be achievable for lakes as large as Pigeon Lake.

In 2013, lake mass change from June to September was estimated to be 24,053 kg (Table 4-4). Examining mass changes in the lake from previous years, a high degree of variability in annual lake TP mass change has been observed. To obtain a more representative number, lake TP mass changes from 2006 onwards were utilized giving an average of 13,265 kg.

Table 4-4 Pigeon Lake Mass Phosphorus Flux, 2013

Date	Lake [TP] (mg/L)	Water Level (masl)	Lake capacity (dam^3)	Lake capacity (L)	TP in lake (kg)	ΔM (kg)
5-Jun-13	0.0163	850.051	628877	$6.29*10^{11}$	10,251	
16-Jun-13	0.0153	850.025	626242	$6.26*10^{11}$	9,582	-669
18-Jun-13	0.0325	850.035	627256	$6.27*10^{11}$	20,386	10,804
26-Jun-13	0.0233	850.065	630296	$6.3*10^{11}$	14,686	-5,700
4-Jul-13	0.0132	850.044	628168	$6.28*10^{11}$	8,292	-6,394
10-Jul-13	0.015	850.035	627256	$6.27*10^{11}$	9,409	1,117
17-Jul-13	0.0189	850.037	627458	$6.27*10^{11}$	11,859	2,450
24-Jul-13	0.0152	850.043	628066	$6.28*10^{11}$	9,547	-2,312
29-Jul-13	0.0232	850.098	633640	$6.34*10^{11}$	14,700	5,154
8-Aug-13	0.0241	849.998	623506	$6.24*10^{11}$	15,026	326

14-Aug-13	0.0298	850.009	624621	$6.25*10^{11}$	18,614	3,587
22-Aug-13	0.0477	849.982	621885	$6.22*10^{11}$	29,664	11,050
28-Aug-13	0.0397	849.965	620162	$6.2*10^{11}$	24,620	-5,043
5-Sep-13	0.0335	849.948	618439	$6.18*10^{11}$	20,718	-3,903
19-Sep-13	0.056	849.89	612562	$6.13*10^{11}$	34,303	13,586
Total						**24,053**

As sampling in the lake did not begin until June, the above inherently assumes that lake phosphorus mass was constant from April until June. While it is acknowledged that this is likely not the case, early season water chemistry data for Pigeon Lake is not available. Furthermore, under ice measurements of lake levels are generally not available due to ice interference. However, as already demonstrated, lake total phosphorus mass changes are quite variable that the value of 13,265 kg likely provides a reasonable estimate for Pigeon Lake.

4.4 Lake Sediment Flux

LS = -7,510 kg

Utilizing the mass budget equation (equation 2), lake sediment flux (LS) can be solved substituting in the numbers provided in the previous sections. Hence:

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

Becomes:

$$13,265 = ((377 + 2,913) + 2,596 + 90 + 120) – (10 + 331) – LS$$

Or:

$$- LS = 13,265 – (6,096) + (341)$$

Solving for the above, LS = -7,510 kg total phosphorus. As explained previously, a negative value for LS indicates phosphorus release from the sediments while a positive indicates phosphorus adsorption to the sediments. Hence, 7,510 kg of total phosphorus are released from Pigeon Lake sediments.

5.0 SUMMARY PHOSPHORUS BUDGET

Figures 5-1 to 5-3 show relative partitioning of nutrient input sources to Pigeon Lake. Total phosphorus removed from the lake (via outflow or licensed withdrawals) was subtracted from the total nutrients entering into Pigeon Lake before calculating relative percentages. Table 5-1 summarizes TP mass flux for all sources.

Table 5-1 Total Phosphorus Mass Flux Sources for Pigeon Lake

Source	P budget term	TP (kg) in	TP (kg) out
Gauged (measured) inflows	I_R	262	
Ungauged (unmeasured) inflows	I_R	115	
Diffuse inflow/runoff	I_R	2,913	
Dustfall/precip	I_P	2,596	
Groundwater	$I_G – O_G$	90	
Sewage	I_A	120	
Diversions (withdrawals)	O_D		10
Gauged outflow	O_R		331
Totals		6,096	341
Net Total In		5,755	
Internal Loading	LS	7,510	

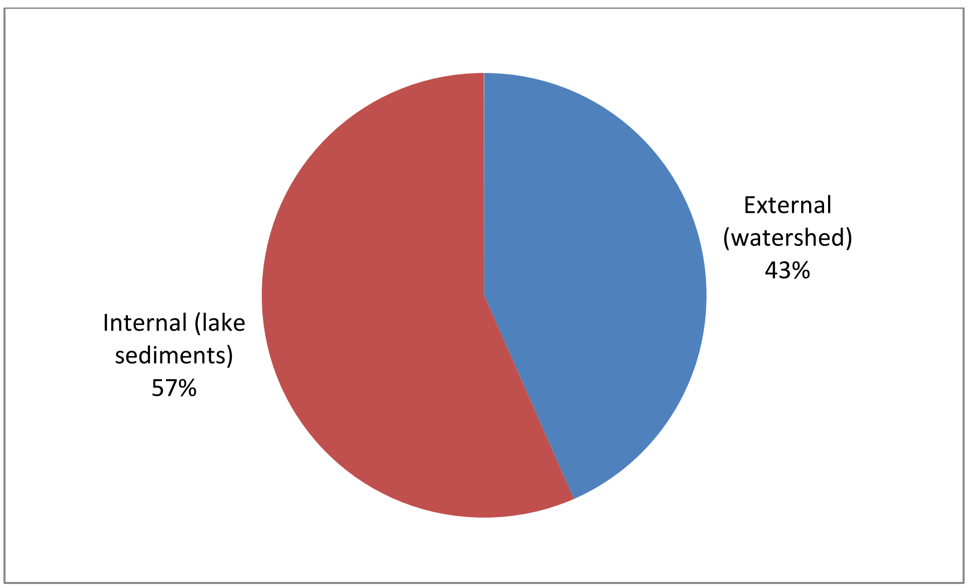

Figure 5-1 Pigeon Lake Total Phosphorus Loading Sources

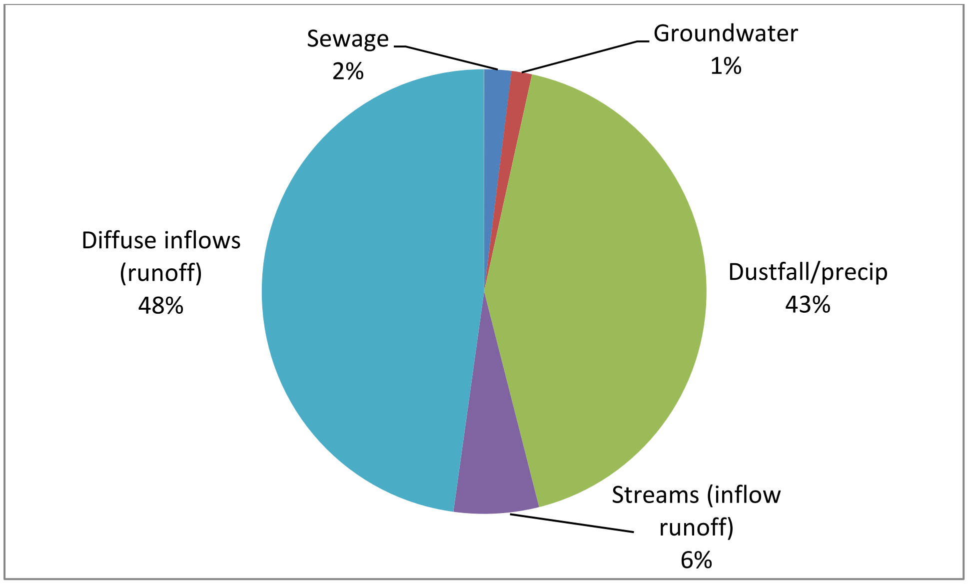

Figure 5-2 Pigeon Lake External Total Phosphorus Loading Sources

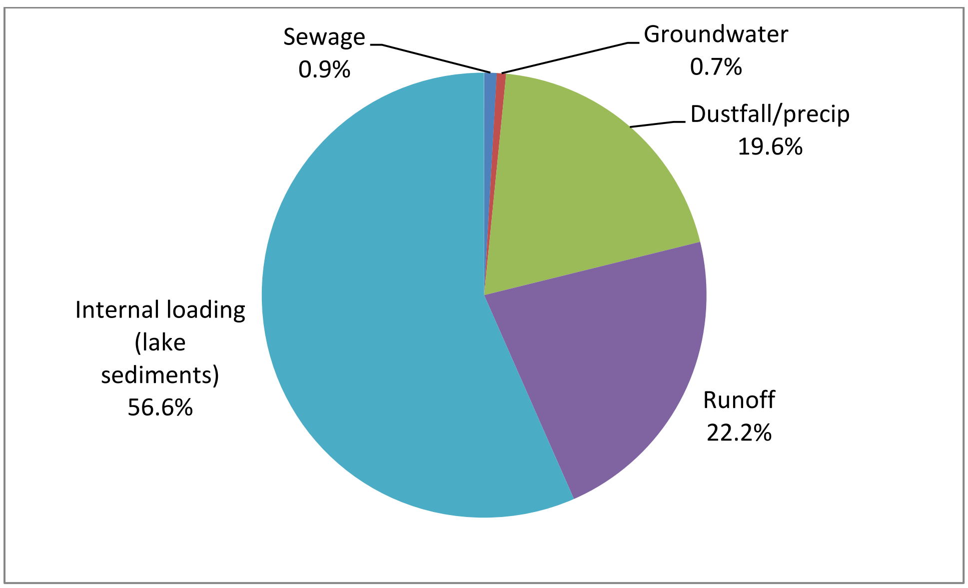

Figure 5-3 Pigeon Lake External and Internal Total Phosphorus Loading Sources[1]

1. Runoff in Figure 5-3 accounts for both measured and unmeasured inflows, diffuse runoff, outflow and water diversion sources.

Internal loading accounts for 57% of total phosphorus loads to Pigeon Lake on an annual basis. This is in line with what has been observed at several other lakes in Alberta (see Table 4 in Emmerton 2011). Looking specifically at external sources of nutrients to Pigeon Lake, diffuse inflows account for the majority of total phosphorus entering the lake (48%) followed by dustfall/precipitation (43%). While sewage only comprised 2% of the external loading source to Pigeon Lake, this number could conceivably be reduced to zero through implementation of improved wastewater systems.

Table 5-2 shows estimated sources of external nutrients to Pigeon Lake calculated in 1989 relative to those calculated in this report. Values were very similar for both nutrient budgets, perhaps not surprising given long-term averages were used where feasible for this report and total phosphorus concentrations have remained relatively constant over time as evidenced by the lack of significant long-term trends in Pigeon Lake data. Additionally, chlorophyll *a* (measure of algal biomass) does not change over the same period 1983 to 2008 (Casey 2011).

Table 5-2 External Total Phosphorus Loads to Pigeon Lake, 1989 and 2013

Source	**1989**[1]	**2013**
Sewage	133	120
Dustfall/Precipitation	2,127	2,596
Watershed (diffuse and point source inflows)	3,372	3,290

1. Mitchell and Prepas 1990

6.0 IMPLICATIONS FOR NUTRIENT MANAGEMENT

One of the primary reasons a more detailed nutrient budget was carried out at Pigeon Lake was to support exploration of watershed and in-lake management of nutrients with the goal of reducing the intensity and frequency of cyanobacterial blooms. Despite the relatively small watershed to lake surface area ratio, total phosphorus loadings from the watershed represent a significant fraction of the overall nutrient budget indicating a need for reducing external loads to the lake. The large internal loading rates also suggest that there are significant phosphorus reserves in the sediments and further exploration of in-lake treatments could be pursued. Pursuing either watershed management or in-lake treatments on their own will likely result in much smaller observed changes, if any at all, over a longer period of time.

As atmospheric deposition and groundwater influx of nutrients to Pigeon Lake are largely out of the control of local watershed groups, watershed management of total phosphorus should focus on the diffuse and point-source discharge as well as sewage inputs to Pigeon Lake. While diffuse inflows contribute the largest fraction of these three, it is also the most difficult to pursue in terms of reducing nutrient inputs as this often requires implementing additional bylaws or encouraging best management practices. These can take a long time to develop and the nature of the diffuse source make it difficult to measure success. Ultimately, with diffuse inflows contributing the largest fraction of controllable phosphorus input to Pigeon Lake, it is important to explore management options.

Control of inflowing wastewater sources may prove expensive up front, but provides the best assurance of measurable success within a lake watershed. Once older properties are converted over to regional wastewater systems (communal pump-out tanks or wastewater lines), the risk of sewage entering Pigeon Lake is minimal. With aging infrastructure and additional development, it is important that all lakes look into reducing potential sewage input. Finally, with point source inflows, there is a high degree of variability seasonally and from year to year making measuring nutrient reductions difficult. However, exploring possibilities to improve conditions of surrounding areas remains with many low cost options available (e.g. riparian restoration). These options should be explored alongside other potential watershed management techniques.

With respect to in-lake management of nutrients, a thorough overview including advantages and disadvantages has been previously prepared (Teichreb 2012). Numerous options are not feasible at Pigeon Lake given its sheer size, technical feasibility and/or legality. Options should continue to be explored however with consideration to economic feasibility and potential impact to Pigeon Lake while being mindful of the practicalities of treating such a large lake. Similar to watershed management options, in-lake management requires thorough planning and exploration to determine the most appropriate and feasible methods specific for Pigeon Lake.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The preceding analysis presented an overview of a lake nutrient budget for Pigeon Lake. While 2013 data was collected in detail, the inherent variability in chemistry and hydrology of Pigeon Lake means that a single year of data is not representative of long-term conditions at the lake. To address this issue, 2013 data were supplemented with longer term data where feasible to develop a more representative picture of the nutrient budget at Pigeon Lake.

Typical of many lakes in Alberta, Pigeon Lake has a high internal total phosphorus load on an annual basis (57%). External sources of phosphorus to Pigeon Lake are dominated by diffuse runoff (48%) and atmospheric deposition (43%). Potential management of nutrients should explore both watershed and in-lake options where feasible.

Additional data collection would enhance the nutrient budget in the future. This would include atmospheric deposition chemistry within the watershed, and early season lake water quality sampling. To account for natural variability in the system as a result of dry/wet years, additional years of monitoring data should be collected from all sources in essence developing a long-term phosphorus budget similar to the 20-year water balance.

While pursuing the above would improve calculated numbers for external sources of phosphorus, internal loading (LS) as derived from the mass balance equation will always have some uncertainty. Large changes in lake total phosphorus mass (ΔM) occur with very small changes in lake levels or TP concentrations owing to the large size of Pigeon Lake and cannot be readily resolved through enhanced lake sampling. Internal loading may be more accurately estimated through more detailed direct measurement such as release of phosphorus from sediment cores in the lab (Auer *et al.* 1993) or even in-situ.

Overall, the phosphorus budget presented in this report provides a better understanding of the relative contributions of nutrients from external and internal sources to Pigeon Lake. Identification of the sources of phosphorus to the lake provides support to ongoing management activities and for development of long-term strategies to reduce phosphorus concentrations in Pigeon Lake.

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