Associated Environmental

REPORT

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

SEPTEMBER 2021

Cover Photo Credits:
Left: Sediment Core taken from Moose Lake in 2019, John Holz, HAB Aquatics
Landsat Satellite image of Moose Lake, July 7, 1989, Eric Dilligeard

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ACKNOWLEDGEMENTS

We thank the Moose Lake Watershed Society and the Lakeland Agricultural Research Association, in particular Kellie Nichiporik, for promoting this project, obtaining funding and for completing several years of tributary sampling. Without Kellie's tireless efforts, this project and the sediment study that provided important supporting data would not have been possible. We also thank the Moose Lake Watershed Society members for attending the online presentation on the draft report, generating an interesting discussion and thereby offering important local perspectives on the study.

Funding for this project was provided by the Alberta Ecotrust Foundation, the Land Stewardship Centre and the Summer Village of Bonnyville Beach. The MD of Bonnyville is acknowledged for funding the phosphorus fractionation and core incubation study, and for providing information on shoreline residences for Moose Lake.

Several other organizations contributed data that were essential to completing the phosphorus budget analyses. Bradley Peter and Caleb Sinn from the Alberta Lake Management Society completed lake sampling and provided lake water quality data. Alberta Environment and Parks staff shared the weir rating curve (Carlin Soehn), a previously completed water balance, and lake level data (German Rojas). Dr. John Holz from HAB Aquatics and Ray Menard from Algae Control Canada conducted sediment coring, phosphorus fractionation and sediment release experiments in 2019 that provided valuable insights into the rates of phosphorus release from Moose Lake sediments.

EXECUTIVE SUMMARY

Moose Lake in the Municipal District of Bonnyville, Alberta, is a popular recreational resource for shoreline residents and visitors, but often experiences heavy summer algae blooms. Phosphorus (P) is usually the main nutrient controlling algal growth; therefore, the most sustainable strategy to reducing algal blooms is to 1) identify the main sources of P to the lake and 2) reduce those main sources through lake and watershed management strategies. While external (watershed) sources of P to Moose Lake are known, their relative importance in terms of P loads compared to internal sources from sediments had not been quantified to date.

The Moose Lake Watershed Society (MLWS) retained Associated Environmental Consultants Inc. (Associated) to quantify external and internal phosphorus loads to Moose Lake. Associated developed a water budget and a phosphorus budget for the lake, using data on water levels and water quality collected by the MLWS and its partners.

Key findings of the study were as follows:

- Seasonally, the internal P loads from sediments represented the majority (60-70%) of phosphorus loads during summer for the bays without large tributary inflows: Vezeau, Bonnyville Bay and Island Bay. It will therefore be useful to assess the feasibility and potential effectiveness of strategies to reduce internal loading from sediments as part of lake and watershed management efforts.
- On an annual and lake-wide basis, the Thinlake River watershed was the largest external source (57%) of water and phosphorus annually to the lake, internal P load from sediments contributed about 20%, and other tributaries and runoff contributed about 19% of the total annual P load.
- Phosphorus inputs from septic systems were minor in comparison to internal and watershed loads, but could be larger if septic systems are not properly maintained or are being flooded.
- Phosphorus loads to Moose Lake vary a lot from year to year. Internal loads will be relatively more important during any dry times in the future; the study period was relatively wet.
- Yelling Creek and Wood Creek had the highest phosphorus concentrations of all sampled tributaries in 2017-2019, consistent with previous results for Yelling Creek from 2005-2007. This indicates that the land use in these watersheds has a large effect on creek and lake water quality; therefore, best management practices and restoration on the land and riparian restoration may be warranted in these areas.
- It is currently unknown if and how the proposed removal of the Mooselake River weir will affect the water and phosphorus budget of Moose Lake. We therefore recommend assessing potential implications of the weir removal for Moose Lake water quality before making a final decision.

In conclusion, this report demonstrated that phosphorus inputs from the bottom sediments to the water in for Moose Lake are significant, likely playing a role in summer algal blooms. In addition, this report confirmed previous estimates of localized elevated phosphorus loads in the watershed. The resulting recommendations can help inform on-going lake and watershed management initiatives by the Moose Lake Watershed Society and its partners.

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LIST OF ABBREVIATIONS

AB	Alberta
AEP	Alberta Environment and Parks
AER	Alberta Energy Regulator
ALMS	Alberta Lake Management Society
FWMC	Flow-weighted mean concentration
MLWS	Moose Lake Watershed Society
P	Phosphorus

GLOSSARY

Anoxic	Containing low or now oxygen
Bathymetry	The shape of the lake bottom
Direct precipitation	Precipitation that falls directly onto the lake. For the purpose of the Phosphorus Budget, that includes rain and snow
Eutrophic	Nutrient rich, high level of aquatic productivity, i.e., algae growth
Evaporation	Process by which water leaves the lake as vapour into the air
Export coefficient	Annual load of a substance, e.g., phosphorus, per surface area land to downstream water bodies in the watershed
Hypereutrophic	Very nutrient rich, highest category of aquatic productivity, i.e., algae growth
'Gross' estimates of phosphorus load	Total phosphorus loads entering the lake water
'Net' estimates of phosphorus load	Phosphorus loads to the lake after accounting for losses of P in the lake due to sedimentation or uptake into the food chain
Oligotrophic	Nutrient-poor, low level of aquatic productivity, i.e., algae growth
Phosphorus budget	An account of all sources and losses of phosphorus to and from a water body
Sublimation	The process of snow and ice turning into water vapour in the air without first melting into water
Storage	For a lake water budget, this is the volume of water in the lake at a certain point in time
Water budget	An account of all sources and losses of water to and from a water body
Watershed	The area of land that drains surface water to a certain water body

1 INTRODUCTION

Moose Lake is located in the Municipal District of Bonnyville, Alberta, about 3.5 km west of the town of Bonnyville and about 240 km northeast of Edmonton (Figure 2-1). It is a popular recreational resource for shoreline residents and visitors, previously served as a raw drinking water source to the Town of Bonnyville, and is home to a large diversity of wildlife, especially waterfowl. Moose Lake often experiences heavy summer algae blooms. Phosphorus (P) is usually the main nutrient controlling algal growth in Canadian lakes; therefore, the most sustainable strategy to reducing algal blooms is often to reduce P inputs to lake (Taranu et al. 2017). Site specific investigations are required to identify the main sources of P to the water body.

The Moose Lake Watershed Society (MLWS) and its partners, such as the Lakeland Agricultural Research Association and the Municipal District of Bonnyville, would like to gain a better understanding of the relative importance of various P sources to Moose Lake to inform lake and watershed management strategies. In 2019, a sediment core study was completed by Algae Control Canada and HAB Aquatics to study phosphorus release rates from sediments. In 2020, the MLWS retained Associated Environmental Consultants Inc. (Associated) to conduct a phosphorus (P) load study of Moose Lake. The goal of the study is to construct a P mass balance that estimates the relative contributions of external and internal P loads into Moose Lake, both annually and seasonally. The methods and results of this study and resulting recommendations for lake and watershed management are presented in this report.

2 STUDY SITE

Moose Lake is located in the Municipal District of Bonneville, in the boreal natural region of Alberta. It is part of the Beaver River basin. The Moose Lake watershed is approximately 755 km^2, while the lake itself is about 40.8 km^2. The lake has a mean depth of 5.6 m and a maximum depth of 19.8 m (University of Alberta 1990). Moose Lake has a complex shape with the following main areas:

- Shallow and well mixed Franchere Bay in the northwest corner, receiving 75% of the total watershed water inputs from Thinlake River; the lake outflow into Mooselake River is also located here;
- Deep (19 m maximum depth) Vezeau Bay in the northeast;
- Shallow and well mixed Main Basin (also called Bonnyville Beach Bay or Bonnyville Bay) located in the centre;
- Pelican Narrows connecting Vezeau Bay and the Main Basin; and
- Very shallow Island Bay in the southwest, which is separated from the Main Basin by several islands and characterized by dense aquatic plants.

Many studies and monitoring programs have been completed on Moose Lake. These are, among others:

- A paleolimnological study to reconstruct historical changes in water quality (Köster et. al 2008);
- Two water balance studies (Alberta Environment 2006, Amec Foster Wheeler 2018);
- Tributary (inflow) sampling and external phosphorus load study (CPP Environmental Corp. 2015);
- Lake water quality sampling by the Alberta Lake Management Society (ALMS) during the open water season for many years (13 years since 2002, ALMS 2020), including multi-basin monitoring in 2016, 2017 and 2020; and
- Ongoing tributary sampling completed by the MLWS in 2014 and annually since 2016 (Kellie Nichiporik, MLWS, personal communication).

These studies have shown that Moose Lake is naturally nutrient rich and currently hypereutrophic, with annual average total P concentrations in lake water ranging from 31 µg/L in 1996 to 109 µg/L in 2013 (ALMS data). Elevated TP concentrations in bottom waters and increasing P concentrations through the summer indicate an internal source of P load to the lake through release from bottom sediment (ALMS 2016, 2017). The importance of internal load for Moose Lake was mentioned in the *Atlas of Alberta Lakes* (Mitchell and Prepas 1990), but this potentially significant source of nutrients to Moose Lake has not been quantified to date. This Moose Lake P Budget study was designed to fill this data gap by quantifying all P loads to Moose Lake, including the internal load.

Figure 1-1 AB / 3/15/2021 / 11:27:57 AM

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FIGURE 2-1: PROJECT LOCATION

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

3 METHODS

The overall study approach was to first estimate water inflows and outflows (i.e., a water budget) and then use the water budget to quantify P inputs and outputs (i.e., a phosphorus budget). Both budgets were calculated on a monthly time-step from January 2017 to December 2019, because detailed water quality data were available for this period from tributaries entering the lake and from the lake itself. Developing the water budget for Moose Lake was an important step to confirm the lake phosphorus budget, as phosphorus is transported into the lake mainly through precipitation and streamflow and is lost from the lake through outflow.

The first step was to develop lake-wide water and phosphorus budgets based on available measured data to gain an overview of all sources to the lake. The second step was to break down the estimates by bay to verify if there are differences among bays in the relative importance of P sources. The bay-based approach was motivated by the complex nature of the lake, where each bay is different from the others in some way. This is reflected in the differences in water quality in each bay as shown in separate samples collected by ALMS in 2017, which were used in the calculation of bay-based P budgets for that year. This section describes the source data and methods used to complete the water and phosphorus budgets for Moose Lake.

3.1 Water Budget

A water budget was developed to quantify the volumes of water into and out of Moose Lake. A simplified schematic of the Moose Lake water budget is shown in Figure 3-1. The terms in Figure 3-1 are described in Table 3-1 and the estimation of each term is described in the following sections. The equation that describes the Moose Lake water budget can be summarized as follows:

$$\Delta S = -E - S_{sub} - Q_M - Q_w + Pr + Q_{sw} \qquad \text{Equation (1)}$$

Where:
ΔS = change in storage
E = evaporation
S_{sub} = sublimation
Q_m = Mooselake River outflow
Q_w = withdrawals
Pr = precipitation
Q_{sw} = tributaries and runoff

Groundwater is another potential way for water to enter and leave the lake. Groundwater was not included in the water budget, as past studies found that on a short time-step (i.e., less than 10 years), the influence of groundwater on inflows and outflows in Moose Lake was negligible (Alberta Environment 2006).

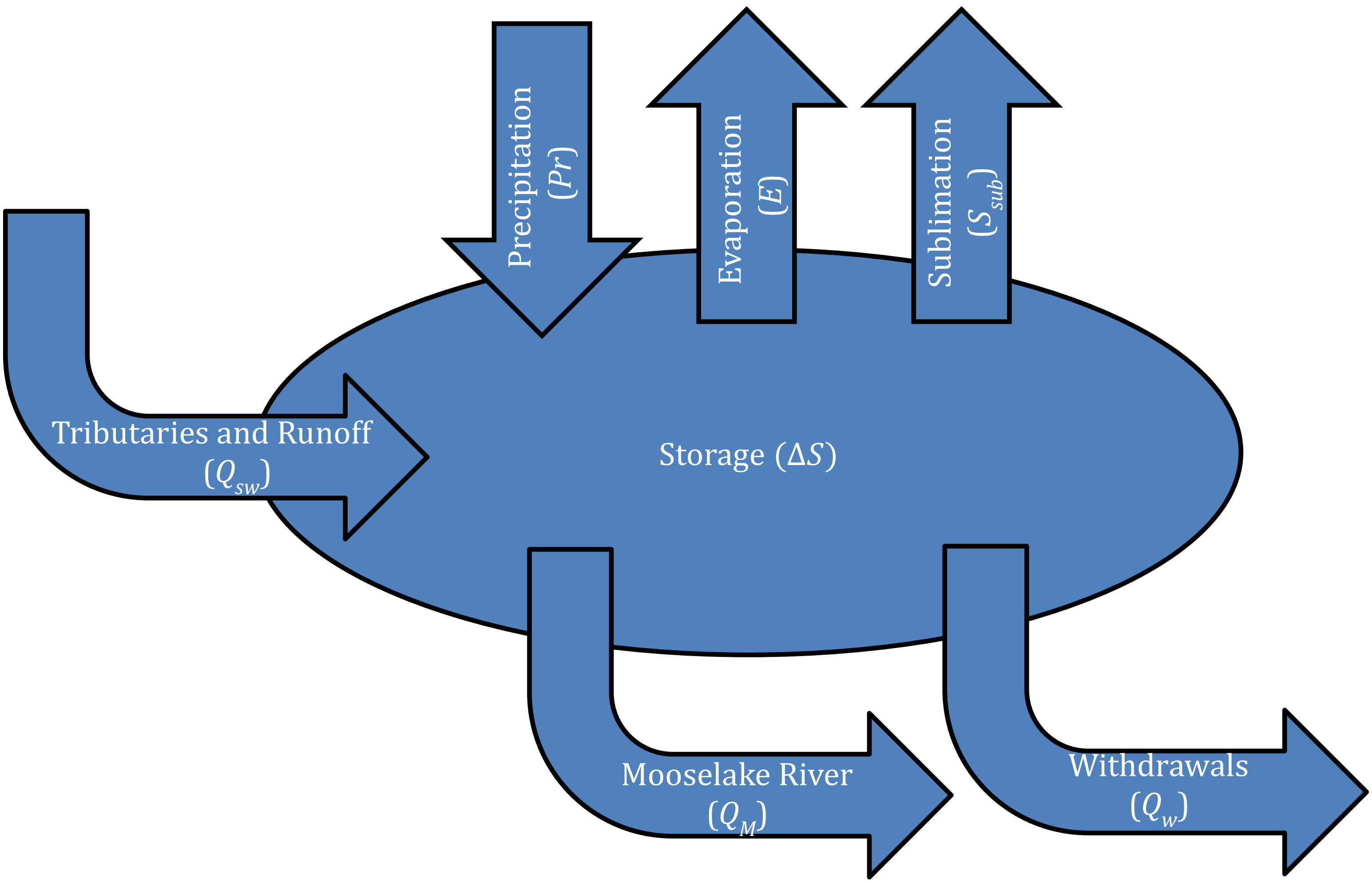

Figure 3-1
Schematic of Water Inputs and Losses in Moose Lake

Table 3-1
Water Budget Terms

Parameter	Equation Term	Input or Output	Description
Storage, change in	(ΔS)	n/a	Total change in water volume in Moose Lake for a given period (e.g., 1 year for annual water budget)
Evaporation	E	Output	The water lost to the atmosphere by the process of water turning into vapour
Sublimation	S_{sub}	Output	The process of snow and ice turning into water vapour in the air without first melting into water
Mooselake River Outflow	Q_M	Output	Outflow through the Mooselake River as measured at the weir location
Withdrawals	Q_w	Output	Licensed withdrawals, in this case for municipal use
Direct precipitation	P	Input	The precipitation (rain or snow) that falls directly into Moose Lake without making any contact with the land
Tributaries and runoff	Q_{sw}	Input	Inflow from all rivers and creeks and direct overland runoff into the lake

3.1.1 Storage (ΔS)

Storage in the lake is continually changing based on the volume of water inputs and water outputs and can only be directly measured with continuous water level recorder(s). Change in storage was calculated here from measured lake levels and the volume of the lake that was calculated using lake bathymetry (i.e., depth contour or lake shape) data.

Monthly lake level records (stage) were available for Moose Lake from Alberta Environment and Parks (AEP, German Rojas, personal communication, 2020) and lake bathymetry (i.e., lake shape) was available from the Alberta Energy Regulator (AER 2006, Figure 3-2). Using these data, the lake volume and surface area at different lake levels were calculated and plotted as stage-storage and stage-surface area curves (Figure 3-3). These curves were used to support the water and phosphorus budgets as lake volume was needed to calculate the total P that is in the lake at any given time and the lake area was needed to calculate losses to evaporation (Section 3.1.2) and sublimation (Section 3.1.3) and direct precipitation on Moose Lake (Section 3.1.6).

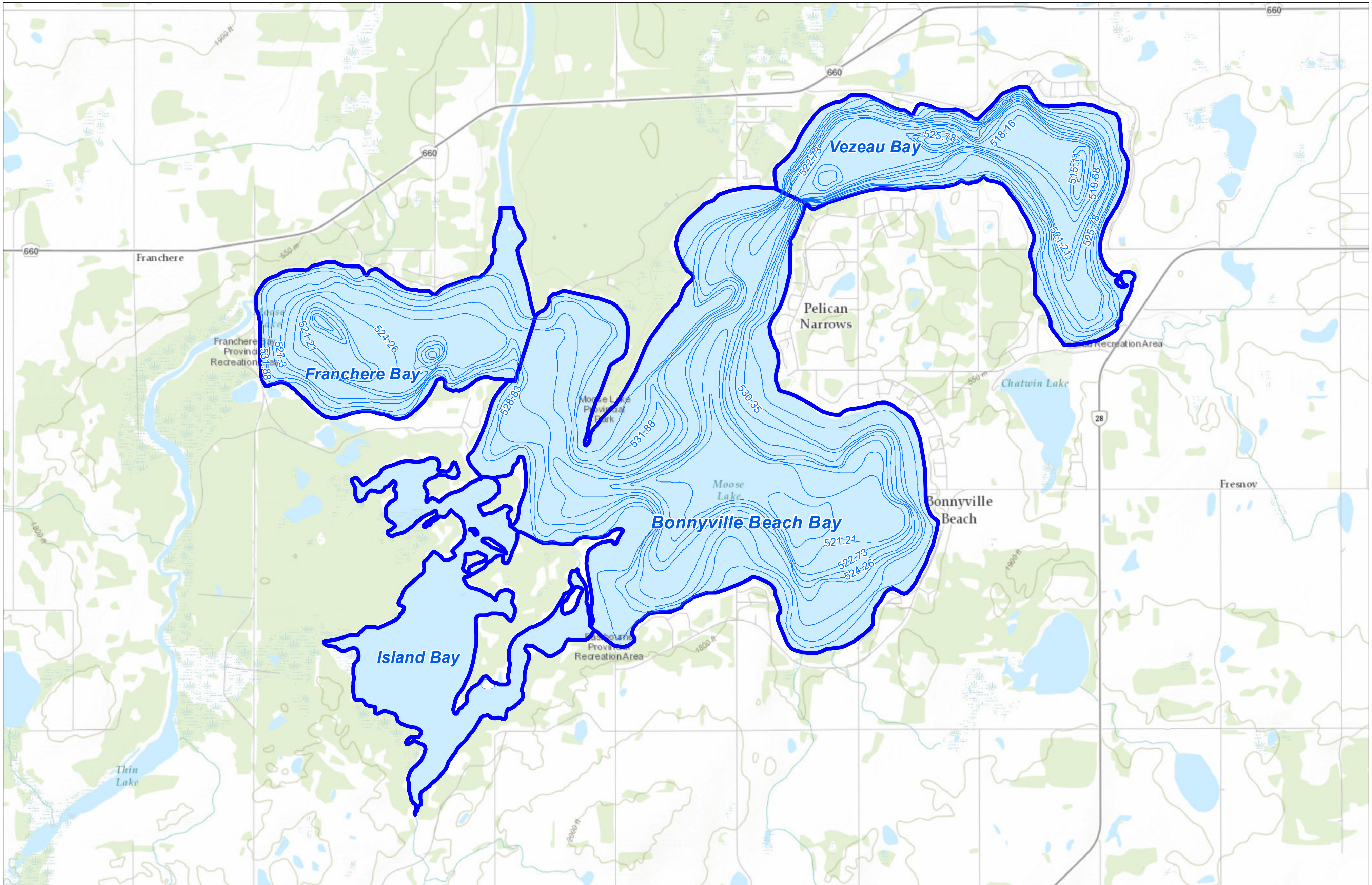

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FIGURE 3-2: MOOSE LAKE BATHYMETRY

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

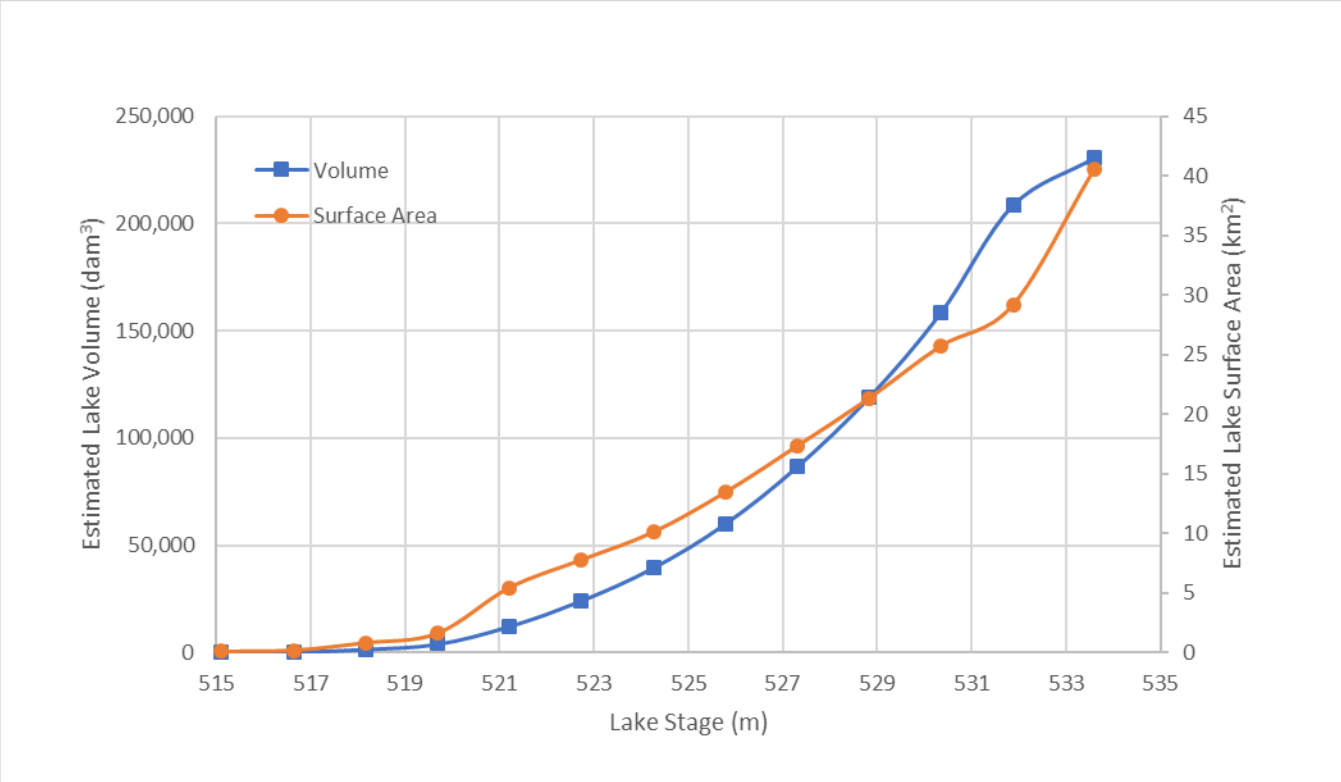

Figure 3-3
Stage Storage and Stage Surface Area Curves for Moose Lake

3.1.2 Evaporation from Lake Surface (E)

Evaporation from the lake's surface was estimated using the Hamon Evaporation Calculation Method (Lu et al. 2005, Appendix A). The Hamon method estimates evaporation water loss using air temperature and daylight hours that were acquired from the Alberta Environment and Parks (AEP) Hoselaw weather station[1], located approximately 4 km south of the shore of Moose Lake. Lake surface area was calculated from the stage-surface area curve (Figure 3-3).

Evaporation was modelled assuming it only occurs when the lake was ice-free. Based on lake ice data provided by MLWS, ice generally forms in early November and fully melts from the lake by mid-May. Therefore, for the water budget it was assumed that the lake is ice-free from May 15 to November 1.

[1] Available online at acis.alberta.ca/weather-data-viewer.jsp

3.1.3 Sublimation from Lake Surface (S_{sub})

During the winter when ice is present on the lake surface, water is lost through sublimation from the accumulated snowpack. The quantity of water lost to sublimation was estimated using the Kuzmin (1972) method (Appendix A). The Kuzmin method uses average air temperature, wind speed and dew point, and the method was applied using climate records obtained from the AEP Hoselaw weather station, including snow depth. Sublimation estimates were applied from November 1 to May 15 when ice was likely present (Section 3.1.2). Lake surface area was calculated using the stage-surface area curve (Figure 3-3).

3.1.4 Mooselake River Outflow (Q_m)

Stream outflows from the lake are only through the Mooselake River on the northwest end of the lake in Franchere Bay. A weir is located 7 km downstream of the outlet of Moose Lake into the Mooselake River. Stream outflows from the lake were estimated based on the weir rating curve provided in the design drawings (Alberta Environment 1984, Appendix B). To account for the hydraulic gradient between the lake outlet and the weir, a 0.25 m correction factor was applied to the Moose Lake levels. The 0.25 m correction factor accounts for the average water elevation difference between the weir crest and the Moose Lake water level recorded by AEP (C. Soehn, personal communication, 2020).

3.1.5 Withdrawals (Q_w)

The Town of Bonnyville previously had a water licence (licence #11460) for water withdrawals from Moose Lake for waterworks purposes. In November 2020, the Town switched their water supply source to Cold Lake, but for the Moose Lake water budget period reported herein, the Town did withdraw water from Moose Lake. Average monthly withdrawal volumes were provided by the Town of Bonnyville (Town of Bonnyville Public Works Department, personal communication, 2021). There are no other licensed water withdrawals from Moose Lake (AEP 2021).

3.1.6 Direct Precipitation on Moose Lake (P)

Direct precipitation on Moose Lake was calculated by multiplying monthly precipitation totals (rain and snow water equivalent) by the surface area of Moose Lake. Precipitation data were obtained from the AEP Hoselaw weather station, and lake surface area values were calculated using the stage-surface area curve (Figure 3-3).

It was assumed that while ice was present on the lake, precipitation was stored as a snowpack on the lake surface. Thus, precipitation that fell on the lake while ice was present was not added to the water budget until April and May. To account for the melting of 25% of the accumulated snow, 25% of the direct precipitation from November to March was added to the April water budget. The remaining 75% was added to the May portion of the water budget, assuming that the majority of ice and snow cover would melt in May. This approximation was used to simulate ice breakup starting in late April, and the lake becoming fully ice-free in May.

3.1.7 Tributaries and Runoff (Q_{sw})

There were two options for calculating inflows to Moose Lake from tributaries: extrapolation and mass balance. The extrapolation method was used by CPP Environmental Corp. (2015), who estimated the inflows from tributaries and direct runoff by extrapolating measured flow from surrounding tributaries. For the CPP (2015) study, measured flow data from the Thinlake River were available, which accounts for most of the flow into Moose Lake, to validate the extrapolations, but winter data were lacking. Flow data were not available from the Thinlake River or any Moose Lake tributaries to validate the model for the years of this study. Therefore, this Moose Lake study used the mass balance method, which estimated inflows using reliable estimates of changes in volume between each month (based on measured lake level), and reliable input data for all other terms within the water budget, except for tributaries and runoff. The tributary data available for extrapolation were from a much smaller creek (Atimoswe Creek) that was outside of the Moose Lake watershed and did not exhibit the same characteristics as the Thinlake River (the largest contributor of water to the Moose Lake), including not having flow in the winter months.

Total tributary inflows were estimated by using all of the other water budget inputs and solving the water budget equation (Section 3.1) for Q_{sw}. This method was validated by comparing the annual discharge per unit area (m^3/ha) estimates to Water Survey of Canada hydrometric gauges located at three nearby locations: Atimoswe Creek (05ED002), Beaver River at Cold Lake (06AD006), and Jackfish Creek (06AC001).

Previous water budget estimates attributed 75% of the total watershed runoff to the Thinlake River inflow during the snow-free months (late April to early November) (University of Alberta 1990). This value is increased to 100% of the calculated inputs when snow is present, based on observations from surrounding Water Survey of Canada (WSC) hydrometric stations for similar sized creeks and rivers, as well as from observations from CPP (2015). Many of the nearby WSC stations showed flow reaching zero around November 1st in smaller creeks, but most of the gauges go offline from mid-November to March, so there is uncertainty in whether there is surface flow through the winter months. Gauges on larger rivers, such as the Beaver River, run year-round and show consistent flow through the winter months.

For the calculation of flow in tributaries other than the Thinlake River, the calculated monthly flow per unit area (m^3/ha) was multiplied by the tributary's watershed area.

3.1.8 Water Budget by Bay

The Moose Lake water budget was further refined to show the water inputs and outputs for Franchere, Bonnyville, Vezeau and Island Bays. The by-bay water budgets did not include any calculations of the exchange of water between bays, and therefore the bay-specific results have a higher level of uncertainty than the lake-wide estimate. Bay boundaries were assigned to locations where the water connections between bays were narrowest, and therefore were somewhat subjective. Using these bay boundaries, the bay surface area and contributing watershed to each bay was delineated using digital mapping. Bay boundaries and contributing watersheds are shown in Figure 3-4.

The calculations for evaporation, sublimation and direct precipitation rely on the surface area of the lake to determine the value. To calculate the terms by bay, the surface area for each bay was used, along with the methods described in the previous sections.

Outflow from the Mooselake River is out of Franchere Bay, and thus was assigned to the Franchere Bay water budget, as were the water inputs from the Thinlake River, which flows directly into Franchere Bay. Withdrawals by the Town of Bonnyville were assigned to Vezeau Bay, based on the location of the intake.

Inputs from the tributaries and runoff were assigned to each bay based on contributing watershed. It was assumed that all land contributes equal amounts of water per surface area into Moose Lake from each watershed, as the watersheds all have similar land uses (Section 3.2.3).

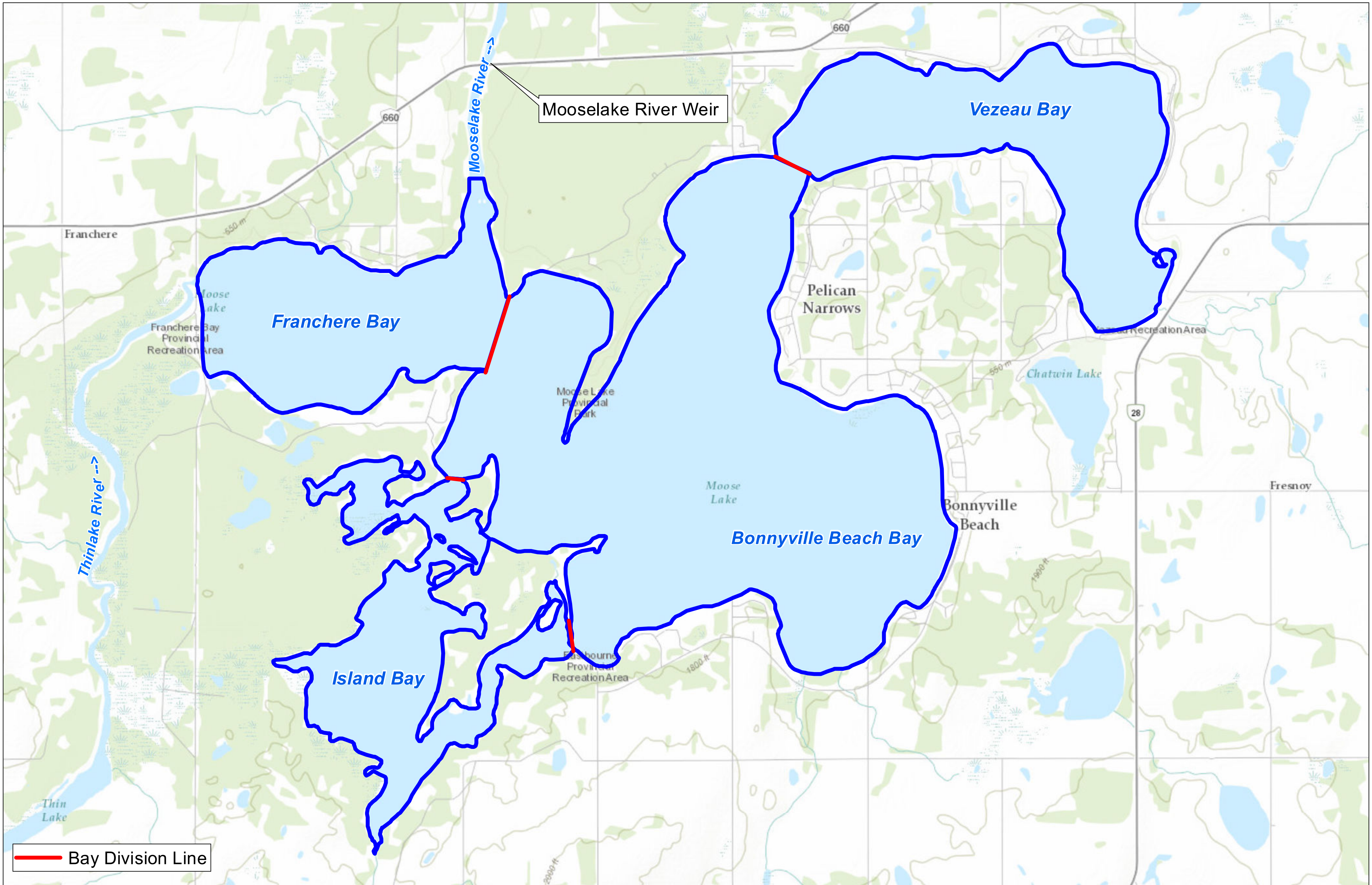

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FIGURE 3-4: MOOSE LAKE BAY DELINEATIONS

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

3.2 Phosphorus Budget

The phosphorus (P) budget consists of the amount of phosphorus coming into and being lost from the lake water. P inputs are either from external loads, which includes watershed inputs and the atmosphere, or internal loads. P is lost from lake water either with water leaving the lake through the Mooselake River or to sedimentation whereby particles and dead aquatic organisms settle to the bottom of the lake (Figure 3-5). The movement of P between lake water and the bottom sediments can occur in both directions (Figure 3-5) and is referred to as a sediment flux in P.

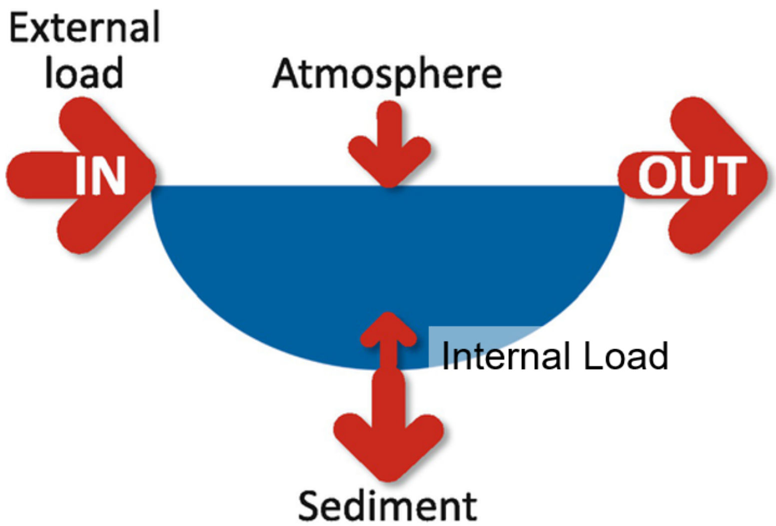

Figure 3-5
Schematic of Phosphorus Inputs and Losses in Moose Lake

For the purpose of the Moose Lake P budget, three types of external P sources and the internal loadings were estimated (Table 3-2). Since this study emphasizes inputs to water (and effects on algal blooms), and external loads are always gross estimates, it is the gross annual influx to the lake (load in kg/year) that is most of interest (see Section 3.2.6 for more discussion on 'gross' versus 'net' estimates).

Table 3-2
P Sources Defined in the Phosphorus Budget

Source	Description
Atmospheric Deposition	Phosphorus deposited on the lake surface through direct precipitation.
Sewage	Phosphorus inputs into the lake from the leaching or flooding of on-site wastewater systems (septic tanks and fields) near the lake's shoreline.
Tributaries and Runoff	Phosphorus eroded or otherwise entrained off the land and deposited into the lake through runoff and tributary surface water.
Internal Loads	Phosphorus released from sediments on the bottom of the lake.

3.2.1 Atmospheric Deposition

Phosphorus inputs from atmospheric deposition were calculated by multiplying the water volume of direct precipitation estimated in the water budget by the average total P concentration in precipitation as measured at Wabamun Lake near Edmonton (Emmerton 2011). Following the same approach as for direct precipitation, 25% of the atmospheric deposition accumulated with snow on the lake's surface from November to March was added to the April P budget, and the additional 75% was added to the May P budget. This was to simulate ice breakup starting in April, and the lake becoming fully ice-free in May.

3.2.2 On-Site Wastewater (Septic) Systems

Dwellings around Moose Lake rely on septic tanks and in-ground dispersal fields for sewage disposal. While septic tanks treat wastewater to a certain extent (e.g., by removing solids), they remove only a small part of the total P before the water is released into the soils in the dispersal fields. The soils initially retain some P but after some time the soil's capacity to retain P is diminished. This water reaches shallow groundwater and eventually the lake. It is therefore assumed that some phosphorus from septic systems reaches Moose Lake.

Monthly contributions of P from sewage was estimated by multiplying the total number of residents residing along the shoreline each month by an average P contribution of 0.015 kg/person/month from septic systems to nearby lakes (Odlifield et al. 2020). This estimate of P contribution was used as it accounts for some attenuation of P within the soils as the wastewater runs through before entering the lake. The estimate assumes that the septic systems are working properly. For the purpose of this estimate, the shoreline population of Moose Lake is defined as those who live within 100 m of the lake's edge. The estimated permanent shoreline population is 1,741 residents, with an additional 271 residents in the summer (S. Brassard, MD of Bonnyville, personal communication).

3.2.3 Tributaries and Runoff

Phosphorus loadings from tributaries were calculated as the product of modelled flow (Section 3.1.7) and measured total P concentrations in streams across the watershed.

P concentrations have been measured by the MLWS in Yelling Creek (tributary to Thinlake River), Wood Creek (Bonnyville Bay), Valere Creek (Vezeau Bay), Mooselake River and Thinlake River (2 locations) from June 2017 to August 2020. Sampling locations and their contributing watershed are shown in Figure 3-5. The concentrations measured in these samples were linearly interpolated between sample dates to create a continuous dataset. Phosphorus loads from each tributary were then calculated on a monthly time-step. Concentration data from January to June 2017 were based on the average of concentration data from January to June 2018-2020.

For sub-watersheds that did not contain sample locations, including all areas that contribute direct runoff to the lake, the concentrations were applied from Moose Lake sub-watersheds with the most similar land use characteristics. For example, the concentration data of Yelling Creek were used for calculating P loads through direct runoff in the Franchere Bay sub-watershed, because the percent land use area is most similar (Table 3-2). Land use characteristic of the sub-watershed are shown in Figure 3-7.

Flow-weighted mean concentrations (FWMC) for phosphorus are representative phosphorus concentrations in runoff from certain areas. FWMCs have previously been presented in the literature for different land uses and therefore were calculated for comparison purposes. FWMCs for each sub-watershed were calculated by dividing the sub-watershed load by the water load from the sub-watershed.

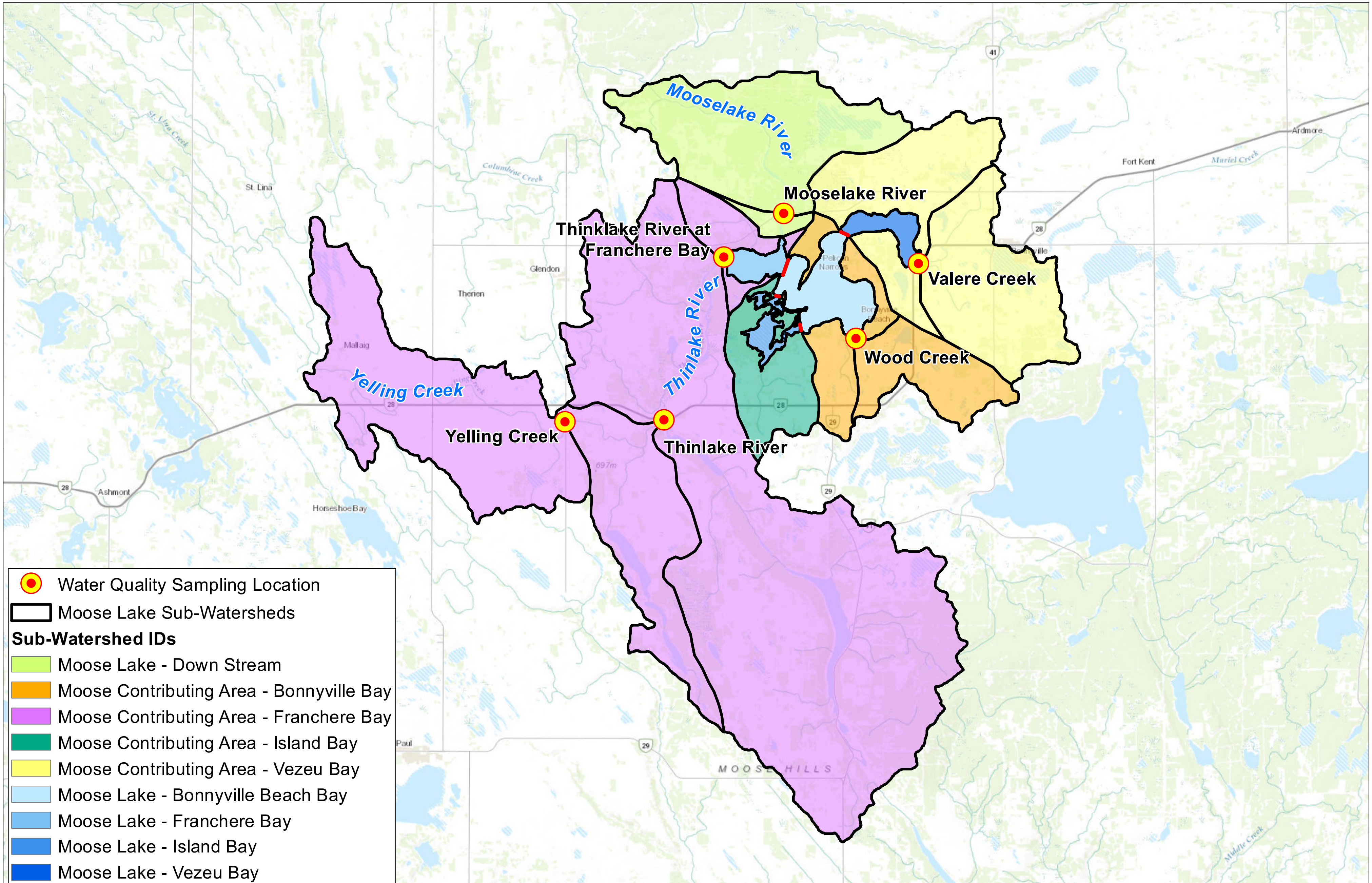

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FIGURE 3-6: WATERSHED WATER QUALITY SAMPLE LOCATIONS

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Moose Lake Phosphorus Budget

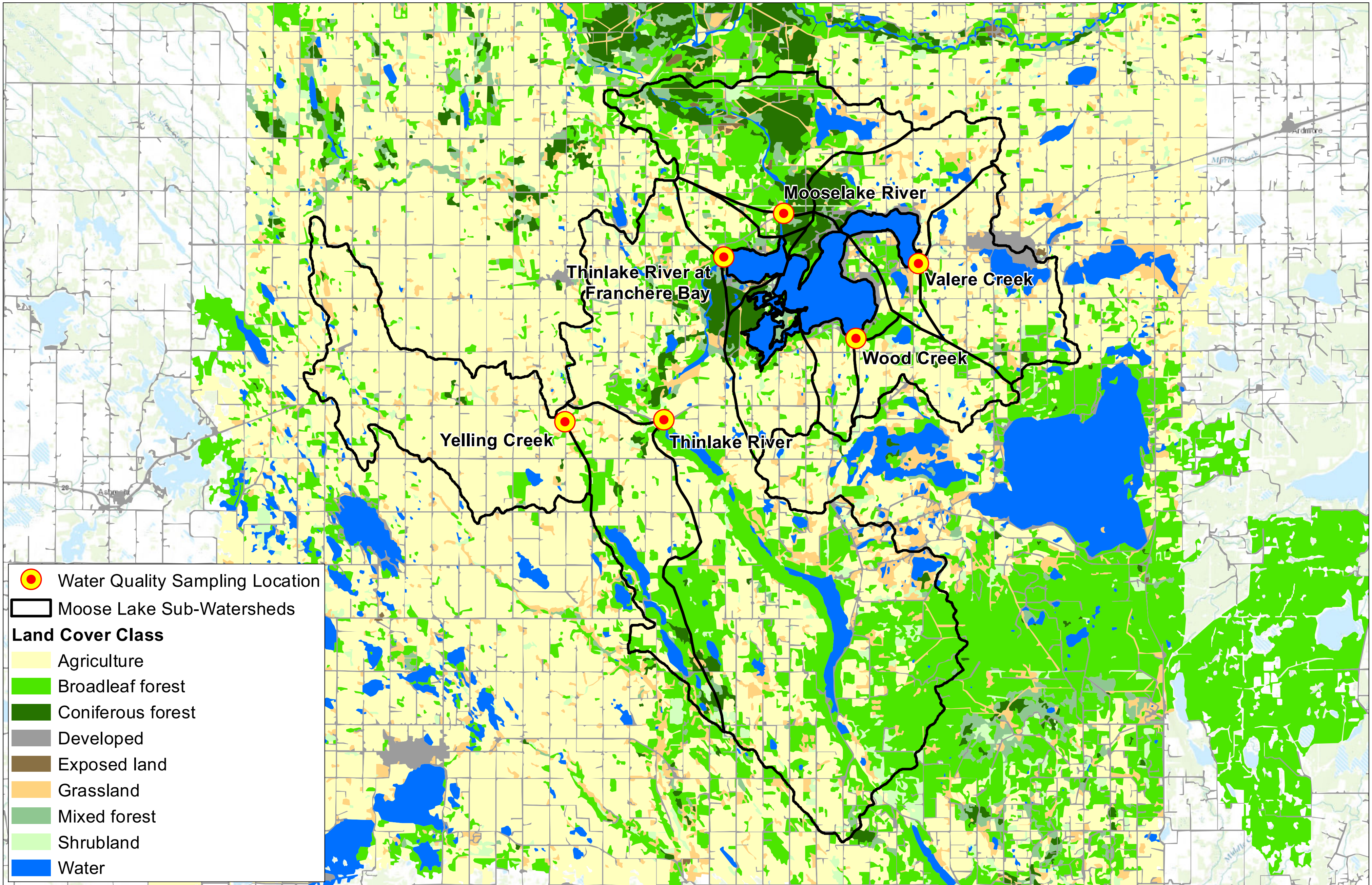

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FIGURE 3-7: LAND USE CHARACTERISTIC BY SUB-BASIN

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

Table 3-3
Sub-basins and Water Quality Data used for their P Load Estimations

Sub-basin	Water Quality Data used for P Budget	Rationale
Franchere Bay	Yelling Creek	Yelling Creek is within the contributing watershed for Franchere Bay and its land use is similar to the entire Franchere Bay watershed.
Bonnyville Bay	Wood Creek Thinlake River	Wood Creek P concentrations were used for calculating P loads just from Wood Creek, as values were two times greater than every other sampling location. For the watershed area outside of Wood Creek, concentrations from the Thinlake River were used, as the land use within the Thinlake River watershed was most similar to the land use within the contributing watershed for Bonnyville Bay.
Vezeau Bay	Valere Creek Thinlake River	Valere Creek P concentrations were used to calculate P loads within the Valere Creek watershed. Thinlake River P concentrations were used to calculate P loads for areas outside of the Valere Creek watershed, as the land use is most similar to that in the Vezeau Bay watershed.
Island Bay	Thinlake River	Thinlake River P concentrations were used to calculate loadings into Island Bay, as land use is most similar to that in the Island Bay watershed.
Thinlake River	Thinlake River	Measured P concentrations at the most downstream point of the Thinlake River were used to calculated P loads.
Mooselake River Outflow	Mooselake River	Measured P concentrations at the Mooselake River outflow were used to calculate P losses, as these were physically within the river.
Withdrawals	Average P concentration of Moose Lake	The average P concentration of Vezeau Bay was used to calculate the P loads lost to withdrawals.

3.2.4 P Loss through Water Outputs

Phosphorus is lost from Moose Lake through the outflow of Mooselake River, withdrawals for the Town of Bonnyville, and losses via lake sedimentation. There was no loss of P to evaporation or sublimation, as phosphorus remains in solution when water evaporates. P losses through the outflow and withdrawals were calculated by multiplying the estimated water losses by the average concentration of total P from the nearest sample location within the lake. Lake sampling locations are shown in Figure 3-8.

3.2.5 P Loss through Sedimentation

Lakes are known as sinks for phosphorus, as demonstrated by the buildup of sediments on the bottom of lakes. This sink, or 'loss' term has been included in lake models as the Retention Coefficient (R_P) and can be calculated as follows (Paterson et al. 2006):

$$R_P = v^* (v+q_S)^{-1} \quad \text{Equation (2)}$$

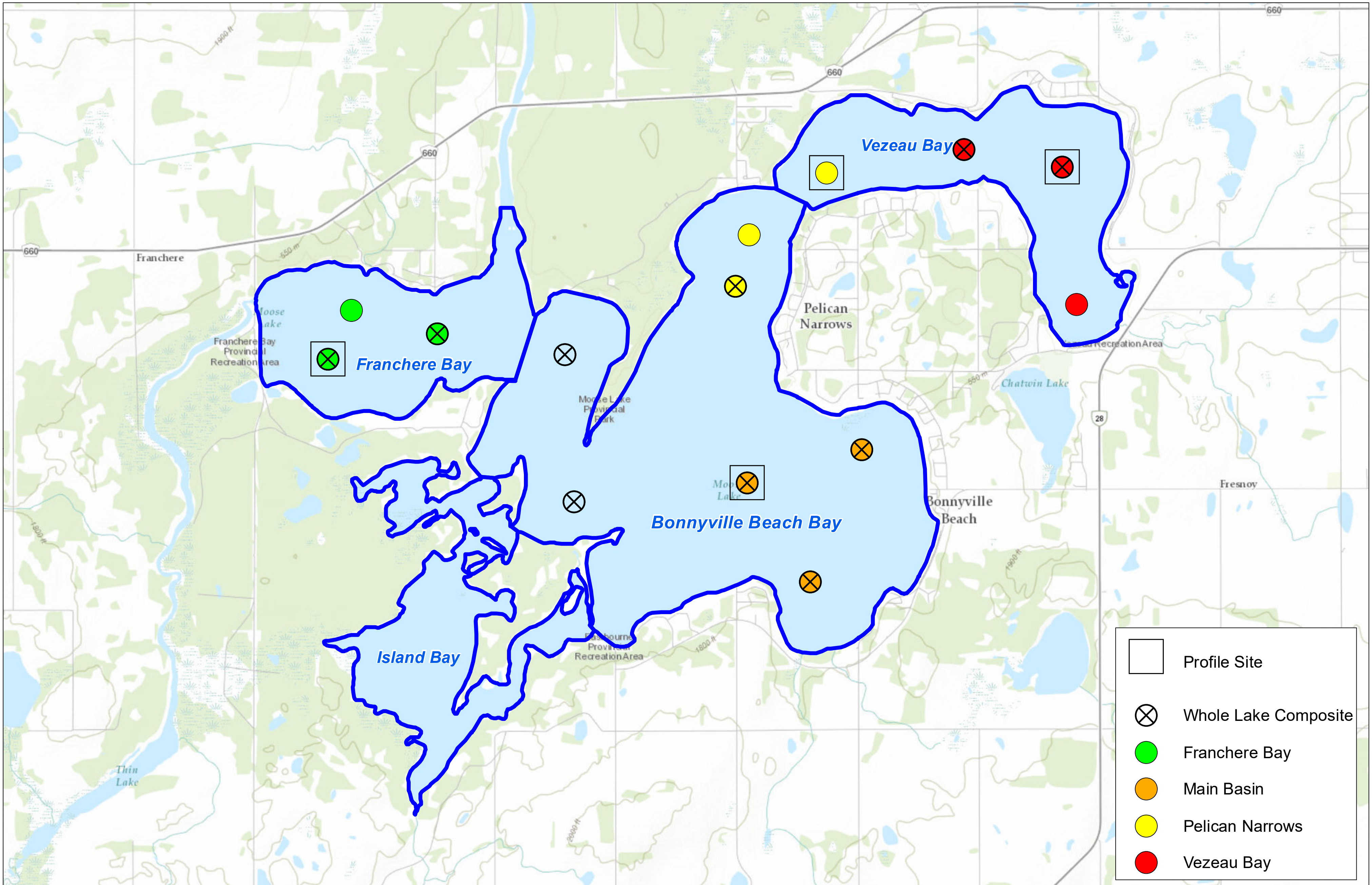
Where:

R_P is the Retention coefficient

v is the settling velocity in m/yr

q_S is the areal water load in m^3 that is calculated as the total water outflows from the lake

Settling velocities differ among lakes and are usually higher in eutrophic lakes. Estimates in the literature range from 10 to 30 m/yr (Sperling 1992, Nürnberg 2009). This study assumed 20 m/yr as it was the only available literature estimate for eutrophic lakes (Sperling 1992).



Associated Environmental

PROJECT NO.:	2020-8719.000.000
DATE:	March 2021
DRAWN BY:	DA

0 2 km

N

FIGURE 3-8: 2017 WATER QUALITY SAMPLING BY BAY

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

3.2.6 Internal Loads

Lake sediments release phosphorus through many mechanisms, including physical (e.g., resuspension by waves), chemical (e.g., desorption, dissociation) and biological (e.g., bacterial degradation of organic matter, migration by algae) processes. The relative importance of the different processes for internal P loads to lakes remains largely unknown, but research indicates that low oxygen levels in the bottom waters and sediments increase the rate of P release, with temperature and pH also playing a role (Orihel et al. 2017).

The phosphorus concentrations in lake waters are the result of both external and internal P loads. External loads are 'gross' estimates (i.e., the total external P inputs without any subtractions). Gross internal loads (influx) are nearly impossible to measure directly in a lake and therefore are only observed as 'net' estimates in a P budget. Net estimates include the outflux of P through sedimentation, which occurs simultaneously and is difficult to measure. Many internal load estimates are therefore usually net estimates. To compare the relative importance of internal loads and external loads for algal growth in a lake, however, gross estimates of internal loads are required. We therefore developed net and gross internal load estimates for the Moose Lake P budget using four different approaches, to increase confidence in internal load estimates for the P budget:

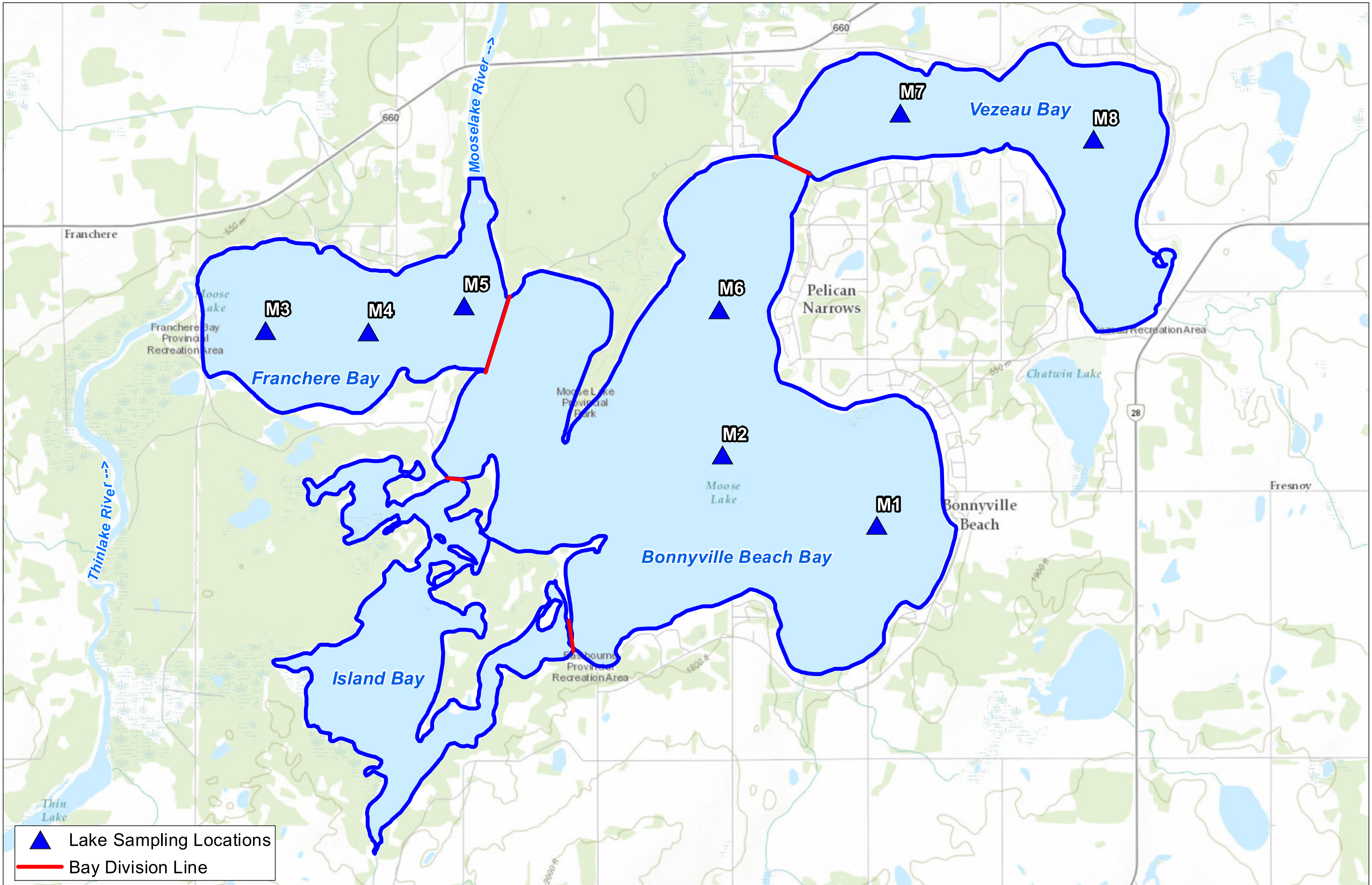
- Release experiments using sediment cores (gross estimate)
- Mass Balance – input vs. outputs and increases in concentrations during summer (net estimate)
- Mass Balance including a loss term for sedimentation (gross estimate)
- Anoxic Factor – release rates based on sediment P concentrations based on empirical data but were designed to estimate gross estimates

As final internal loads for building the lake P budget, we used an average of the two gross estimates that were based on measured data in Moose Lake: the release experiments and mass balance. The anoxic factor estimate was presented as a comparison, along with a discussion on how applicable it is for Moose Lake.

3.2.6.1 Release Experiments on Moose Lake Sediments

Algae Control Canada and HAB Aquatics collected eight sediment cores across Moose Lake in July 2019 to conduct laboratory-based sediment P flux experiments (Figure 3-9). The sediment cores were incubated for 12 days under anoxic conditions. Changes in P concentrations in the water overlying the sediment throughout the experiment were used to calculate an average P release rate from sediments in each core.

The average of release rates in two cores in each bay (Franchere, Bonnyville and Vezeau) was used for bay-specific release rates. The average of all core release rates was used for estimating total Moose Lake internal load. Release rates were multiplied by the estimated area of anoxic sediments to calculate a summer internal P load from sediments. The area of anoxic sediments was estimated by identifying the depth of anoxia in dissolved oxygen profiles taken by ALMS and using bathymetry data to calculate the surface area of that depth contour. This approach is conservative, because sediments underlying oxygenated waters can also be anoxic and release substantial amounts of P (Tammeorg et al. 2020).



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DATE: March 2021
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0 1.5 km

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FIGURE 3-9 : 2019 CORING LOCATIONS FOR SEDIMENT FLUX STUDY

Moose Lake Watershed Society

Moose Lake Phosphorus Budget

Associated Environmental

3.2.6.2 Mass Balance

The mass balance approach has often been used in Alberta to develop phosphorus budgets, e.g., for Pigeon Lake (Teichreb et al. 2013) and for high-level estimates of internal loads for a number of lakes by Alberta Environment (Dave Trew, personal communication, 2019). This approach is based on the increase of P concentrations in the lake in combination with a water budget and estimates of external loads as follows (modified from Teichreb et al. 2013):

$$\Delta M = (I_R + I_P + + I_S) - (O_D + O_O) - (LS) \qquad \text{Equation (2)}$$

The approach to estimating the terms in this equation is summarized in Table 3-3.

Table 3-4
Inputs to Mass Balance Equation for Internal Loads

Equation Term	Description	Methodology
ΔM	Change in lake mass of total phosphorus for a certain period of time	Difference between P mass in the lake from the lowest to highest seasonal TP measurement
I_R	P input from tributaries and runoff	Result from section 3.2.3
I_P	P input from precipitation	Result from section 3.2.1
IS	P input from sewage	Result from section 3.2.2
O_D	P loss through diversion (withdrawals)	Result from section 3.2.4
O_O	P loss through outflow	Result from section 3.2.4
LS_{net}	"net" TP mass flux either into (+) or out of (-) the lake sediments, including loss to sedimentation and any fluxes due to groundwater	Calculated by solving Equation (2)
O_S	P loss through sedimentation	

Equation (2) was solved for LSnet, to estimate the "net" internal P load. To calculate the "gross" P flux (LS_{gross}) out of the sediments, a sedimentation term O_s, was added to the net internal load term follows:

$$LS_{gross} = LS_{net} - O_{S}, \qquad \text{Equation (3)}$$

3.2.6.3 Phosphorus Fractionation

Phosphorus occurs in many different forms in sediments. Some forms are released back to the water when conditions are favourable, while others are permanently bound to sediment particles. These different forms of P can be identified through a series of laboratory procedures, called phosphorus fractionation. Duplicate cores were collected from six locations (M 1, 2, 3, 5, 7, 8) during the fieldwork described for the P Flux experiments. These were sectioned into layers of 2-cm thickness for the top 10 cm of the core and into 5-cm layers for sediments between 10 cm and 25 cm core depth. Sediments were submitted to IEH Analytical Laboratories for P fractionation analysis. The resulting amount of loosely bound, iron bound and calcium bound and organic P were added to calculate the releasable fractions, which was then used in the Anoxic Factor approach to estimate internal loads (Section 3.2.6.4).

3.2.6.4 Anoxic Factor (after Nürnberg)

The approach developed by Nürnberg (2009) was used to estimate theoretical internal load rates. This approach is based on mean summer P concentrations in lake water, depth of lake, sediment P concentrations, and empirical data from a large set of other lakes to estimate internal P load from sediments. The equation for polymictic basins presented in Nürnberg (2009) was applied to estimate internal loads for the entire lake and bay-specific loads for the polymictic bays Franchere, Island and Bonnyville Bays. The equation for dimictic basins (Nürnberg 1988) was applied to the dimictic Vezeau Bay. Details on these equations are provided in Appendix A.

4 RESULTS

This section first presents the water budget and then the phosphorus budget for Moose Lake, based on data between 2017 and 2019.

4.1 Water Budget

4.1.1 Water Budget for the Lake

The average annual water budget from 2017 to 2019 shows that Thinlake River is the primary source of water to Moose Lake, accounting for 62% of the total inflow (Figure 4-1). The data. Other tributaries and direct runoff from the watershed accounted, on average, for 21% while direct precipitation accounted for about 17%. The Mooselake River outflow accounted for the largest water loss from the lake (78%), while evaporation accounted for 18%, and sublimation and withdrawals were minor losses (4% and <1%, respectively) (Figure 4-1).

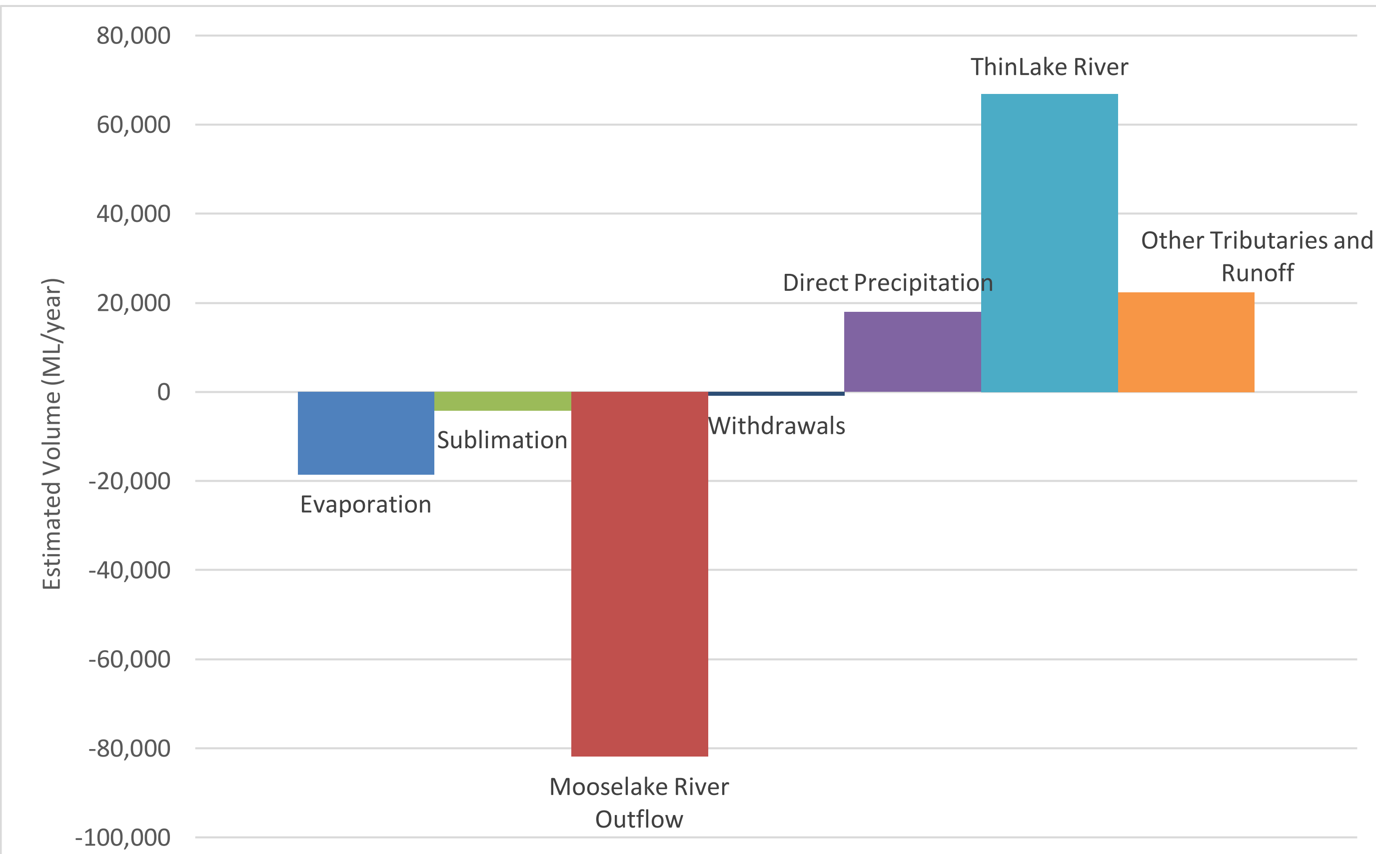

Figure 4-1
Average Annual Water Inputs and Outputs to Moose Lake 2017-2019

Proportions for each input and output appear to be similar among individual years (Figure 4-2). The years 2017 and 2018 were similar, with input and outputs quantities being very close in total volume, while 2019 had lower volumes of both inputs and outputs.

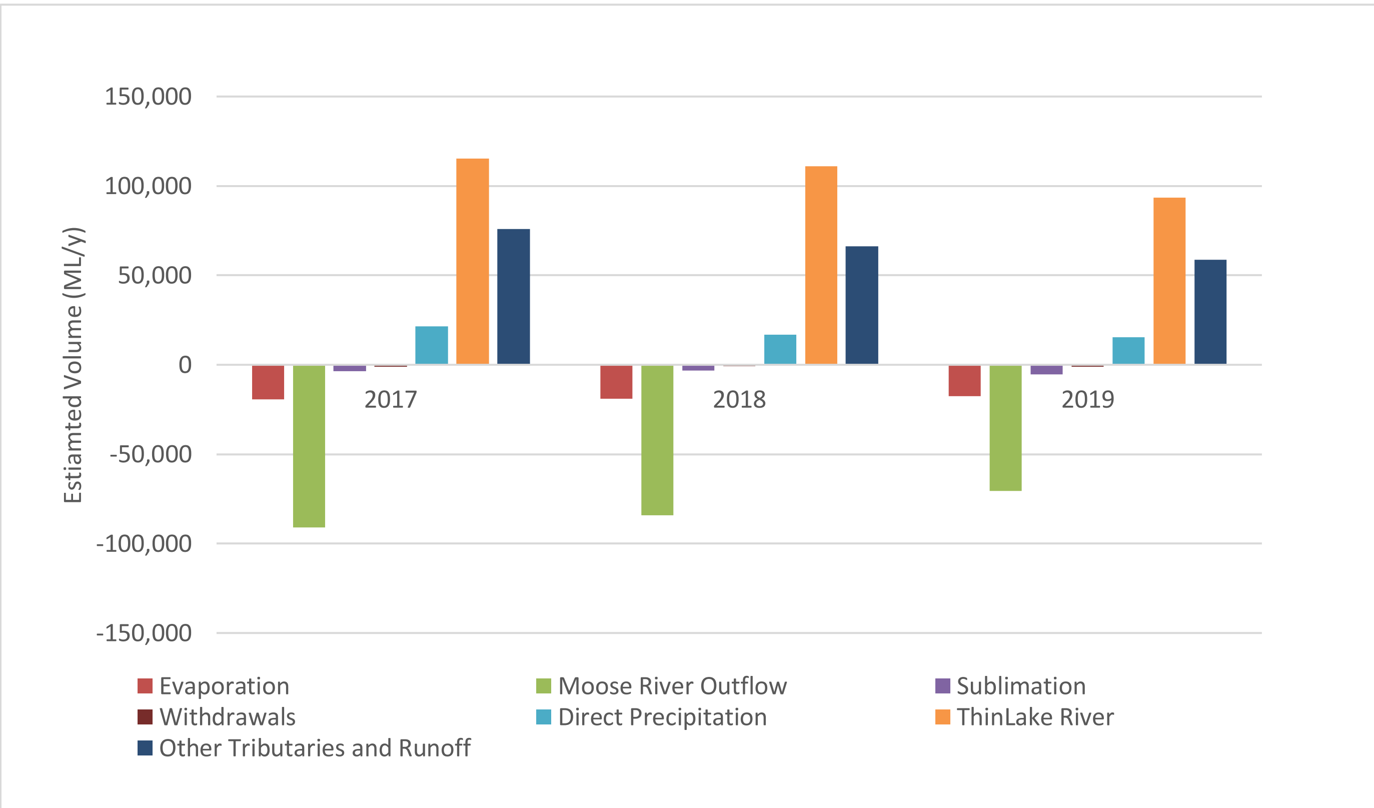

Figure 4-2
Individual Year's Water Inputs and Outputs for the 2017-2019 Moose Lake Water Budgets

The changes in storage (as indicated by lake levels) in Moose Lake show that the sum of the water inputs was slightly greater than the sum of the outputs from 2017 through 2019 (Figure 4-3). 2017 was the only year when annual inputs were greater than annual outputs (net gain in water volume). The average annual lake level declined between 2017 and 2019 by 6.5 cm, due to the net loss in water volume from 2018 to 2019; but such small variations are naturally expected. The balance of inputs and outputs varied seasonally, with output volumes exceeding input volumes between July and November of each year, which is reflected in a seasonal decline of the lake level.

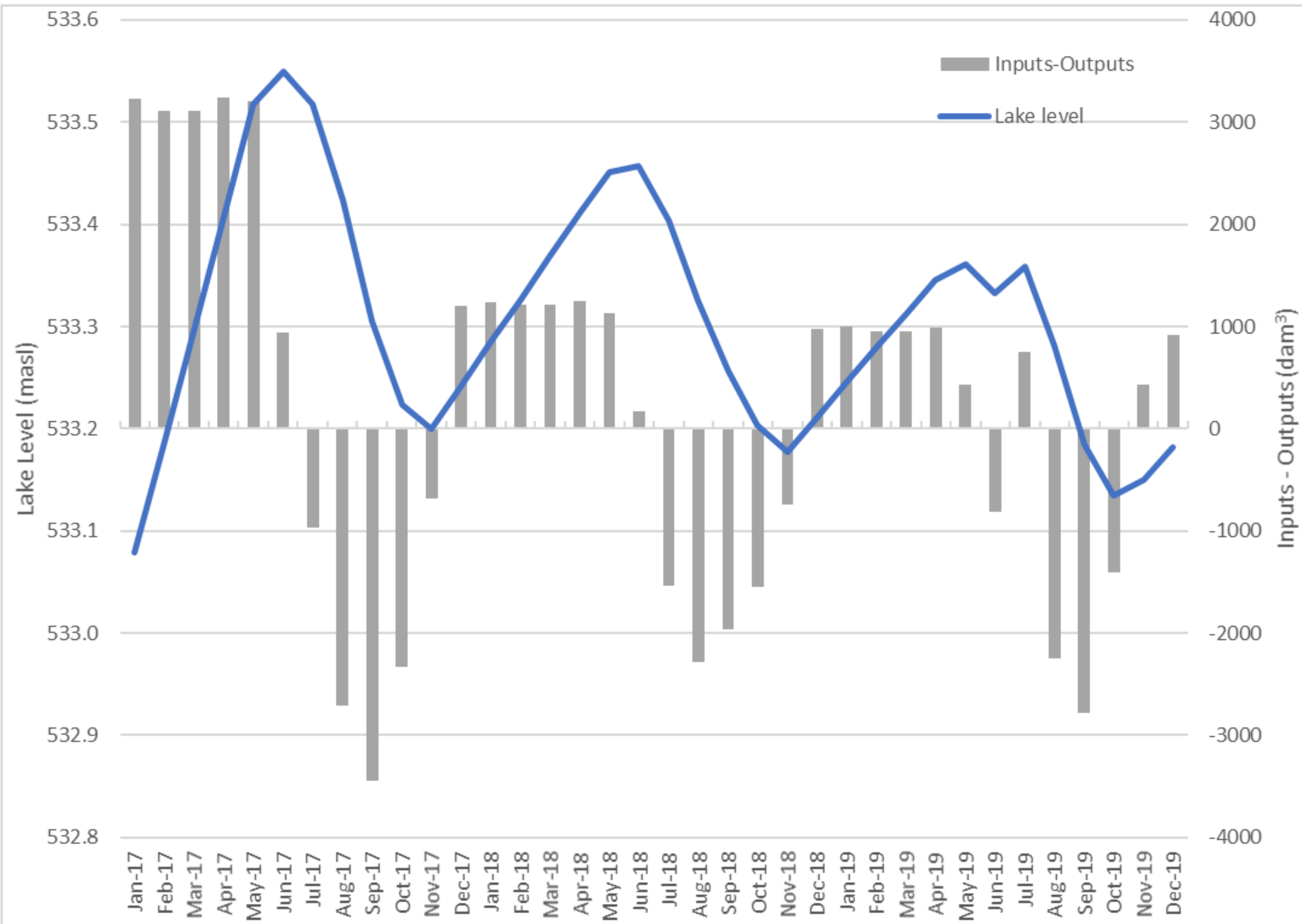

Figure 4-3
Change in Lake Levels Plotted against Monthly Water Budget Results 2017-2019

Our water budget resulted in an average annual water yield of 49.2 mm from the Moose Lake watershed. This estimate was similar to the average estimates for boreal areas with moderate agricultural use in Alberta (53 mm), but greater than previous estimates by CPP (2015) (23 mm) and average estimates for the parkland natural region (Table 4-1). Since Moose Lake is in the boreal natural region (Aquality and Alberta Environment 2005), this estimate appears to well represent average conditions in this area. The difference in estimates by CPP can be attributed to the differing climatic conditions in the year's models, as the early 2000s were dry in Alberta (CPP 2015), which could explain why the lower estimates were more similar to averages from the drier parkland natural region at that time. When comparing to nearby creeks and rivers (Atimoswe Creek, Beaver River, and Jackfish Creek) for the same period, our estimated water yield for Moose Lake was smaller. Geographic and land use variability within these watersheds could explain the differences in yield, in particular loss to evaporation from larger surface areas at Kehewin, Bangs, Thin, Chickenhill and Bentley Lakes. Overall, these results demonstrate the high natural inter-annual variability in water supply to Moose Lake.

Table 4-1
Estimated Average Water Yield for Moose Lake, March 1 to October 31

Location	Average Water Yield (mm)	Source	Years Used in Estimate
Moose Lake (this study)	49.2	Calculated	2017-2019
Other estimates:			
Parkland in Alberta (moderate intensity agriculture)	21.8 (parkland)	Donahue 2013	Based on climate normal (1981-2010)
Alberta Boreal (moderate intensity agriculture)	53 (boreal)	Donahue 2013	Based on climate normal (1981–2010)
Moose Lake	23	CPP 2015	2005-2007
Atimoswe Creek	80.4	WSC Gauge (05ED002)	2017-2019
Beaver River	76.8	WSC Gauge (06AD006)	2017-2019
Jackfish Creek	69.6	WSC Gauge (06AC001)	2018-2019

4.1.2 Water Budget by Bay

For water budget by bay, the single largest water input (Thinlake River) and output (Mooselake River) flow through Franchere Bay (Figure 4-4). This combination of a large input and output in one bay likely results in a certain amount of 'shortcutting,' where a portion of water entering Franchere Bay doesn't mix with all water in the lake but instead leaves the lake directly through the outflow without moving into other areas of the lake.

Our method did not account for water exchange between bays, so the degree to which the water from Thinlake River affects water quality in other bays of the lake remains unknown at this time. Detailed hydrodynamic modelling, ideally supported by measurement of water currents within the lake, would be required to quantify this degree of water exchange between bays.

Output quantities from evaporation and sublimation, as well as input quantities from other tributary and runoff were similar across the four bays, as the surface area and catchment areas are similarly sized.

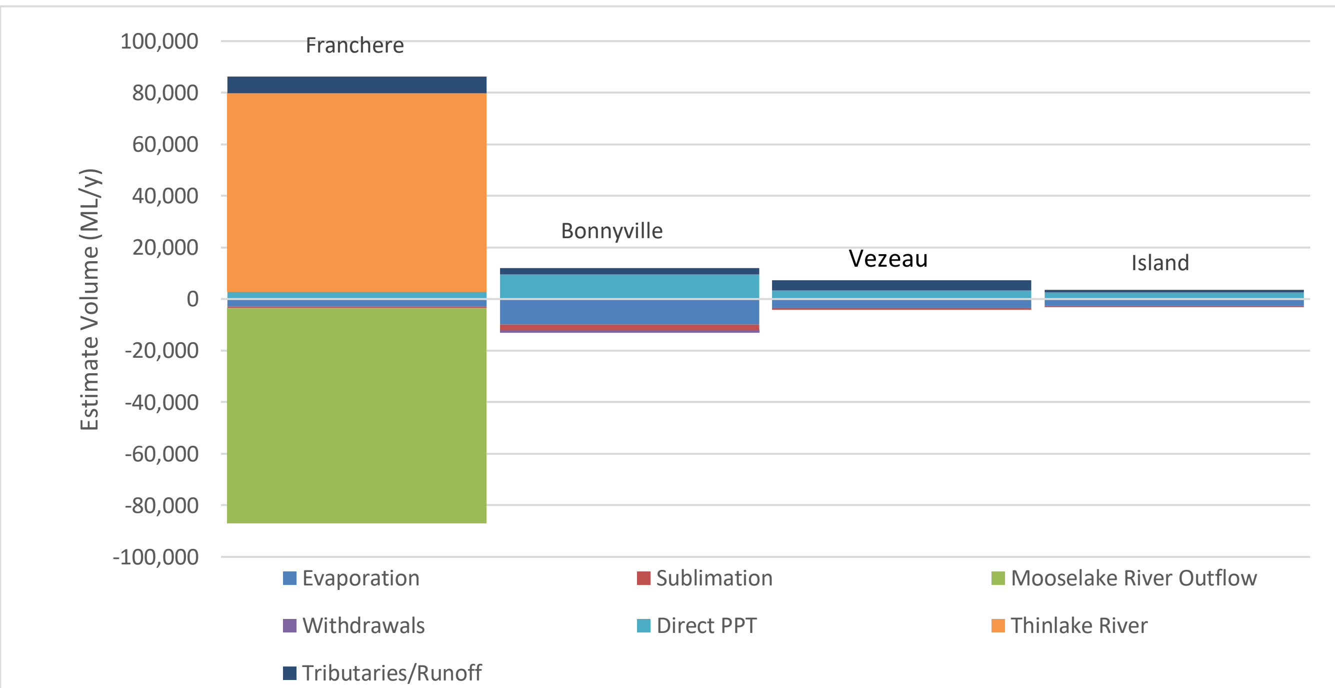

Figure 4-4
Average Water Input and Outputs by Bay for the 2017-2019 Moose Lake Water Budgets

4.2 Phosphorus Budget

Phosphorus loads were categorized into external loads (i.e., atmospheric depositions, tributaries/runoff, and septic fields) and internal loads (influx from bottom sediments). This section summarizes tributary phosphorus concentrations, presents phosphorus inputs and outputs by category, and develops an overall phosphorus balance for the lake and individual bays.

4.2.1 Tributary and Runoff P Concentrations

Yelling Creek, which drains into Franchere Bay, had the greatest flow-weighted mean concentration (FWMC) of all sample locations (1.45 mg/L). Wood Creek, which drains into Bonnyville Bay, had a similar FWMC as Yelling Creek of 1.31 mg/L. Valere Creek and the Thinlake River had similar FWMC of 0.38 mg/L and 0.33 mg/L, respectively. The greater P concentrations in Yelling Creek and Wood Creek are likely related to the high percentage of agricultural land use in the watersheds, close to the stream banks.

Table 4-2
Phosphorus Flow Weighted Mean Concentration for Each Bay and Sample Location

		Sample Locations			
Year	Unit	Thinlake River (Franchere Bay)	Yelling Creek (Franchere Bay)	Wood Creek (Bonnyville Bay)	Valere Creek (Vezeau Bay)
2017	mg/L	0.29	1.17	1.36	0.60
2018		0.36	1.58	1.29	0.27
2019		0.33	1.58	1.29	0.27
2017-2019		0.33	1.45	1.31	0.38

4.2.2 External Loads

4.2.2.1 External Loads for the Lake

On average, Moose Lake received an estimated 36 tonnes of P per year from external sources in 2017-2019 (Figure 4-5). Thinlake River, the largest contributor of water, accounted for the majority of external P loads to Moose Lake (72%). Other tributaries and runoff contributed a quarter of the load and loads from atmospheric deposition and septic systems were minor.

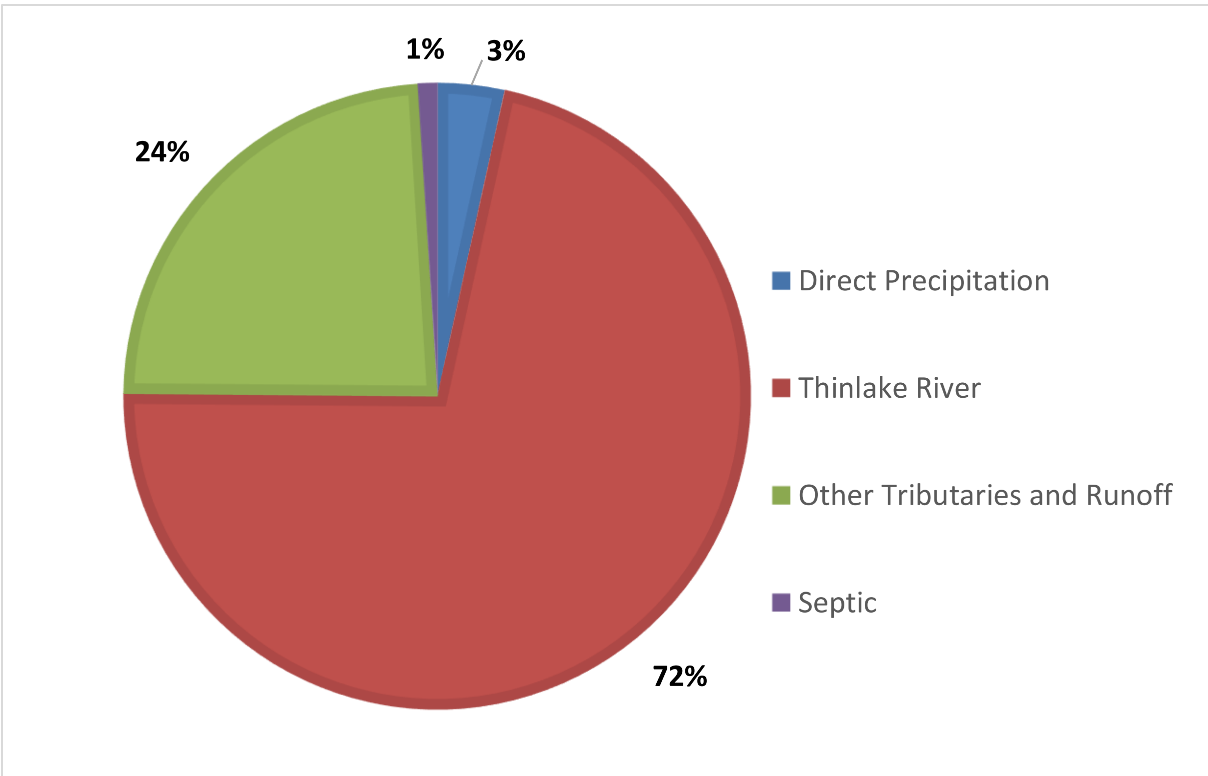

Figure 4-5
Average Annual P Inputs from External Loads 2017-2019

The annual external P loads were largest in 2018, with an estimated load of 44 tonnes (Figure 4-6). This was likely due to the largest water inputs during this year, because external loads depend heavily on the amount of water entering the lake. Loads in 2017 were approximately 35 tonnes, while 2019 had an estimated P load of 29 tonnes (Figure 4-6).

Our external load estimate was higher than two estimates presented in previous studies (Table 4-3). The main reasons for this is likely that our study years followed a wetter period than the previous studies that were conducted during or after longer periods of dry weather.

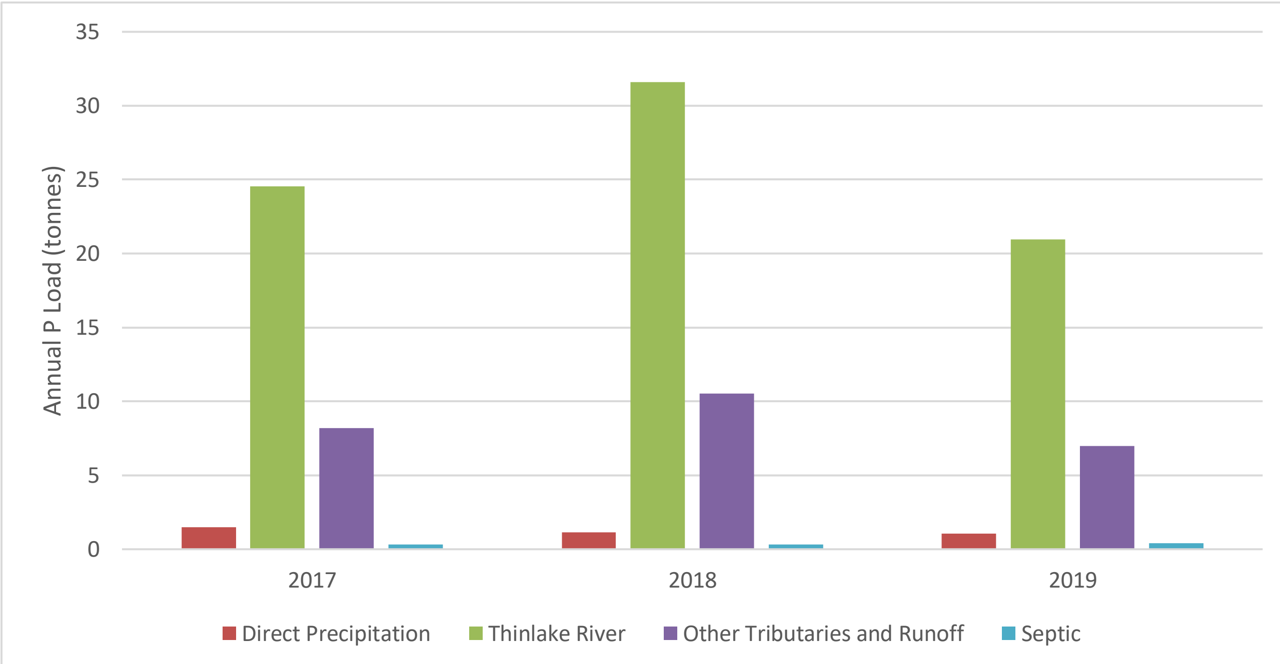

Figure 4-6
Estimated External P Loads to Moose Lake by Year, 2017-2019

Table 4-3
External P Load Estimates of this Study Compared to Previous Studies

Study	External Load (tonnes/yr)	Method	Years	Average precipitation in decade (mm/yr)*
This Study	36	Measured tributary concentrations and water mass balance model	2017-2019	464
CPP (2015)	19	Measured tributary concentrations and extrapolated water budget	2005-2007	427
Mitchell and Prepas (1990)	10	Likely based on literature review data from other locations.	1980s	405

*Average annual precipitation at Cold Lake, for 2010-2019 (this study), 1998-2007 (CPP 2015) and 1980-1989 (Mitchell & Prepas 1990).

4.2.2.2 External Loads by Bay

The largest inputs of P among the individual bays were estimated for Franchere Bay. This is the result of the dominating water inputs through the Thinlake River inflow in this bay. Interestingly, Franchere Bay also had the most inputs from other tributaries and runoff, despite being similarly sized to the other bays. This was driven by a period of high P concentrations in Yelling Creek from summer 2018 to spring 2019, exceeding 1 mg/L (Appendix C). Bonnyville Bay and Vezeau Bay received similar P loads from tributaries and runoff. Tributaries and runoff into Island Bay contributed a very small overall amount of P to the lake, likely due to the lack of human land use around Island Bay. These estimated P loads do not account for the exchange of water and P between bays. Therefore, a certain, but unknown amount of P load likely reaches all bays from Thinklake River as well, especially in winter and spring when the lake levels increase (see Figure 4-4).

P contributions from on-site wastewater treatment systems (septic fields) is estimated to be greater in the bays with larger shoreline populations (Bonnyville and Vezeau Bays) but is negligible compared to all other external inputs.

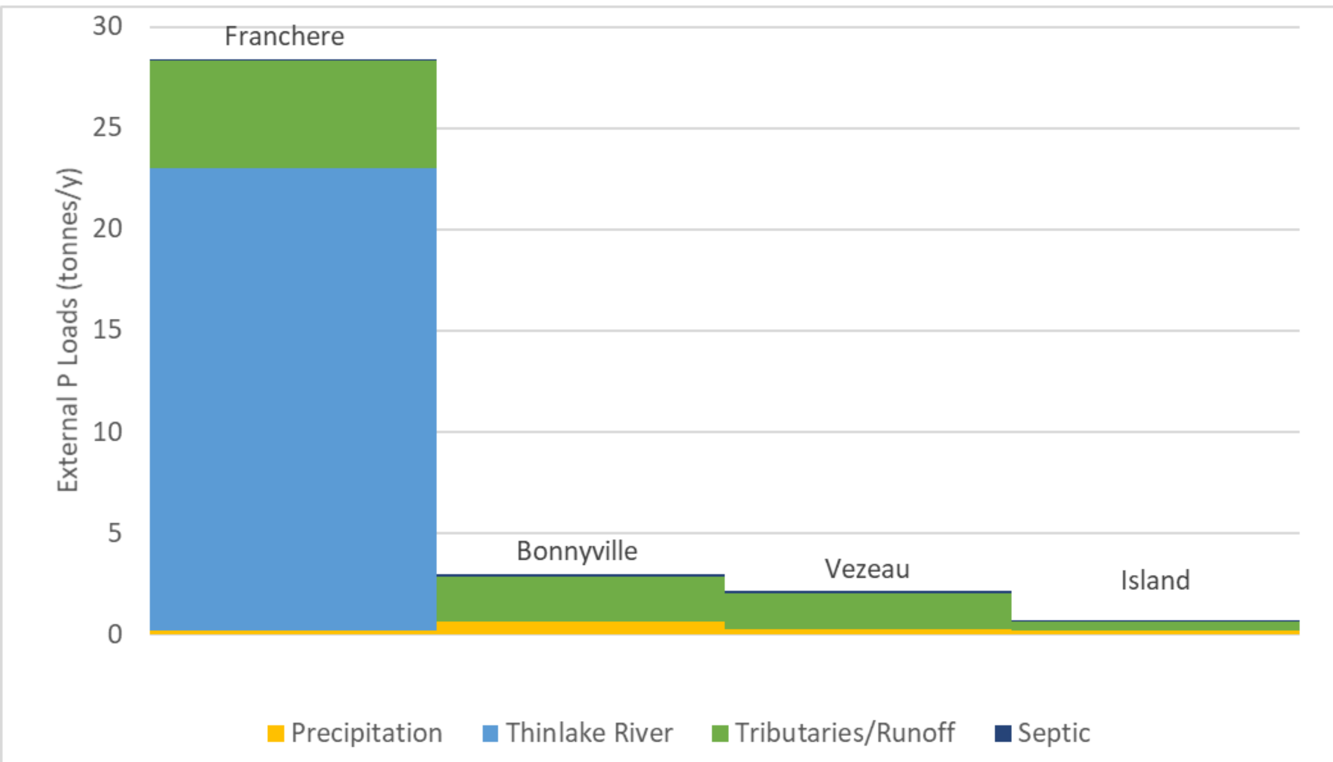

Figure 4-7
Average of Estimated External Loads by Bay 2017-2019

4.2.3 Phosphorus Export Coefficients

Export coefficients represent the P load that is transported via overland flow per unit of surface area and are usually expressed as kg/ha/yr. These coefficients are related to soil erodibility and erosivity, land use/land cover, precipitation, and topography. The estimated average annual export coefficients for the entire Moose Lake watershed ranged from 0.48 kg/ha/y in 2019 to 0.92 kg/ha/y in 2018 (Table 4-4). The average export coefficient was 0.69 kg/ha/y of P, similar to what is seen in other agricultural watersheds in Alberta (Donahue 2013).

The average P export coefficient for the watershed is almost three times greater than the coefficient previously calculated by CPP (2015) of 0.25 kg/ha/year. This difference in P export can likely be attributed to the wetter weather that increased inflows in 2017 and 2018, as well as improved data collection. CPP's estimates had fewer sample locations for P concentration data and did not include the two creeks that consistently had the greatest concentrations of P in the data used for this study, Lower Yelling Creek and Wood Creek. Without these two creeks, the average concentration of total P in the watershed and the total load would have been significantly lower.

Table 4-4
Estimated Export Coefficients for the Entire Moose Lake Watershed

Year	Estimated P Export Coefficient (kg/ha/y)
2017	0.68
2018	0.92
2019	0.48
Average 2017-2019	0.69

P export coefficients for the individual bays and the Thinlake River watershed ranged from 0.12 kg/ha/y in Island Bay to 0.25 kg/ha/y in Bonnyville Bay, while the estimated average export from Thinlake River was 1.01 kg/ha/y (Table 4-5). The P export coefficients in all bays were similar across the three years, while the Thinlake River P export coefficient was substantially greater in 2018 than in 2017 and 2019. When comparing to literature values, Franchere, Vezeau and Island Bays have export coefficients that are similar to those of native shrubland and forested lands in Alberta, which range from 0.219 to 0.312 kg/ha/y (Donahue 2013). The Thinlake River export coefficients are similar to native grazing use in Alberta (Donahue 2013). The Thinlake River export coefficient was estimated at 0.15 kg/ha/year (CPP 2015), which is about one-tenth of the value estimated in this project. CPP's values were significantly lower as their calculations were based on a water budget model that assumed no flow in Thinlake River from June through April (i.e., anytime outside spring freshet).

Table 4-5
Estimated Export Coefficients for Individual Watersheds around Moose Lake, 2017-2019

Year	Estimated P Export Coefficient (kg/ha/y)				
	Thinlake River Watershed	Franchere Bay (excluding the Thinlake River)	Bonnyville Bay	Vezeau Bay	Island Bay
2017	0.88	0.18	0.28	0.19	0.17
2018	1.44	0.15	0.26	0.09	0.10
2019	0.70	0.09	0.21	0.10	0.08
Average 2017-2019	1.01	0.14	0.25	0.13	0.12

Differences in export coefficient among bays were not related to land cover data in the Moose Lake watershed, as land use is similar among all sub-watersheds. Despite the increased P export coefficient, the Thinlake River sub-watershed contains less agriculture (40% of the area) than most other individual bay watersheds (Table 4-6). Urban land uses and exposed land could also create increased P loads, but those land uses are also lowest in the Thinlake River watershed. The elevated P export from the Thinlake River watershed could thus be related to the types of agriculture (e.g., livestock, annual vs. perennial crops, tillage practices, etc.), proximity of agriculture to water courses (especially any feedlots or winter feeding areas), land use practices in agricultural or developed areas, terrain slopes, and/or riparian function. It is also due to the quantity of water in the Thinlake River and that the Thinlake River is the only tributary that was assumed to flow through the winter months.

Table 4-6
Land Use in the Moose Lake Watershed and Subwatersheds

Land Use Type	Land Use Area Proportions (%)					
	Thinlake River Watershed	Franchere Bay (excluding the Thinlake River)	Bonnyville Bay	Vezeau Bay	Island Bay	Average for Entire Moose Lake Watershed
Agriculture	40%	39%	54%	53%	51%	48%
Forest	37%	39%	25%	18%	30%	30%
Urban	6%	10%	12%	12%	6%	9%
Exposed Land	<1%	1%	<1%	<1%	<1%	<1%
Grassland	7%	6%	3%	8%	6%	6%
Shrubland	4%	2%	3%	1%	4%	3%
Water	5%	4%	4%	8%	3%	5%

4.2.4 P Losses through Outflow

About 10 tonnes of phosphorus were removed from the lake through the Mooselake River outflow and withdrawals, with the Mooselake River outflow accounting for 99.5%. After subtracting this loss from the total external P loads of 36 tonnes, the remaining 26 tonnes were retained in the lake annually. This P would be stored in the water column, in the bottom sediments, and taken up into biomass through the aquatic food web.

4.2.5 Internal Loads

4.2.5.1 Release Experiments

The total internal P load estimated from core incubation release rates and estimated area of sediment anoxia during summer for Moose Lake was 8.35 tonnes. The average release rate was 3.5 $g/m^2/d$, with the highest release rate observed in the core taken in the deep centre of Vezeau Bay (Table 4-6). The proportion of releasable P in sediments unexpectedly did not correlate with the release rate, with lowest releasable P in Vezeau Bay. The individual bay estimates were lowest for Franchere Bay and about equal between Bonnyville and Vezeau Bay. The sum of these values (7,300 kg) was similar to the whole lake estimate but does not add up to the total because they were calculated individually based on bay-specific bathymetry, bay P concentrations and sediment chemistry.

Table 4-7
Releasable Phosphorus and Sediment P Flux in Moose Lake Sediment Cores

<table>
<tr><th>Core #</th><th>Bay</th><th>Releasable P (mg/kg)</th><th>Anoxic Release Rate ($g/m^2/d$)</th><th>Internal Summer P Load per Bay (kg)</th></tr>
<tr><td>1</td><td>Bonnyville</td><td>9,453</td><td>3.3</td><td rowspan="2">2,730</td></tr>
<tr><td>2</td><td>Bonnyville</td><td>10,313</td><td>1.6</td></tr>
<tr><td>3</td><td>Franchere</td><td>8,260</td><td>3.6</td><td rowspan="3">1,110</td></tr>
<tr><td>4</td><td>Franchere</td><td>7,130</td><td>-</td></tr>
<tr><td>5</td><td>Franchere</td><td>4,096</td><td>2.5</td></tr>
<tr><td>6</td><td>Bonnyville</td><td>10,454</td><td>-</td><td></td></tr>
<tr><td>7</td><td>Vezeau</td><td>7,408</td><td>2.9</td><td rowspan="2">2,640</td></tr>
<tr><td>8</td><td>Vezeau</td><td>6,393</td><td>7.2</td></tr>
<tr><td></td><td>Whole Lake</td><td>7,938</td><td>3.5 (Average)</td><td>8,350</td></tr>
<tr><td></td><td>Island Bay</td><td>-</td><td>Assumed: 3.5</td><td>820</td></tr>
</table>

4.2.5.2 Mass Balance

The average internal load to Moose Lake for 2017-2019 during summer estimated by mass balance was 8,880 kg (Table 4-8). This value is similar to the estimate obtained from the release experiments (8,350 kg). The closeness of the results from the two methods provides confidence in the internal load estimates generated in this study. We therefore used an average of these estimates in our final P budget. The summer internal loads were assumed to represent annual total internal loads, as we do not have data for winter and release rates are usually very low in winter.

Table 4-8
Internal Load estimated by Mass Balance

Bay	Concentration Change (mg/L)	Volume Change (m^3)	Mass Change (kg)	External Load (kg)	Outflow Loss (kg)	Sedimentation Loss (kg)	Gross Internal Load (kg)
Whole Lake	0.037	4,420,312	8,539	9,369	1,591	8,299	8,880
Vezeau Bay	0.04	1,959,378	4,472	1,377	150	1,283	1,889
Franchere Bay	0.053	1,624,219	14,455	4,676	1,398	2,941	5,502
Bonnyville Bay	0.037	1,095,428	2,250	1,278	199	1,234	1,035
Island Bay	0.033	710,248	787	319	41	306	25

Note: these estimates were calculated using summer data.

4.2.5.3 Anoxic Factor

Release rates estimated by the methods presented in Nürnberg (1988 and 2009) were about double the release rates observed in the core P flux experiments. Accordingly, the estimated internal loads (influx to lake water) resulting from this method were higher. An exception to that was Vezeau Bay, because the Nürnberg method relies on phosphorus concentrations in the sediments and Vezeau Bay contained the least releasable phosphorus.

Table 4-9
P Release Rate (Nürnberg) compared to P flux Study

Bay	Summer P Release Rate (Nürnberg) $mg/m^2/d$	Winter P Release Rate (Nürnberg) $mg/m^2/d$	Annual Gross Internal P Load (Nürnberg) kg
Whole Lake	6.27	1.21	15,859
Vezeau Bay	1.48	1.96	885
Franchere Bay	5.38	0.93	1,973
Bonnyville Bay	7.52	1.30	8,472
Island Bay	6.27	1.08	1,826

4.2.6 Phosphorus Budget Summary

4.2.6.1 P Budget for the Lake

The total annual phosphorus loads to Moose Lake in the years 2017-2019 were dominated by inflows from Thinlake River (57%, Figure 4-9). The remaining watershed contributed about one fifth of the load (19%) through direct runoff from surrounding lands and tributaries. Sediment release contributed also one fifth (20%) of the total loads to the lake. Sedimentation is the main path for phosphorus loss from lake water, with an average annual loss of 31 tonnes. The Moose River Outflow is the second largest path of phosphorus loss from the lake water (about 10 tonnes/yr, Figure 4-10).

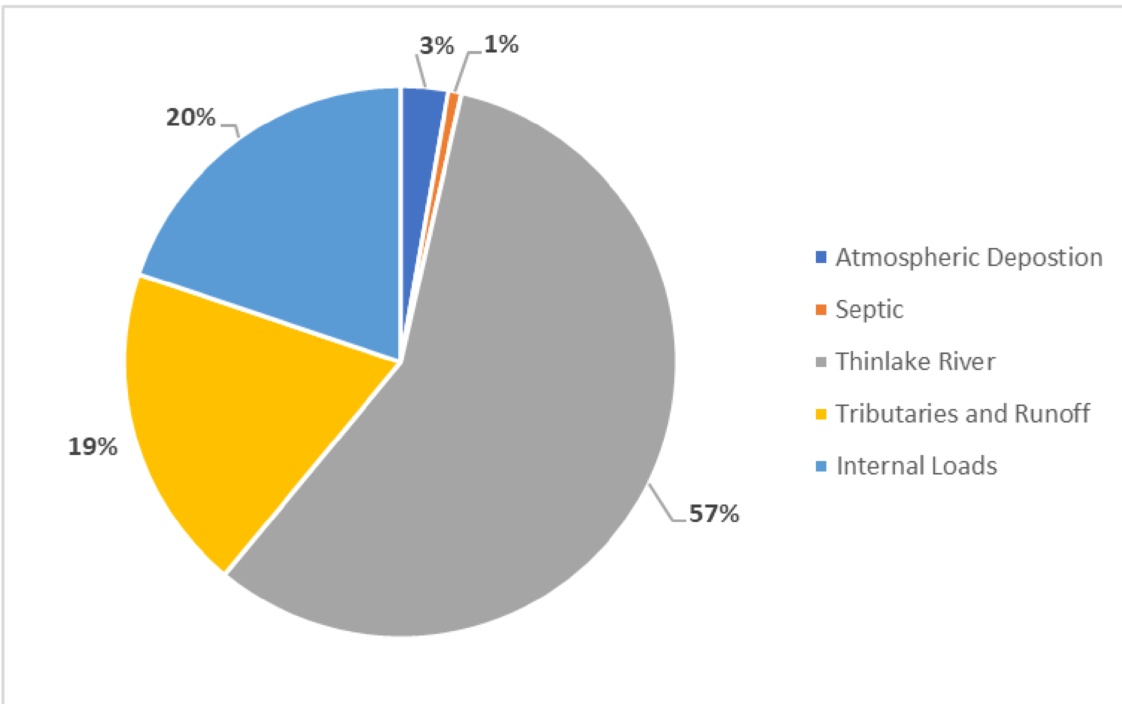

Figure 4-8
Average Annual P loads for Moose Lake (2017-2019)

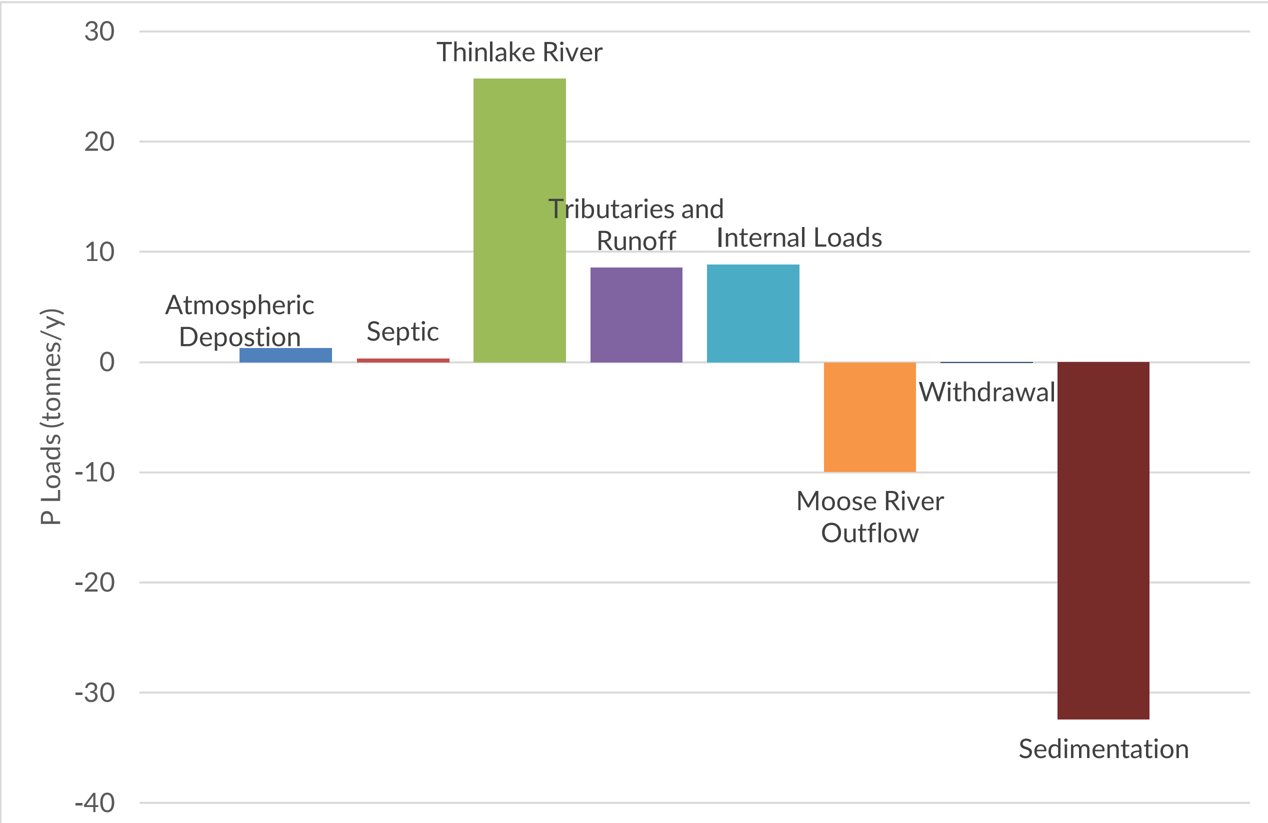

Figure 4-9
P Loads and Losses by Source or Pathway

4.2.6.2 P Budget by Bay

As expected from the results of the water budget, the largest inputs of P to the lake and losses from the lake through the outflow occurred in Franchere Bay (Figure 4-11). This does not account for between-bay exchange, i.e., the possibility that the inflow from Thinlake River makes it into other bays of the lake, or that water coming into individual bays from external sources eventually leaves the lake through the outflow. The bay P budget estimates therefore have a higher level of potential error.

Bay-based P budgets do; however, demonstrate the potentially large importance of internal P loads from the sediments in individual bays, especially in summer. For example, Bonnyville Bay and Vezeau Bay P budgets indicate that internal load provides about half of the total annual P load to these bays and the majority (60%) of P during summer, when algae typically develop blooms in Moose Lake (Figure 4-12).

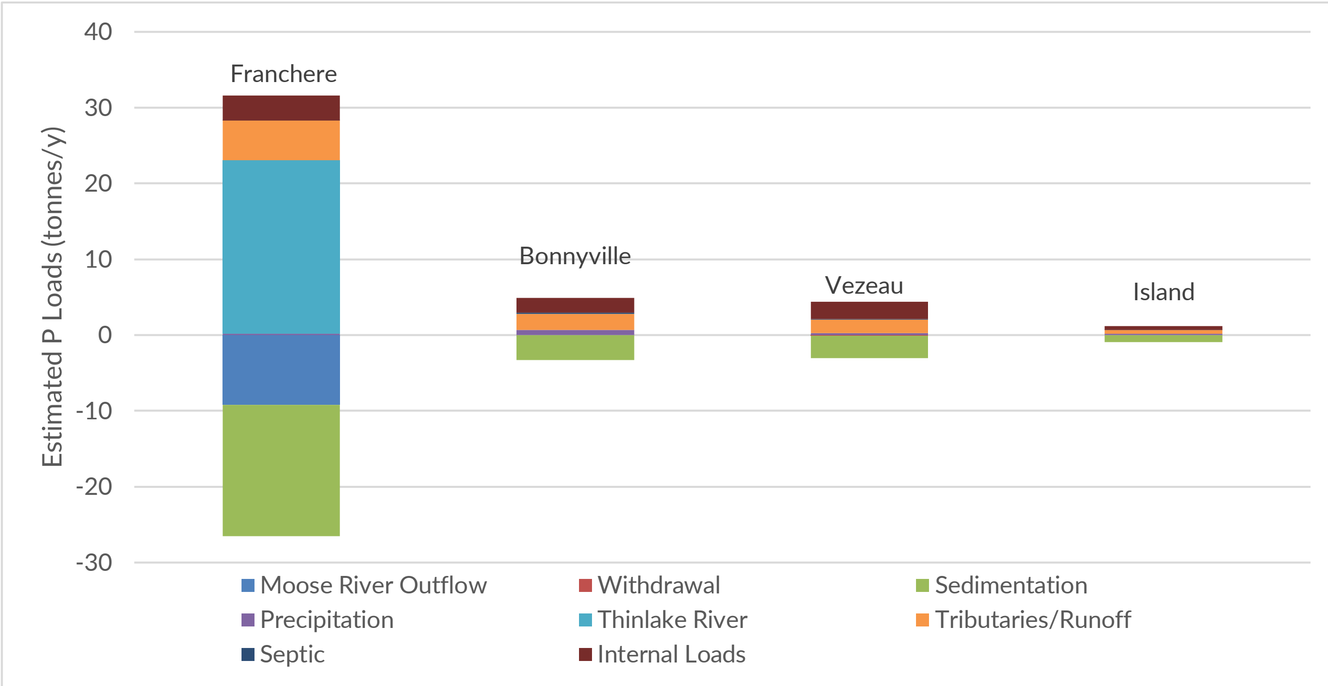

Figure 4-10
Average Annual P Loads by Bay and Source

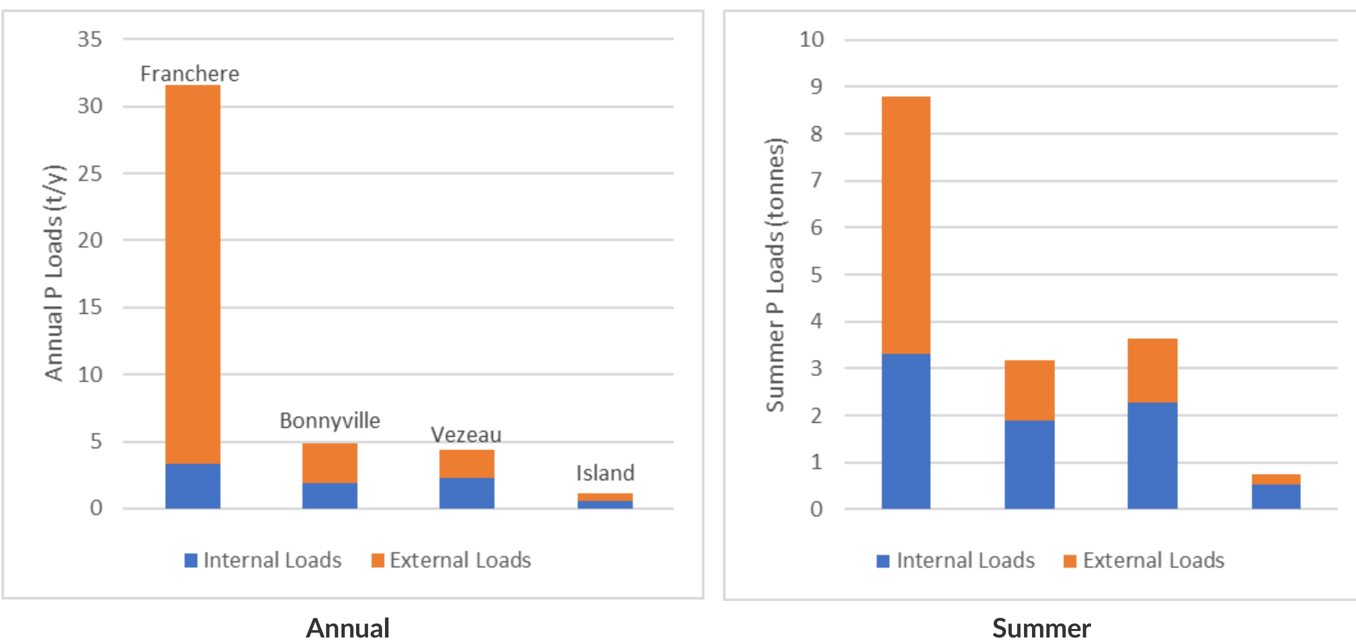

Figure 4-11
Annual and Summer Internal Loads vs External P Loads by Bay

4.2.6.3 Discussion: Uncertainties in P Budget Estimates

A certain level of uncertainty is associated with all estimates in the phosphorus budget. The best estimates are those that are based on measured data, such as volumes of precipitation, water withdrawals, and lake outflows. The overall annual lake water budget is therefore considered relatively reliable as these inputs and the outflows were measured and the total watershed input was inferred from those data.

The largest unknown in the water budget equation is groundwater. Previous water balances indicated that Moose Lake receives a net input of groundwater but that contributions on a month-to-month basis are relatively small (Alberta Geological Survey 2004, in Alberta Environment 2006). Since our water budget was based on a mass balance, this net groundwater input is included in our tributary and runoff term. This means that water and phosphorus inputs from the watershed may be slightly overestimated, as they include the groundwater term.

External phosphorus loads from the watershed into Moose Lake were based on interpolation of measured TP concentrations in creeks at specific discharge levels across the hydrograph between the sampling times. This method may miss peaks in creek P concentrations during high runoff events, introducing some potential for error. The three years of data, however, showed consistent patterns of higher phosphorus concentrations in Yelling and Wood Creeks compared to the other locations; therefore, the conclusions on relative importance of creeks for the external phosphorus load to Moose Lake and opportunities for nutrient reductions in the watershed are reliable.

Winter load estimates from external sources are the most uncertain because no flow and water quality measurements under ice were available for Thinlake River. Water budget modeling based on level measurements showed, however, that it contributed inflow to the lake during the winters in 2017-2019. Phosphorus concentrations were interpolated between the last measurement in fall and the first measurement in the following spring (usually a 6-months gap in data), which would introduce uncertainty as well.

Precipitation and septic system contributions were based on literature values from other locations and are therefore not site-specific. However, even if these generic estimates were to be doubled or tripled, the contribution of septic field seepage would remain below 10% of the total lake phosphorus budget. For the Bonnyville Bay and Vezeau Bay specific phosphorus budgets, however, where septic inputs were estimated at 6% contribution each, increased septic system phosphorus loads due to failing systems, pervious soils, shallow groundwater tables or flooding during high lake levels, could make a difference for water quality in those bays.

The break-down by bay ignores water exchange between bays that likely occurs during times of rapid lake level fluctuations and through wind-induced lake currents. The largest effect of this is likely that the Thinlake River water entering Franchere Bay in spring may distribute into the other bays. A secondary effect would be the water loss of one bay into another during decreasing lake levels, for example water leaving Vezeau Bay into Bonnyville Bay. Therefore, the annual water and phosphorus budgets by bay underestimate the relative importance of inputs from Thinlake River inputs. Relative contributions during summer, however, are likely more reliable, because lake levels decreased during that time and errors would only be associated with losses from one bay to another but not be associated with any specific inflow such as Thinlake River. As the internal load estimates were based on summer data, they were likely the least affected by errors due to between-bay water exchanges.

Generally, uncertainties around the internal load estimates can be significant because of multiple assumptions and uncertainties related to the inputs. Internal load estimates derived from mass balance, which are calculated as the residual after all the other P budget components are accounted for, are sensitive to uncertainty in the data inputs. The internal load estimates from release experiments assume that P is released from the sediments to lake water at the same rate as in the laboratory, which cannot be verified in the field at Moose Lake. The internal load estimates based on Anoxic factor assume that the equations presented by Nürnberg et al. developed for other lakes are applicable to Moose Lake. While each of these methods has potential errors, these three approaches are entirely independent methods and therefore served as a cross check to each other. The internal load estimates for the entire lake that used lake-specific data, i.e., the mass balance and P release experiment methods, were within 6% of each other (i.e., 8,880 kg from the mass balance and 8,350 kg from the release experiment estimates), providing confidence in the resulting internal load estimates for Moose Lake.

5 SUMMARY AND RECOMMENDATIONS

The key findings of this study are:

- The Thinlake River watershed was the largest external source (57%) of water and phosphorus to the lake;
- Internal load from sediments contributed about 20% of the total P load to the lake;
- Other tributaries and runoff also contributed about 19% of the total external load;
- Phosphorus inputs from the atmosphere and onsite wastewater systems were minor in comparison to internal and watershed loads;
- The internal loads represented a large proportion (60-70%) of phosphorus loads during summer for the bays without large tributary inflows: Vezeau, Bonnyville Bay and Island Bay;
- Watershed inputs were more than double during the three years covered by this study than previous estimates that were calculated during times of moisture deficits. This highlights the large interannual variability of phosphorus loads to Moose Lake based on variations in weather. Internal loads will become relatively more important during any dry times in the future;
- Yelling Creek and Wood Creek had the highest phosphorus concentrations of all sampled tributaries in 2017-2019, consistent with results for Yelling Creek from 2005-2007.
- The largest uncertainties in the P budget are associated with winter water quality and flows in Thinlake River, groundwater inflows and outflows, and bay-based internal loads.

Based on these findings, there is value in refining the phosphorus budget estimate as follows:

- Conduct water quality and flow monitoring in Thinlake River during the winter months to better estimate stream inputs when most of the flow is thought to be derived from baseflow rather than overland runoff. Laboratory analyses should be for both total P and total dissolved P, as in previous tributary sampling;
- Conduct additional years of bay-specific lake water quality sampling at the same time as tributary sampling to increase confidence in bay-specific internal load estimates; and
- Evaluate phosphorus contributions and losses through groundwater.

The study has several implications for lake and watershed management, as outlined below:

- Elevated phosphorus concentrations in Yelling Creek and Wood Creek indicate that the land use in these watersheds has a large effect on creek water quality and the mass of P entering the lake. An agricultural use study should be considered to identify land uses and activities that may be the source of nutrients in this watershed and where best management practices at the source may be warranted. In addition, the already completed riparian health assessment in Yelling Creek can be used to continue identifying site-specific opportunities for riparian restoration that can help reduce the transport of nutrients from the land to water; such an assessment is also recommended for Wood Creek.
- Internal loads from sediments are an important source of phosphorus to Bonnyville and Vezeau Bays, especially during summer. The relative importance of internal loads will increase during drier than normal years as watershed runoff decreases. It will therefore be useful to assess the feasibility and potential effectiveness of strategies to reduce internal loading from sediments as part of lake and watershed management efforts.

- Estimated septic system contributions of phosphorus to the lake were relatively small but assumed proper functioning of the systems. If these assumptions are not valid, then the P contributions from on-site wastewater could be larger. To minimize potential effects, new septic systems must be designed and installed according to the Alberta Private Sewage Regulation. Existing systems require regular pumping of septic tanks and system maintenance as best management practices to limit P inputs to the lake, especially in the more densely developed Vezeau and Bonnyville Bays.
- There are plans to remove the weir on Mooselake River (AMEC 2018). A study indicated that lake levels will change minimally with weir removal unless reed beds and beaver dams are removed with the weir (AMEC 2018). If reedbeds and beaver dams are removed, however, this will cause a significant drop in lake levels (0.25 to 1.0 m in change). This change could adversely affect fish habitat and may result in changes to nutrient cycling processes in the lake, but the potential of such effects has not been assessed. We therefore recommend assessing potential implications of the weir removal for Moose Lake water quality before making a final decision.

In conclusion, this report demonstrated that phosphorus inputs from the bottom sediments to the water in for Moose Lake are significant, likely playing a role in summer algal blooms. In addition, this report confirmed previous estimates of localized elevated phosphorus loads in the watershed. The resulting recommendations can help inform on-going lake and watershed management initiatives by the Moose Lake Watershed Society and its partners.

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APPENDIX A - EQUATIONS

Evaporation Equation – Hamon Method

According to the Hamon method, daily evaporation E (mm) can be estimated by the following equation:

$$E = 0.63D^2 10(\frac{7.5T_a}{T_a + 273})$$

Where T_a is air temperature and *D* represent the maximum sunshine duration ratio estimated by the following equation:

$$D = \frac{1}{9}\cos^{-1}[-\tan(\phi) * \tan\{23.45° \sin(\frac{J-80}{365})\, 360°\}],$$

Where ϕ represent the latitude and *J* is the Julian day.

Sublimation – Kuzmin equation

The sublimation rate in mm/day is calculated using the following equation:

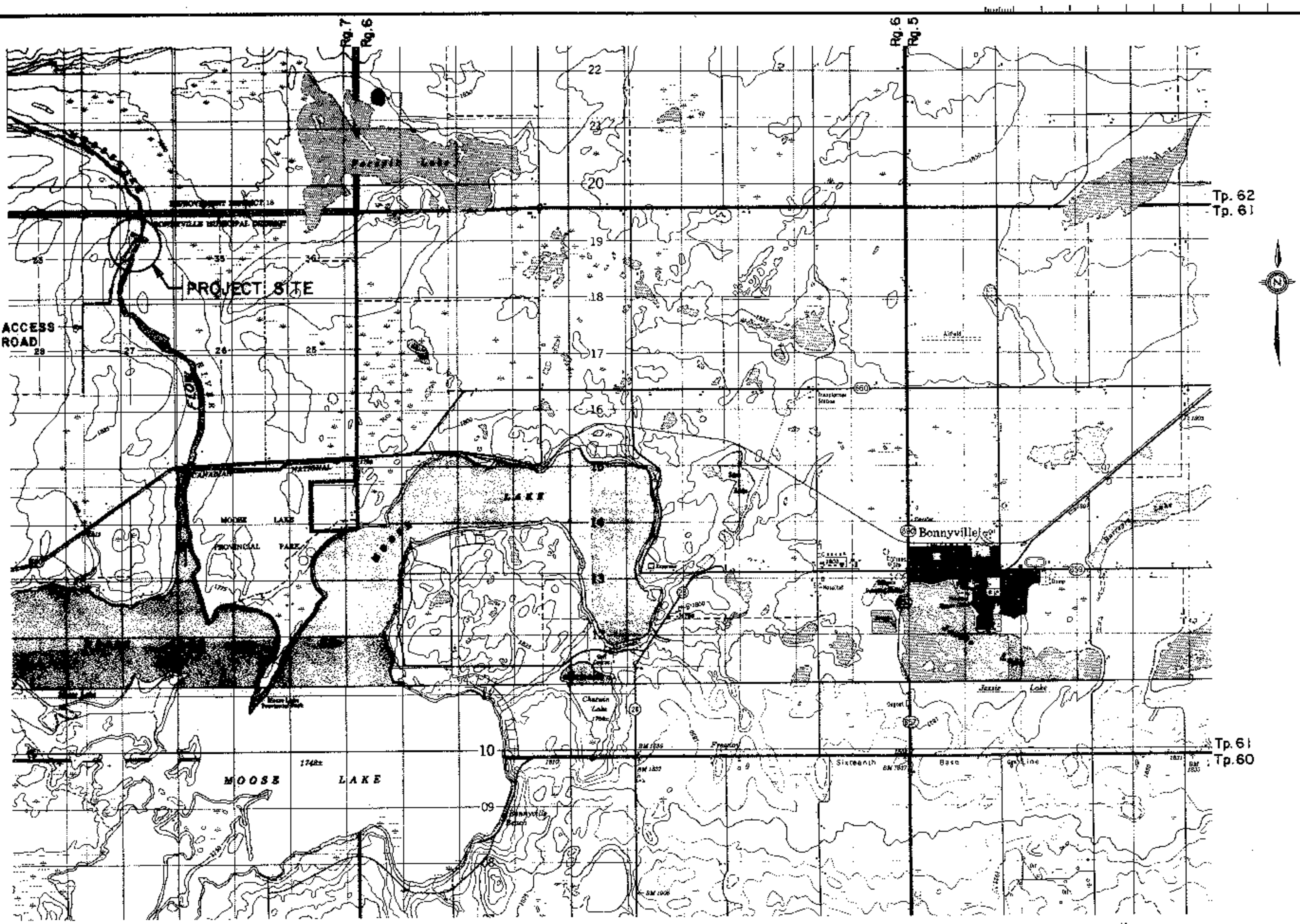
$$M_{subl} = (0.18 + 0.098 * v_{ave}) * (P_{sat} - P_{vap})$$

Where V_{ave} (m/s) is the wind velocity at 10m, and P_{st} and P_{ave} (mb) are the saturated vapour pressure and vapour pressure, respectively.

Anoxic Factor Internal Load Equations

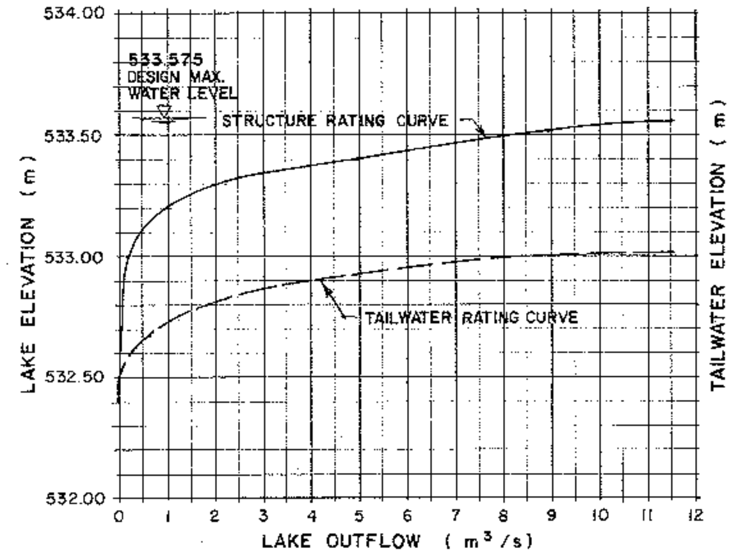
To do for final

APPENDIX B - WEIR DESIGN DRAWINGS AND RATING CURVE



LOCATION PLAN

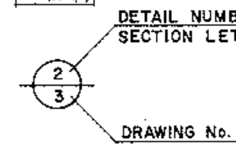
SCALE 1:50 000



STRUCTURE RATING CURVE

LEGEND :-

- RIPRAP
- PITRUN GRAVEL
- TAMPED IMPERVIOUS BACKFILL
- TAMPED BACKFILL
- COMPACTED FILL



LIST OF DRAWINGS

SHEET No.	DRAWING TITLE
1.	INDEX
2.	CONTROL STRUCTURE - EARTHWORK DETAILS & BOREHOLE LOCATION PLAN
3.	CONTROL STRUCTURE - EARTHWORK DETAILS
4.	EXISTING STRUCTURE - CROSS SECTIONS
5.	CONTROL STRUCTURE - CONCRETE OUTLINES
6.	FISHWAY - CONCRETE OUTLINES
7.	CONTROL STRUCTURE - REINFORCING DETAILS
8.	FISHWAY - REINFORCING DETAILS
9.	VERTICAL SLOT BAFFLE, TRASHRACK AND MISCELLANEOUS DETAILS
10.	CONTROL STRUCTURE - WALKWAY AND FISHWAY DECKING
11.	CONTROL STRUCTURE - FENCING DETAILS
12.	SAFETY BOOM

MOOSE LAKE STABILIZATION

CONTRACT No. 86 - 0530

CERTIFIED AS CONSTRUCTED
May 2/86

MARK	NATURE OF REVISION	DATE	ENG.	DWN.
1				
2				
3				
4				
5				

Alberta ENVIRONMENT — DESIGN AND CONSTRUCTION DIVISION

SUBMITTED C. Luka... DATE Sept. 4/84
APPROVED ... DATE Sept. 4/84
DESIGNED ... CHECKED ...
DRAWN F.F. CHECKED John ...

MOOSE LAKE STABILIZATION

INDEX

SCALE AS SHOWN | SHEET 1 OF 12 | A.C.
DATE AUGUST, 1984 | DWG. No. MSEL2-E-84-05

MICROFILM DATE ______
DRAWING FILE No. MSEL2 0564 A.C.
CENTRAL FILE No. ______
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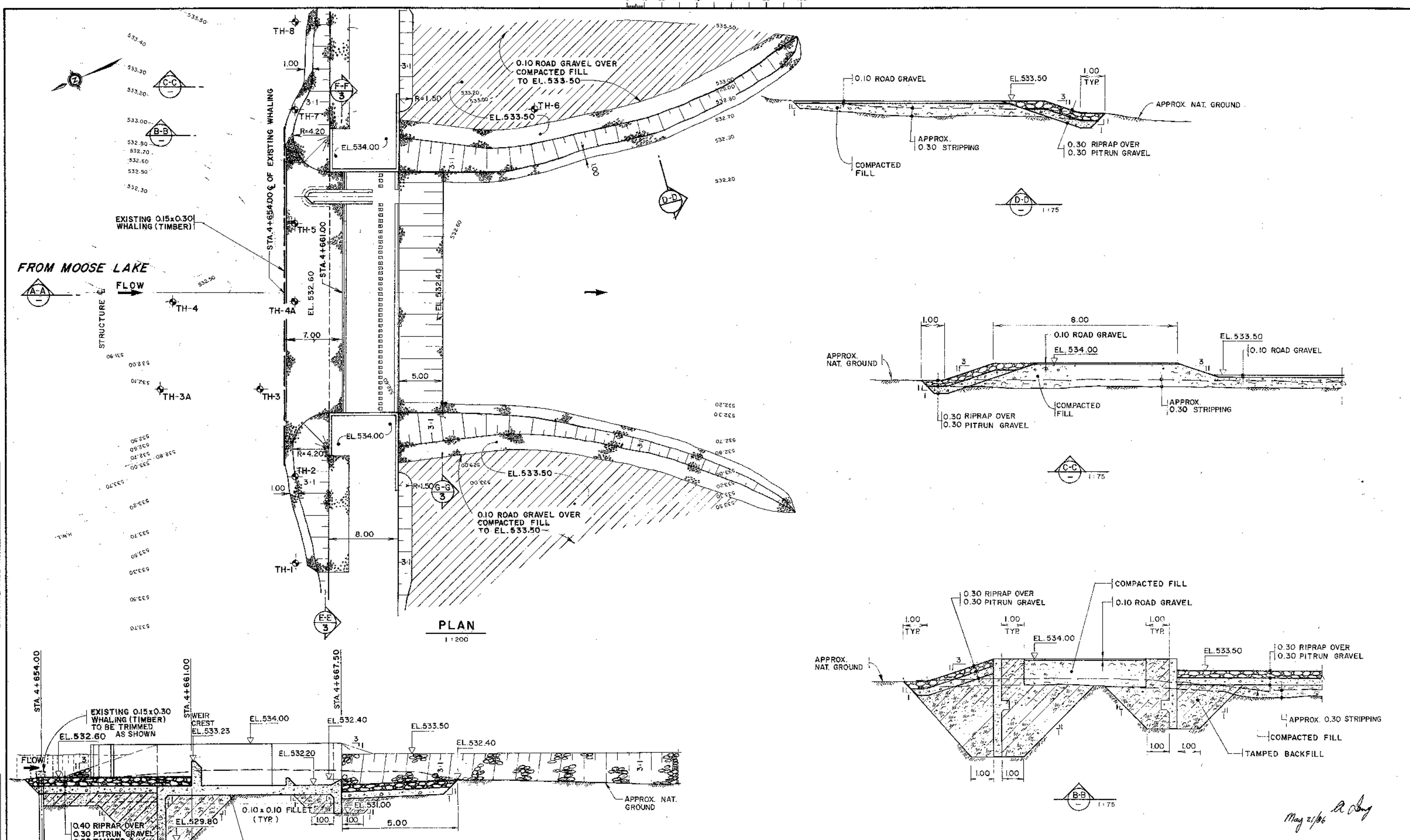

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CENTRAL FILE No.

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Alberta ENVIRONMENT — DESIGN AND CONSTRUCTION DIVISION

SUBMITTED: Sept 4/84 — DESIGNED — CHECKED — APPROVED — DRAWN F.F. — DATE Sept 4 '84 — CHECKED

MOOSE LAKE STABILIZATION

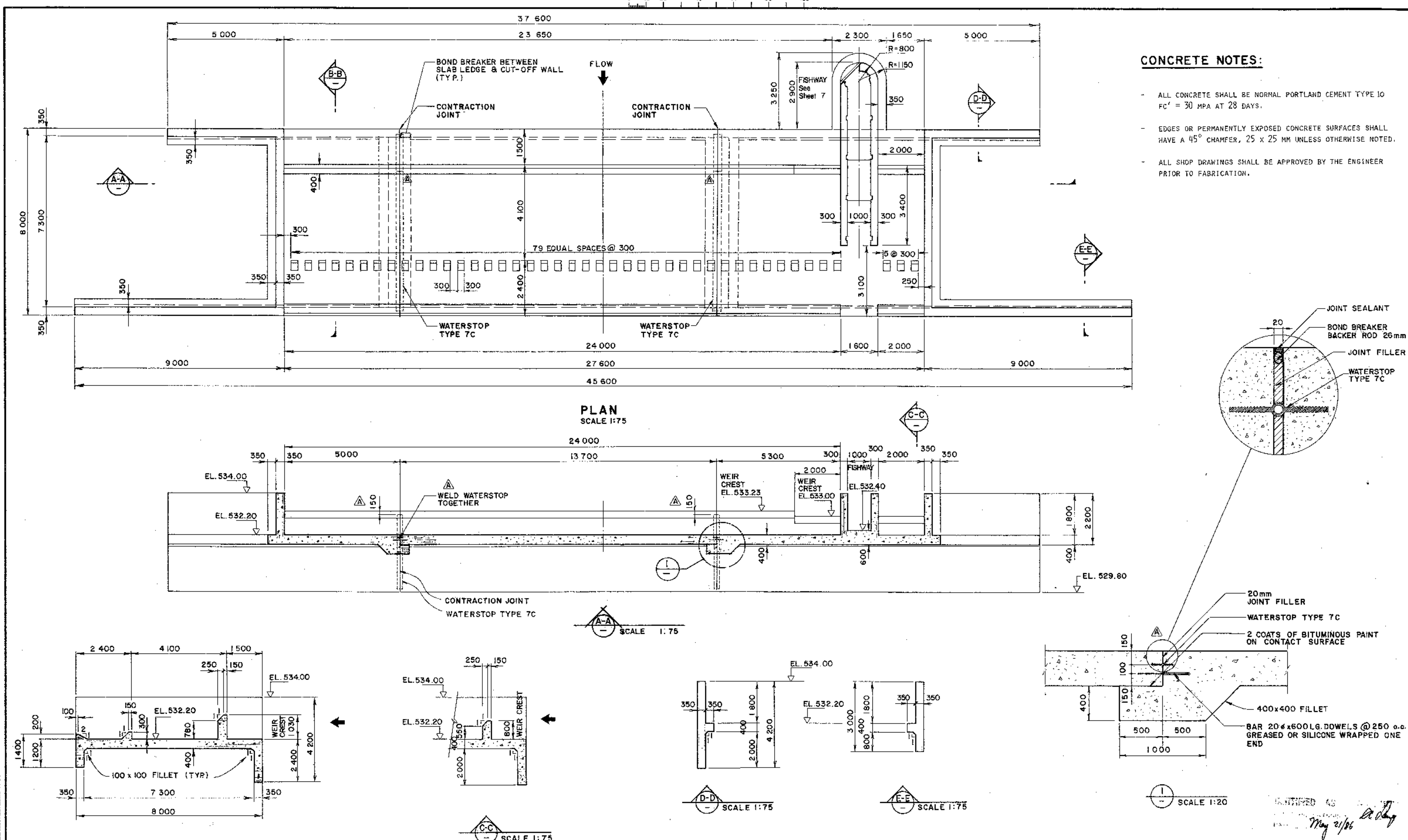
CONTROL STRUCTURE

EARTHWORK DETAILS & BOREHOLE LOCATION PLAN

SCALE AS SHOWN — SHEET 2 OF 12 — A.C.

DATE AUGUST, 1984 — DWG. No. MSEL2-E-84-06

P1-560x860



CONCRETE NOTES:

- ALL CONCRETE SHALL BE NORMAL PORTLAND CEMENT TYPE 10 FC' = 30 MPA AT 28 DAYS.
- EDGES OR PERMANENTLY EXPOSED CONCRETE SURFACES SHALL HAVE A 45° CHAMFER, 25 x 25 MM UNLESS OTHERWISE NOTED.
- ALL SHOP DRAWINGS SHALL BE APPROVED BY THE ENGINEER PRIOR TO FABRICATION.

MARK	NATURE OF REVISION	DATE	ENG.	DWN.
E				
D				
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B				
A	CLARIFICATION OF CONTRACTION JOINT & ADDED WATERSTOP ON WEIR	OCT. 1984		

Alberta ENVIRONMENT — DESIGN AND CONSTRUCTION DIVISION

SUBMITTED / DATE / APPROVED / DATE — DESIGNED / CHECKED / DRAWN F.F. / CHECKED

MOOSE LAKE STABILIZATION

CONTROL STRUCTURE

CONCRETE OUTLINES

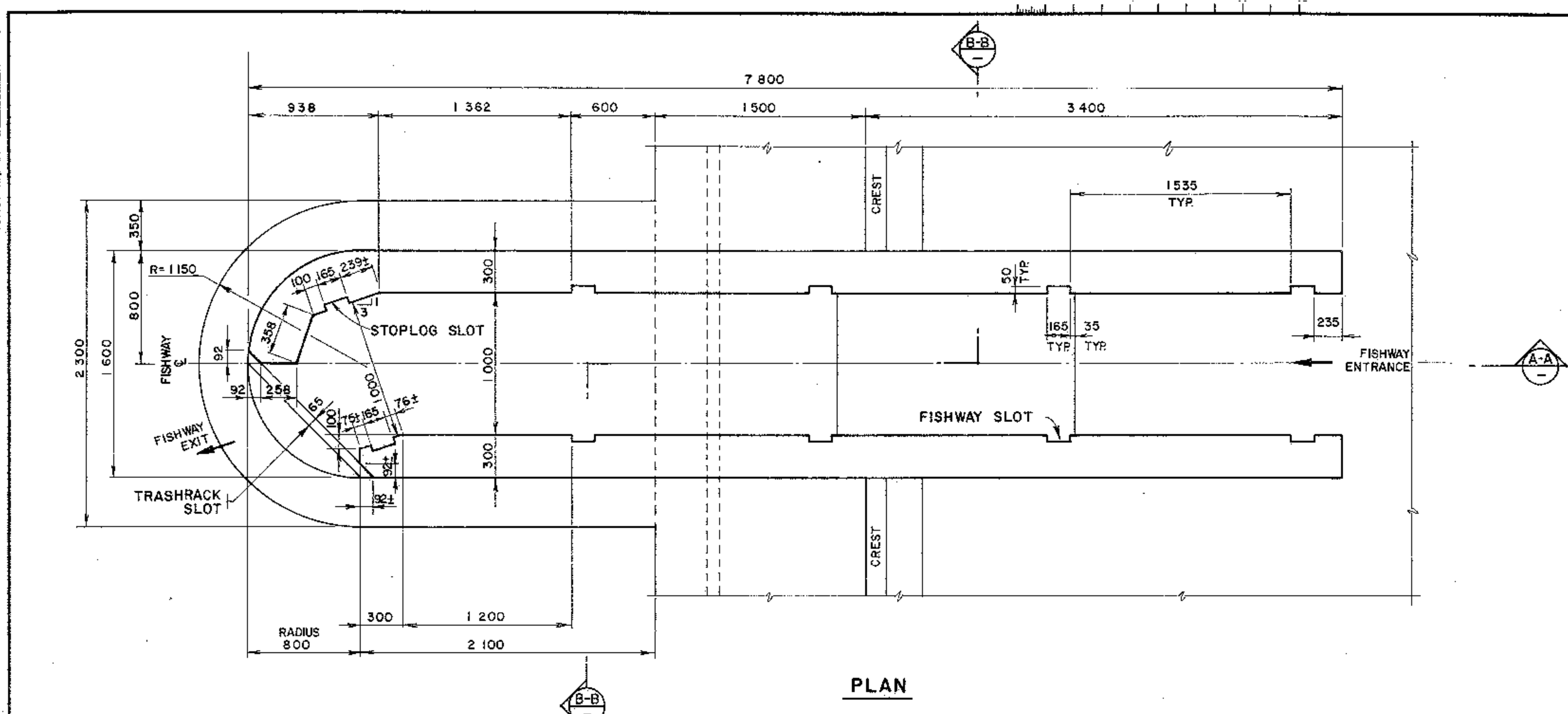
SCALE AS SHOWN — SHEET 5 OF 12 — A.C.

DATE AUGUST, 1984 — DWG. No. MSEL2-E-84-09

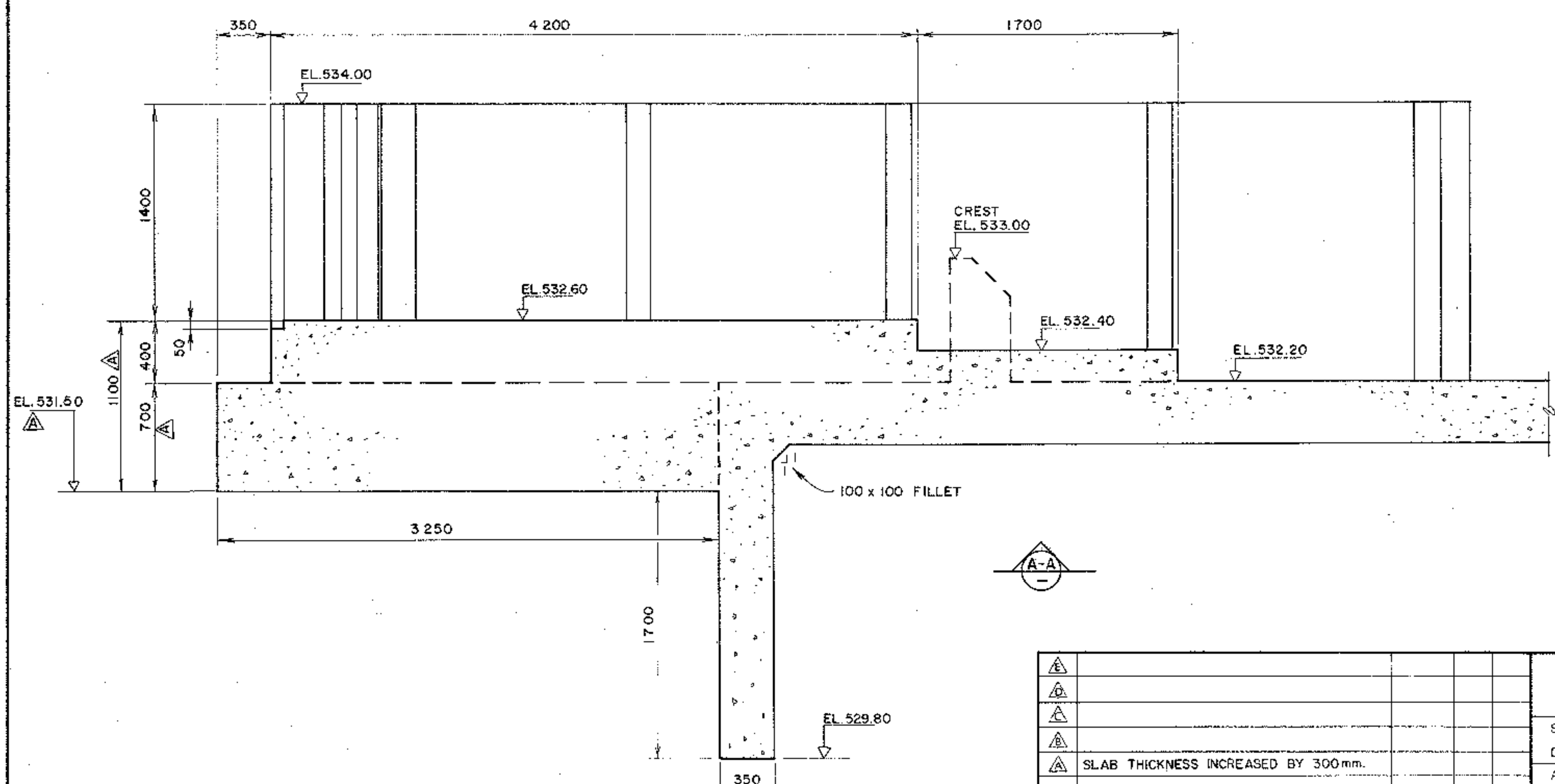
DRAWING FILE No. MSEL2 0984 A.C.

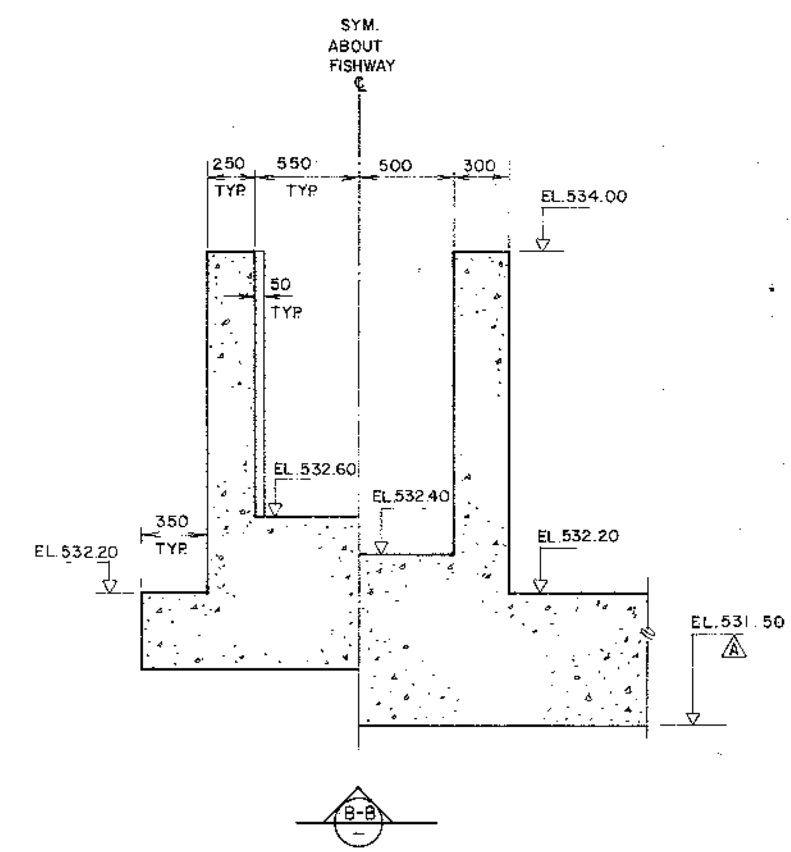
P1-560x860

NOTE:
FOR CONCRETE NOTES, SEE SHEET 5.



PLAN





May 21/86

MARK	NATURE OF REVISION	DATE	ENG.	DWN.
A	SLAB THICKNESS INCREASED BY 300 mm.			

Alberta ENVIRONMENT — DESIGN AND CONSTRUCTION DIVISION

SUBMITTED	DESIGNED
DATE Sept 4/84	CHECKED
APPROVED	DRAWN F.F.
DATE Sept 4/84	CHECKED

MOOSE LAKE STABILIZATION
FISHWAY
CONCRETE OUTLINES

SCALE	1:20	SHEET 6 OF 12	A.C.
DATE	AUGUST, 1984	DWG. No. MSEL2-E-84-10	

MICROFILM DATE
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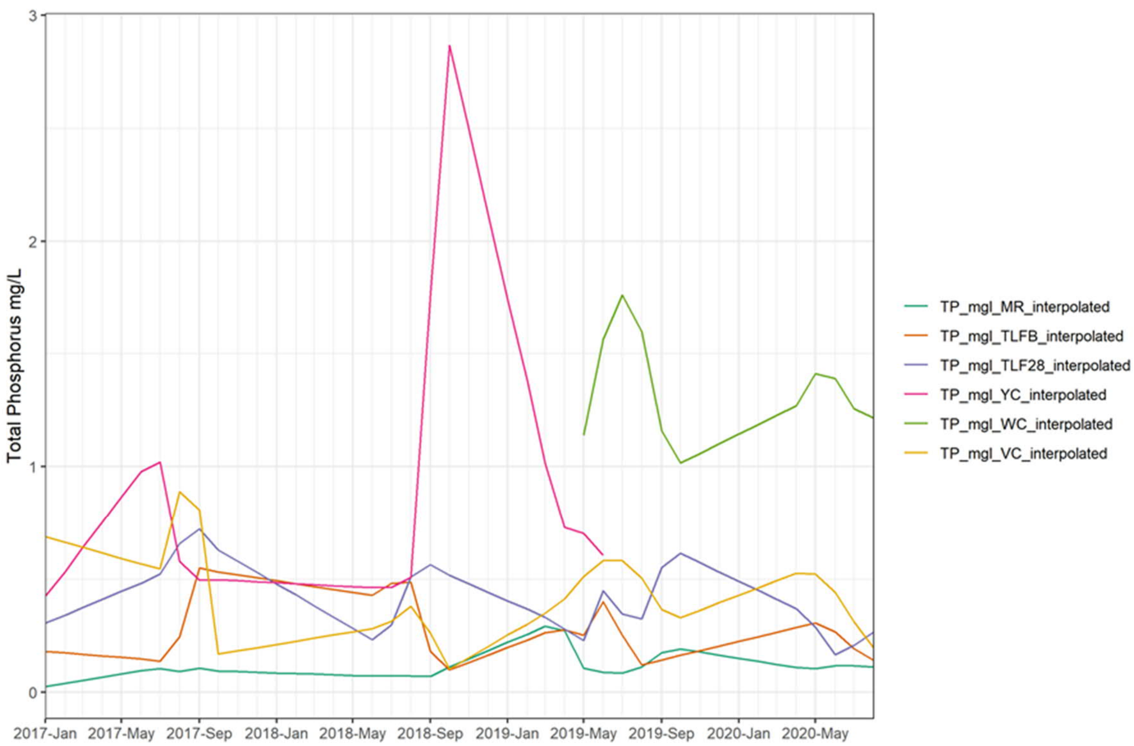
APPENDIX C - TRIBUTARY PHOSPHORUS CONCENTRATION DATA



Phosphorus Concentrations in Tributaries in the Moose Lake Watershed, Interpolated between Sample Dates

MR: Mooselake River
TLFB: Thinlake River at mouth to Franchere Bay
TL: Thinlake River upstream of Yelling Creek confluence
YC: Yelling Creek
WC: Wood Creek
VC: Valere Creek