Wabamun Lake:
Eutrophication Modelling with BATHTUB

Prepared by A. Tuininga (AEP), D.O. Trew, and M.E. Shain (NSWA). July 2015.

1 Introduction

Phosphorus is considered to be the most common limiting chemical factor controlling algal growth in freshwater lakes (Schindler et al. 2008). The nitrogen content of freshwater lakes can also be an important factor and may influence the patterns of algal succession that occur during the open-water growing season (Prepas and Trimbee 1988). Other factors such as salinity, turbidity and physical mixing patterns are important determinants of the quantity and types of algae that develop (Bierhuizen and Prepas 1985).

Algal blooms are a major feature of summer water quality in Alberta lakes, affecting water transparency and aesthetics directly, and other lake features such as oxygen concentrations and cyanotoxicity. The control of excessive summer algal blooms is therefore an important goal of lake management in this province.

The development of eutrophication models has become commonplace in lake research and management disciplines, and they are used as diagnostic tools to quantify pollution sources and evaluate long-term management options for lakes (OECD 1982; Rast et al. 1989). The refinement and application of eutrophication models has been an ongoing focus in limnology since the first watershed/lake nutrient relationships were developed in the 1960s (Vollenweider 1968).

2 BATHTUB

BATHTUB is an empirical eutrophication model developed by the United States Army Corps of Engineers for use on reservoirs and lakes (Walker 2006). The model was designed to calculate water and nutrient mass balances that replicate lake processes over a broad time scale. Besides simulating current conditions, BATHTUB can be used as a planning and educational tool for evaluating future watershed development/restoration scenarios.

It predicts steady-state (average) concentrations, and in the case of Alberta lakes is best used to characterize conditions during the open-water season. Nutrient and algal dynamics vary extensively between winter and summer in this region. From an ecological and lake management point of view both seasons are extremely important. However, the recreational user focus and most sampling activity occur during the summer.

This report summarizes the preliminary calibration and application of BATHTUB (Version 6.14) to Wabamun Lake during the open-water season. The purpose of this project is to provide further information and insights to support the development of a long-term watershed management plan for the Wabamun Lake basin. The primary intent of this modelling application is identify and quantify phosphorus sources in the watershed (tributary streams) and along the shoreline (local contributing areas) in addition to the other major sources (internal loading, atmospheric deposition, water diversion).

The model requires data for lake water quality, atmospheric loadings, tributary loadings, point sources, hydrology and lake morphometry. The model develops mass balances and simulates current water quality based on empirical algorithms built into the model. Water balances are also calculated and presented. The challenge in setting up the model is to achieve a reasonably strong simulation of current conditions, i.e., a good calibration. Achieving hydrological accuracy is fundamentally important to achieving nutrient prediction accuracy.

Future development and restoration scenarios can be developed by applying different nutrient runoff estimates to simulate land cover change. In the simplest development scenarios, stream nutrient loadings associated with forested watersheds may be increased to represent stream loadings from agricultural watersheds. In the simplest restoration scenarios, the stream nutrient loadings associated with agricultural watersheds may be decreased to represent stream loadings from forested watersheds. Diversion scenarios can also be evaluated by testing proposed transfer volumes and nutrient characteristics of new water sources. Unlike other lakes, Wabamun also has future coal mine reclamation scenarios to be considered.

BATHTUB has been tested in preliminary applications for a number of lakes in Alberta (Pine, Baptiste, Lake Isle, Lac Ste. Anne, Lac St Cyr, Lesser Slave, Pigeon, and Mayatan) by Alberta Environment and Parks (AEP) and North Saskatchewan Watershed Alliance (NSWA) staff. The model uses empirical nutrient relationships from ecoregions and research initiatives conducted elsewhere, mainly in the U.S.A. Therefore, not all of its features are directly applicable to Alberta lakes; professional diligence is required when interpreting and communicating results. In its application to Wabamun, BATHTUB does provide a reasonable overview of current processes affecting lake nutrient dynamics, and this is further strengthened by the use of local watershed data.

3 Data Sources

Wabamun Lake presents a unique challenge in modelling. It consists of numerous tributaries and local contributing areas (Figure 1) which have been identified using ArcGIS and for which current land cover estimates (forest, agriculture, urban) have been individually quantified. The lake is relatively shallow, has a long fetch and is well mixed. It has a small watershed to lake surface area ratio (4:1). It has a moderate flushing rate, which has been enhanced in recent years (post-1997) by the diversion of water via TransAlta's Sundance operations. The diversion water is of high quality and contains extremely low phosphorus levels. The introduction of this low nutrient water has caused a decline in lake phosphorus levels (Casey 2011); the east basin may have been influenced to a greater degree. The diversion was necessitated by the development of the Highvale Coal Mine, which interrupted normal runoff patterns to the lake, creating an annual hydrologic deficit.

Background information and morphometric characteristics of Wabamun Lake were taken from the "*Wabamun Lake State of the Watershed Report*" (Aquality 2013) and the Phase One draft report for the "*Wabamun Lake Sub-watershed Land Use Plan*" (Stantec 2015).

Nutrient data used in the model were averaged from lake composite sample data collected by Alberta Environment and Parks from 2007-2008, and 2010-2013. Recent nutrient data were not available for the watershed tributaries and therefore historical annual flow-weighted mean concentrations (AFWMCs) for runoff from agricultural and forested land cover areas were used; these data were collected at Wabamun Lake in 1981 in an intensive watershed study (Mitchell & Trew 1982).

The watershed of the lake was divided into sub-watersheds and local contributing areas using ArcGIS Shawn Keizer, AEP (pers. comm.). The 2010 land cover data were provided by ABMI. The land cover data were applied to the sub-watershed delineations using ArcGIS to determine sub-watershed land cover areas needed by BATHTUB to calculate nutrient loads from individual tributaries and local contributing areas.

Long-term hydrologic data were provided by TransAlta which is required to report annually to determine their mining impact on the lake (Klohn Crippen Berger 2013). This water balance summarizes the long term precipitation and evaporation amounts, lake level, licensed diversions, runoff and the water treatment plant input to Wabamun Lake. The appropriate AFWMCs and runoff data were then applied to each landscape unit specifically.

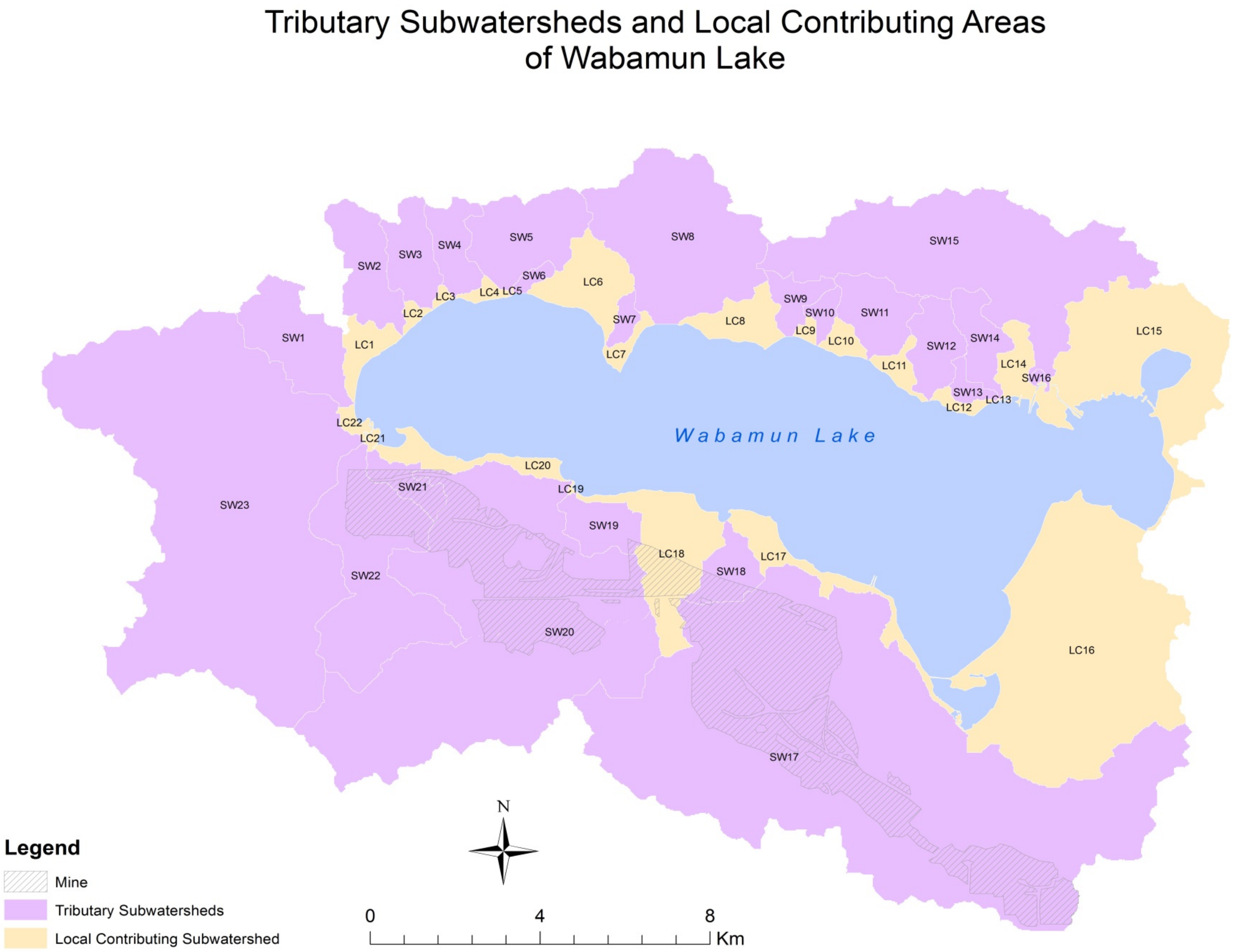


Figure 1: Sub-watersheds of Wabamun Lake

4 Model Selections

The "Model Selections" (options) provided in the BATHTUB program enable it to calculate various lake attributes using empirical relationships. There are often a number of Selections to choose from. For instance, there are nine Selections available for total phosphorus; one has been determined to be a reasonable fit for Alberta lakes (Table 1).

In all cases it is the modeller's responsibility to choose the Selection that best represents the limnological processes for the lake in question. This requires a broad knowledge of limnological characteristics for the lake and the natural region. Once the most appropriate model selections are determined, further "calibration" steps may be required to align predicted and observed values. The degree of calibration required varies from variable to variable.

Table 1: Model Selections utilized for the Wabamun Lake BATHTUB Model

Variable	Selection #	Description
Conservative Substance	0	Not Computed *
Total Phosphorus	8	Canfield & Bachman (1981), Natural Lakes $0.162(Wp/V)^{0.458}$
Total Nitrogen	4	Bachman (1980), Volumetric Load $0.0159(Wn/V)^{0.59}$
Chlorophyll *a*	4	P, Linear $B = K\ 0.28\ P$
Transparency	3	Secchi vs. Total Phosphorus, CE Reservoirs $S = K\ 17.8\ P^{-0.76}$
Longitudinal Dispersion	2	Constant-Numeric – Fixed Dispersion Rate $D = 1000\ KD$
Phosphorus Calibration	1	Decay Rates – Apply calibration factors to sedimentation rates *
Nitrogen Calibration	1	Decay Rates – Apply calibration factors to sedimentation rates *
Error Analysis	1	Consider model error and data error
Availability Factors	0	Ignore *
Mass Balance Tables	1	Use predicted segment concentration to calculate outflow and storage terms *
Output Destination	2	Excel worksheet

* Default model equation
Wp = Total Phosphorus Loading (kg/yr)
V = Total Volume (hm^3)
Wn = Total Nitrogen Loading (kg/yr)
B = Chlorophyll *a* concentration (mg/m^3)
K = Calibration Factor (Global factor x Segment factor)
P = Total Phosphorus Concentration (mg/m^3)
S = Secchi Depth (m)
D = Dispersion Rate (km^2/yr)

5 Data Inputs

5.1 Global Variables

Global variables are fixed values for the year in question and include the averaging period, precipitation and evaporation rates, atmospheric deposition rate for nutrients and storage gain (Table 2).

The averaging period is the time step that a model uses to calculate the water and nutrient mass balances. This application of BATHTUB uses a full calendar year as the averaging period and calculates annual average values or annual totals for various parameters. Most lake water quality data for Alberta are collected during the open water season (May - October) or a shorter period thereof. Most tributaries flow over 6 – 7 months (March/April – October). These open water season data have been applied as the "annual" data for the purposes of this evaluation.

Atmospheric deposition data for total phosphorus were unavailable for 2012, so rates were taken from Bierhuizen and Prepas (1985), with the assumption that deposition rates have remain unchanged. Deposition data for other nutrient fractions were taken from Trew, Beliveau and Yonge (1987); the modelling program requires that all categories of "global variable" data be entered (Table 2).

The storage gain was assumed to be zero over the long-term. The use of longer term hydrologic data removes the effects of short-term variability in water balance components. The outlet weir structure sets the target lake level elevation to be met.

Table 2: Global Variables Utilized for the Wabamun Lake BATHTUB Model

Variable	Mean	Reference
Averaging Period	1	Walker (2006)
Precipitation (m)/avr period	0.5112	1951-2012 precipitation average Klohn Crippen Berger (2013)
Evaporation (m)/avr period	0.65	1960-2004 natural evaporation average Klohn Crippen Berger (2013)
Storage Gain (m)/avr period	0	Assumed long-term change in storage
Atmospheric Loads (mg/m^2/yr)		
Total Phosphorus	23.7	Bierhuizen and Prepas (1985)
Orthophosphate	8.14	Trew, Beliveau and Yonge (1987)
Total Nitrogen	457.64	Trew, Beliveau and Yonge (1987)
Inorganic Nitrogen	258.02	Trew, Beliveau and Yonge (1987)
Conservative Substance	6.522	Trew, Beliveau and Yonge (1987)

5.2 Segments

The Segments section in BATHTUB is divided up into four sub-sections. The first is a morphometry section that provides the model with the physical characteristics of the lake. The second is the observed water quality of the lake. The third and fourth sections are internal loading (Section 5.2.4) and "calibration" (Section 7), respectively.

5.2.1 Morphometry

In this application, Wabamun Lake is represented as a single segment; eastern, central and western portions of the basin were not modelled separately.

Morphometric data (Table 3) were obtained from Stantec (2015). The shallow nature of the lake and its long exposed length promote vertical mixing; the mixed layer depth was set to the maximum depth of the lake. Therefore, the hypolimnetic thickness was set at 0 meters.

Table 3: Morphometry Characteristics of Wabamun Lake

Variable	Wabamun Lake	Reference
Surface Area (km^2)	80	Stantec (2015)
Mean Depth (m)	5.1	Alberta Geological Survey (2008)
Length (km)	19.2	Schindler et al. Lake Wabamun Report (2004)
Mixed Layer Depth (m)	11	Maximum depth Stantec (2015)
Estimated Mixed Depth (m)	4.6	Estimated by BATHTUB – value not used
Hypolimnetic Thickness (m)	0	

5.2.2 Observed Water Quality

Wabamun Lake has been sampled frequently by Alberta Environment and Parks and these monitoring data were used in the model. The west and east basins were sampled separately in 2007-2008 and these data were averaged with the main basin composite data from 2010-2013 to represent the current, overall nutrient conditions in the lake (Table 4).

Table 4: Average Water Quality Data for Wabamun Lake

Variable	Wabamun Lake	Reference
Non-Algal Turbidity (1/m)	0.20	Calculated by BATHTUB (1/Secchi – 0.025*chl-a) minimum = 0.08
Total Phosphorus (ppb)	29.8	AEP unpublished data
Total Nitrogen (ppb)	984.5	AEP unpublished data
Chlorophyll *a* (ppb)	10.71	AEP unpublished data
Secchi Depth (m)	2.14	AEP unpublished data

5.2.3 Tributaries

Each input/output (tributary, local contributing area, diversion, and outflow) is classified as a "tributary" in the language of BATHTUB. The total annual inflow (runoff) and AFWMCs had to be specified for each "tributary" in order that loads (kg/yr) could be calculated by the model. Long-term average runoff values calculated for the Water Survey of Canada gauge at Tomahawk Creek (Klohn Crippen Berger 2013) were used in this analysis. Empirical nutrient AFWMCs for agricultural and forested lands in the Wabamun Lake watershed, as reported by Mitchell and Trew (1982), were used and conservative urban runoff values were derived from data reported by Jeje (2006) (Table 4). The area and land cover composition of each tributary and local contributing area was determined by ArcGIS (Table 5). The appropriate nutrient and flow data were assigned to that land unit.

The Highvale Coal Mine lands were excluded from the initial model set-up, as all runoff in the mine site is captured and diverted away from the lake. However, in the modelling of a future mine reclamation scenario (Section 8) the coal mine lands are re-introduced as active hydrologic components of the watershed.

Measured outflow data for Wabamun Creek are very incomplete, and for this modelling exercise had to be estimated from simulated values for 1982-1992 (Seneka 2002). The 2012 TransAlta water balance report did not provide a volume of water leaving the lake although it presented a graph of outflow volumes during the summer months (Klohn Crippen Berger 2013).

BATHTUB utilizes annual flow data in units of cubic hectometers (hm^3). Flow data from the water balance had to be converted for use in the model. BATHTUB requires nutrient units in parts per billion and therefore all flow-weighted mean concentrations (parts per million) also had to be converted.

Table 5: Runoff and Annual Flow-Weighted Mean Concentrations Assigned to the Tributaries of Wabamun Lake

Land Cover	Runoff (m/yr)	Total Phosphorus (ppb)	Total Nitrogen (ppb)
Agriculture	0.0823	409	2240
Forest/Natural	0.0823	167	1060
Developed	0.0823	750	3000

Table 6: “Tributaries” of Wabamun Lake

Trib. Name	Seg.	Type	Total Watershed Area (km^2)	Annual Flow Rate (hm^3/yr)	TP (ppb)	TN (ppb)	Type 2: NPS Land Cover Areas		
							Ag. (km^2)	Forest/ Natural (km^2)	Dev. (km^2)
LC	1	2	50.98				6.5	32.52	11.96
SW1	1	2	4.47				0.24	3.61	0.62
SW2	1	2	3.48				0.85	2.07	0.55
SW3	1	2	2.55				0.87	1.25	0.44
SW4	1	2	2.08				0.92	0.86	0.3
SW5	1	2	4.8				3.41	0.79	0.6
SW6	1	2	0.36				0.02	0.11	0.23
SW7	1	2	0.58				0.09	0.29	0.21
SW8	1	2	11.82				5.66	4.68	1.47
SW9	1	2	1.12				0.62	0.46	0.04
SW10	1	2	0.55				0.37	0.17	0.01
SW11	1	2	2.52				0.98	1.35	0.19
SW12	1	2	2.32				0.29	1.41	0.62
SW13	1	2	0.6				0	0.37	0.24
SW14	1	2	1.51				0.29	0.73	0.48
SW15	1	2	15.5				7.38	5.39	2.73
SW16	1	2	0.06				0	0	0.06
SW17	1	2	30.55				10.83	14.61	5.1
SW18	1	2	1.25				0.52	0.58	0.15
SW19	1	2	1.92				0.91	0.72	0.3
SW20	1	2	25.9				11.43	11.84	2.63
SW21	1	2	0.39				0.004	0.22	0.16
SW22	1	2	8.27				4.1	3.17	1
SW23	1	2	43.09				24.5	16.95	1.64
Licenses	1	4	0	1.934	29.8	984.5			
Wabamun Creek Outflow	1	4	296.66	6.323	29.8	984.5			
Water Treatment Plant	1	3	0	10.272	2.8	296			

5.2.4 Internal Load

Both internal and external sources of phosphorus contribute to lake eutrophication. In shallow Alberta lakes phosphorus concentrations increase rapidly in mid to late summer as phosphorus is released from lake bottom sediments in a process referred to as “internal loading”. Net internal loading rates for Wabamun Lake were obtained from an extensive summary of shallow lakes data (Sosiak and Trew 1996) in which 10 year average rates were determined for individual lakes. Winter internal loading rates were assumed to be negligible. The summer rates had to be converted to an annual rate (Table 7) to correspond with the averaging period (Section 5.1).

Calculation:
Total internal load for summer = 1.2 $mg/m^2/day$
Daily (annual) internal loading rate = 1.2 * (50 / 365) = 0.16 $mg/m^2/day$

Table 7: Annual Internal Loading Rate Utilized in Wabamun Lake BATHTUB Model

Variable	Wabamun Lake
Total Phosphorus ($mg/m^2/d$)	0.16

6 Simulation of Current Conditions

BATHTUB calculates a preliminary water balance and phosphorus budget from the data entered into the model; the results for Wabamun Lake are presented in Tables 8 and 9.

6.1 Water Balance

As noted in Section 3.0, the input hydrologic data were all based on the average long-term data for runoff, precipitation and evaporation; this helps to reduce hydrologic variability and creates a better steady state simulation.

The model calculates the total inflow and outflow based on the bathymetry, precipitation, evaporation, tributary volumes and change in storage data that were provided. BATHTUB also calculates an “advective outflow” which it describes as the water balance error (Table 8). In a perfectly calibrated model, the balance of all inflows and outflows should match the change in storage. When they do not match, the model calculates the positive or negative error as a volume and displays it as the advective outflow (in this case 8.7 hm^3). This volume is added (or subtracted if a negative volume) from the gauged outflow volume to give a new total outflow volume that reflects the total water balance data as provided. Uncertainty with the historic outflow estimates utilized may be the primary cause of the error value in this application to Wabamun Lake.

6.2 Preliminary Phosphorus Budget

The preliminary (uncalibrated) phosphorus budget calculated by BATHTUB is presented in Table 9. The total external phosphorus load is estimated at 8,034 kg and the internal load at 4,675 kg; the total load is estimated at 12,709 kg per year. Given the hydrologic and nutrient inputs discussed above, BATHTUB predicted an area – weighted (whole lake) mean total phosphorus (TP) concentration of 38 ppb.

Table 8: Water Balance for Wabamun Lake Calculated by BATHTUB

Trib. #	Type	Segment	Name	Area (km^2)	Flow (hm^3/yr)	Runoff (m/yr)
1	2	1	LC	51.0	4.2	0.08
2	2	1	SW1	4.5	0.4	0.08
3	2	1	SW2	3.5	0.3	0.08
4	2	1	SW3	2.5	0.2	0.08
5	2	1	SW4	2.1	0.2	0.08
6	2	1	SW5	4.8	0.4	0.08
7	2	1	SW6	0.4	0.0	0.08
8	2	1	SW7	0.6	0.0	0.08
9	2	1	SW8	11.8	1.0	0.08
10	2	1	SW9	1.1	0.1	0.08
11	2	1	SW10	0.6	0.0	0.08
12	2	1	SW11	2.5	0.2	0.08
13	2	1	SW12	2.3	0.2	0.08
14	2	1	SW13	0.6	0.1	0.08
15	2	1	SW14	1.5	0.1	0.08
16	2	1	SW15	15.5	1.3	0.08
17	2	1	SW16	0.1	0.0	0.08
18	2	1	SW17	30.5	2.5	0.08
19	2	1	SW18	1.3	0.1	0.08
20	2	1	SW19	1.9	0.2	0.08
21	2	1	SW20	25.9	2.1	0.08
22	2	1	SW21	0.4	0.0	0.08
23	2	1	SW22	8.3	0.7	0.08
24	2	1	SW23	43.1	3.5	0.08
25	4	1	Licenses		1.9	
26	4	1	Wabamun Creek Outflow	296.7	6.3	0.02
27	3	1	Water Treatment Plant		10.3	
PRECIPITATION				80.0	40.9	0.51
NONPOINT INFLOW				216.7	17.8	0.08
POINT-SOURCE INFLOW					10.3	
***TOTAL INFLOW				296.7	69.0	0.23
GAUGED OUTFLOW				296.7	8.3	0.03
ADVECTIVE OUTFLOW				0.0	8.7	876.06
***TOTAL OUTFLOW				296.7	17.0	0.06
***EVAPORATION					52.0	

Table 9: Preliminary (uncalibrated) TP budget calculated by BATHTUB for Wabamun Lake

Trib. #	Type	Segment	Name	Load (kg/yr)	% Total	Conc. (mg/m^3)	Export (kg/km^2/yr)
1	2	1	LC	1404.0	11.0	344.6	27.5
2	2	1	SW1	96.0	0.8	260.9	21.5
3	2	1	SW2	91.0	0.7	318.7	26.2
4	2	1	SW3	73.6	0.6	349.4	28.9
5	2	1	SW4	61.3	0.5	358.1	29.5
6	2	1	SW5	162.7	1.3	411.8	33.9
7	2	1	SW6	16.4	0.1	552.9	45.5
8	2	1	SW7	20.0	0.2	411.4	34.4
9	2	1	SW8	345.6	2.7	355.5	29.2
10	2	1	SW9	29.7	0.2	321.8	26.5
11	2	1	SW10	15.4	0.1	340.4	28.0
12	2	1	SW11	63.3	0.5	305.1	25.1
13	2	1	SW12	67.4	0.5	353.1	29.1
14	2	1	SW13	19.9	0.2	396.4	33.2
15	2	1	SW14	49.4	0.4	400.3	32.7
16	2	1	SW15	491.0	3.9	384.9	31.7
17	2	1	SW16	3.7	0.0	750.0	61.7
18	2	1	SW17	880.1	6.9	350.2	28.8
19	2	1	SW18	34.7	0.3	337.6	27.8
20	2	1	SW19	59.0	0.5	371.7	30.8
21	2	1	SW20	709.8	5.6	333.0	27.4
22	2	1	SW21	13.0	0.1	412.4	33.4
23	2	1	SW22	243.3	1.9	357.5	29.4
24	2	1	SW23	1158.9	9.1	326.8	26.9
25	4	1	Licenses	73.1		37.8	
26	4	1	Wabamun Creek Outflow	203.5		37.8	0.7
27	3	1	Water Treatment Plant	28.8	0.2	2.8	
PRECIPITATION				1896.0	14.9	46.4	23.7
INTERNAL LOAD				4675.2	36.8		
NONPOINT INFLOW				6109.2	48.1	342.6	28.2
POINT-SOURCE INFLOW				28.8	0.2	2.8	
***TOTAL INFLOW				12709.2	100.0	184.2	42.8
GAUGED OUTFLOW				276.6	2.2	37.8	0.9
ADVECTIVE OUTFLOW				365.9	2.9	37.8	36665.1
***TOTAL OUTFLOW				642.5	5.1	37.8	2.2
***RETENTION				12066.7	94.9		

Outflow Rate (m/yr)	0.2	Nutrient Resid. Time (yrs)	1.2133
Hydraulic Resid. Time (yrs)	24.0	Turnover Ratio	0.8
Reservoir Conc. (mg/m^3)	38	Retention Coef.	0.949

7 Calibration

The model's optional *calibration factors* were then applied to better align predicted and observed concentrations after initial set-up. Calibration is often needed because the model's Selections do not precisely represent the nutrient relationships that are observed in Alberta lakes (Section 4).

The initial "whole lake" model predictions for TP, TN, chlorophyll *a* and Secchi were 38 ppb, 465 ppb, 10.6 ppb and 1.1 m, respectively. The observed whole lake mean concentrations for TP, TN, chlorophyll *a* and Secchi were 30 ppb, 987 ppb, 10.7 ppb, and 2.2 m respectively. The initial model configuration over-predicted total phosphorus and under-predicted total nitrogen and Secchi depth; Chlorophyll *a* was well predicted. Calibration factors were then applied to align the predicted and observed data.

For phosphorus and nitrogen, BATHTUB used sedimentation rate adjustments; these factors are presented in Table 10. For chlorophyll *a* and Secchi depth, BATHTUB used simple multiplication factors to match the predicted and observed values; these are also presented in Table 10.

Table 10: Calibration Factors Applied to BATHTUB Predictions for Wabamun Lake

Variable	Wabamun Lake
Total Phosphorus	1.28
Total Nitrogen	0.405
Chlorophyll *a*	1.28
Secchi Depth	1.6

A particularly large calibration factor was required for TN. Nitrogen fixation and N-sediment release processes are not currently incorporated in the model processes for Alberta lakes. The calibration adjustment reduced phosphorus to observed levels which then required a re-adjustment of chlorophyll *a* values.

7.1 Calibrated Total Phosphorus Budget

The final, calibrated total phosphorus budget is presented in Table 11. Loadings from individual tributaries and all local contributing (LC) areas combined are presented. The total phosphorus budget is also summarized as a pie chart in Figure 2. The phosphorus budget estimated a total external load of 8,033 kg and internal load of 4,675 kg for a total of 12,709 kg per year.

Table 11: Calibrated total phosphorus budget for Wabamun Lake

Trib. #	Type	Segment	Name	Load (kg/yr)	% Total	Conc. (mg/m^3)	Export ($kg/km^2/yr$)
1	2	1	LC	1404.0	11.0	334.6	27.5
2	2	1	SW1	96.0	0.8	260.9	21.5
3	2	1	SW2	91.0	0.7	318.7	26.2
4	2	1	SW3	73.6	0.6	349.4	28.9
5	2	1	SW4	61.3	0.5	358.1	29.5
6	2	1	SW5	162.7	1.3	411.8	33.9
7	2	1	SW6	16.4	0.1	552.9	45.5
8	2	1	SW7	20.0	0.2	411.4	34.4
9	2	1	SW8	345.6	2.7	355.5	29.2
10	2	1	SW9	29.7	0.2	321.8	26.5
11	2	1	SW10	15.4	0.1	340.4	28.0
12	2	1	SW11	63.3	0.5	305.1	25.1
13	2	1	SW12	67.4	0.5	353.1	29.1
14	2	1	SW13	19.9	0.2	396.4	33.2
15	2	1	SW14	49.4	0.4	400.3	32.7
16	2	1	SW15	491.0	3.9	384.9	31.7
17	2	1	SW16	3.7	0.0	750.0	61.7
18	2	1	SW17	880.1	6.9	350.2	28.8
19	2	1	SW18	34.7	0.3	337.6	27.8
20	2	1	SW19	59.0	0.5	371.7	30.8
21	2	1	SW20	709.8	5.6	333.0	27.4
22	2	1	SW21	13.0	0.1	412.4	33.4
23	2	1	SW22	243.3	1.9	357.5	29.4
24	2	1	SW23	1158.9	9.1	326.8	26.9
25	4	1	Licenses	57.7		29.9	
26	4	1	Wabamun Creek Outflow	188.8		29.9	0.6
27	3	1	Water Treatment Plant	28.8	0.2	2.8	
PRECIPITATION				1896.0	14.9	46.4	23.7
INTERNAL LOAD				4675.2	36.8		
NONPOINT INFLOW				6109.2	48.1	342.6	28.2
POINT-SOURCE INFLOW				28.8	0.2	2.8	
***TOTAL INFLOW				12709.2	100.0	184.2	42.8
GAUGED OUTFLOW				246.5	1.9	29.9	0.8
ADVECTIVE OUTFLOW				261.0	2.1	29.9	26155.6
***TOTAL OUTFLOW				507.5	4	29.9	1.7
***RETENTION				12201.7	96.0		

Outflow Rate (m/yr)	0.2	Nutrient Resid. Time (yrs)	0.9585
Hydraulic Resid. Time (yrs)	24.0	Turnover Ratio	1.0
Reservoir Conc. (mg/m^3)	30	Retention Coef.	0.96

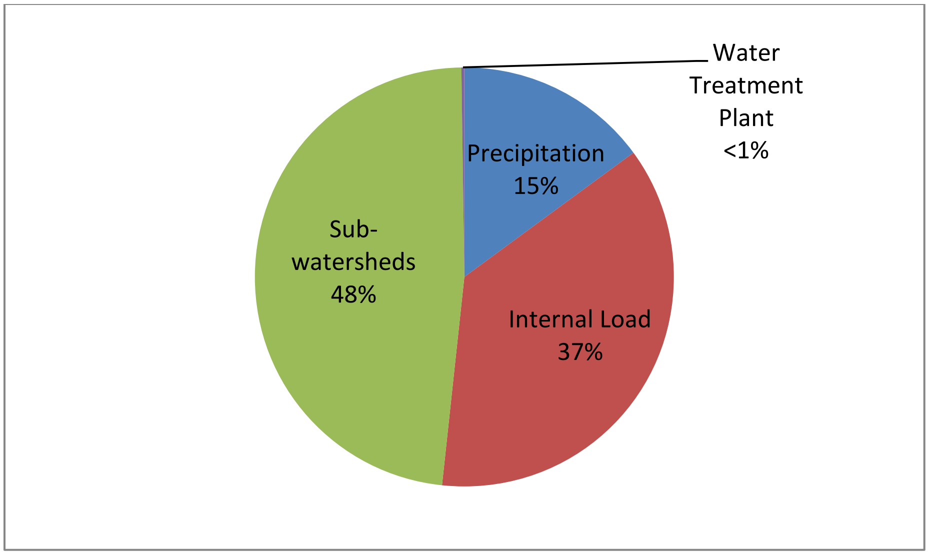


Figure 2: Total Phosphorus Budget for Wabamun Lake Calculated by BATHTUB

The detailed phosphorus loading data for individual tributaries are illustrated in a stacked column chart (Figure 3). The relative contributions to the phosphorus loads from agricultural, forested and developed lands within each tributary sub-watershed are illustrated within each column. The larger sub-watersheds with large proportions of agricultural and developed land will provide the largest phosphorus load to the lake. The highest loads are evident from the LC unit, and tributaries SW5, SW8, SW15, SW17, SW20 and SW23.

In the case of the single LC area (described as Tributary #1), the runoff is presumed to enter the lake diffusely. This combined area contains the largest amount of developed lands and is modelled as having the highest total phosphorus load running into the lake. Because of this, a secondary modelling analysis was conducted in which individual local contributing areas were delineated and assessed (Section 7.2).

BATHTUB also calculates a new flow-weighted annual total phosphorus concentration for each tributary, based on the final load and total flow, which in turn reflect the individual various land cover portions, AFWMCs and runoff data assigned to each tributary (Figure 4). Modelled stream concentrations above 400 mg/m^3 are shown in red and reflect tributary sub-watersheds with combinations of high agricultural and/or urban lands. Streams shown in yellow have total phosphorus concentrations in the range of 200-400 mg/m^3 and reflect tributary sub-watersheds with mixed/moderate levels of forested, agricultural and developed lands. Streams shown in green have total phosphorus concentrations below 200 mg/m^3 and reflect mainly forested lands with little/no development.

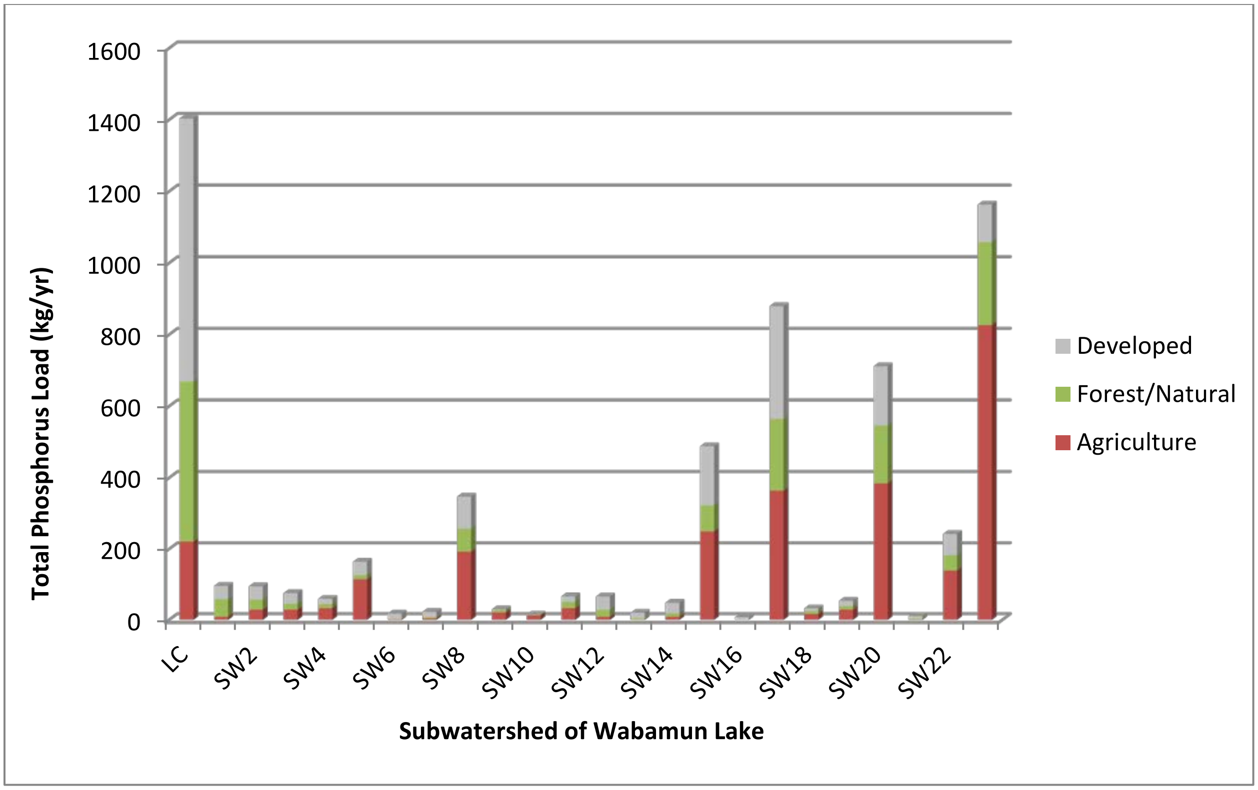


Figure 3: Total Phosphorus loads Calculated by BATHTUB for Tributaries of Wabamun Lake

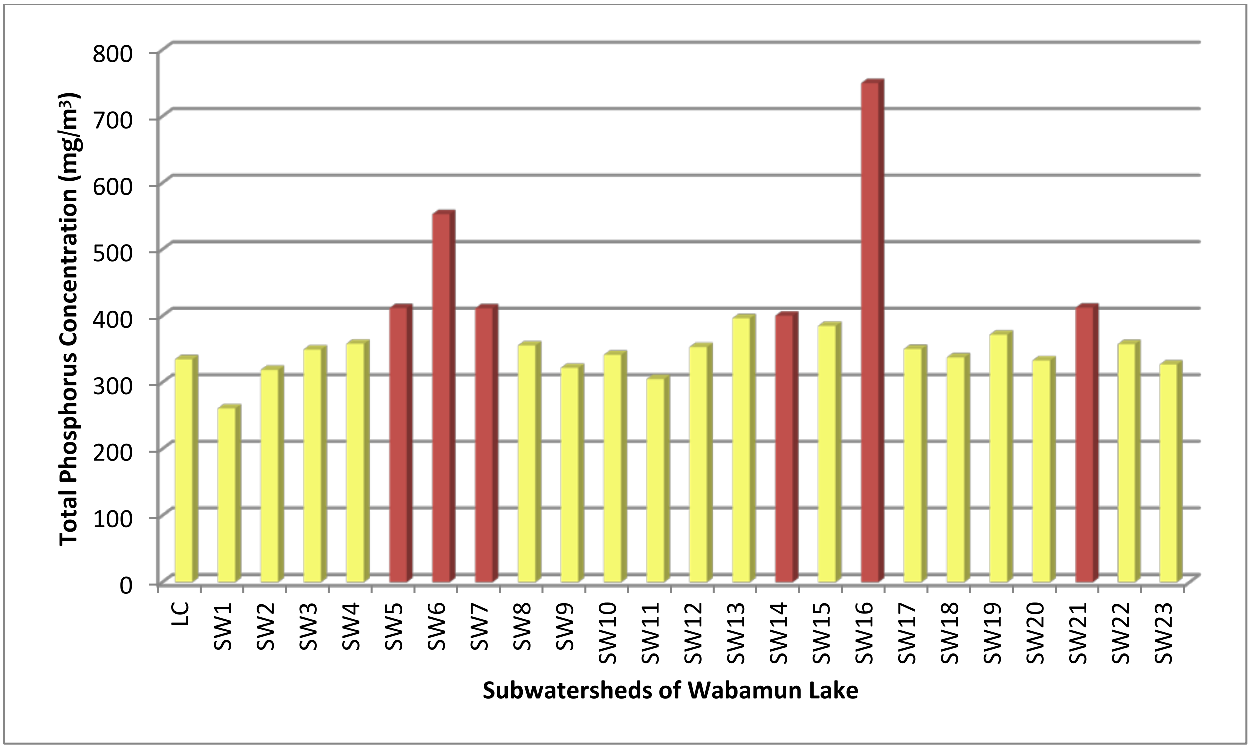


Figure 4: Flow-Weighted TP concentrations for the 23 (+LC1) Tributaries of Wabamun Lake

7.2 Local Contributing (LC) Areas

The single LC area was further sub-divided between each of the subwatersheds to create 22 individual LC areas. The amounts of agricultural, forested and developed land were determined for each LC area by ArcGIS. The same runoff and AFWMCs values were used for the land cover areas and the model was run with this further refinement to determine which LC areas would contribute most to the annual total phosphorus load (Figure 5).

Similar to the analysis of the phosphorus loads and concentrations for tributaries, the local contributing areas that are the largest, and which contain the most developed and agricultural lands, have the greatest loading potential. The flow weighted phosphorus concentration for the LC areas (Figure 6) are higher compared to the average for the tributaries (Figure 4) because the majority of urban development is located in the LC areas (LC6, LC15, LC16, LC17, and LC18).

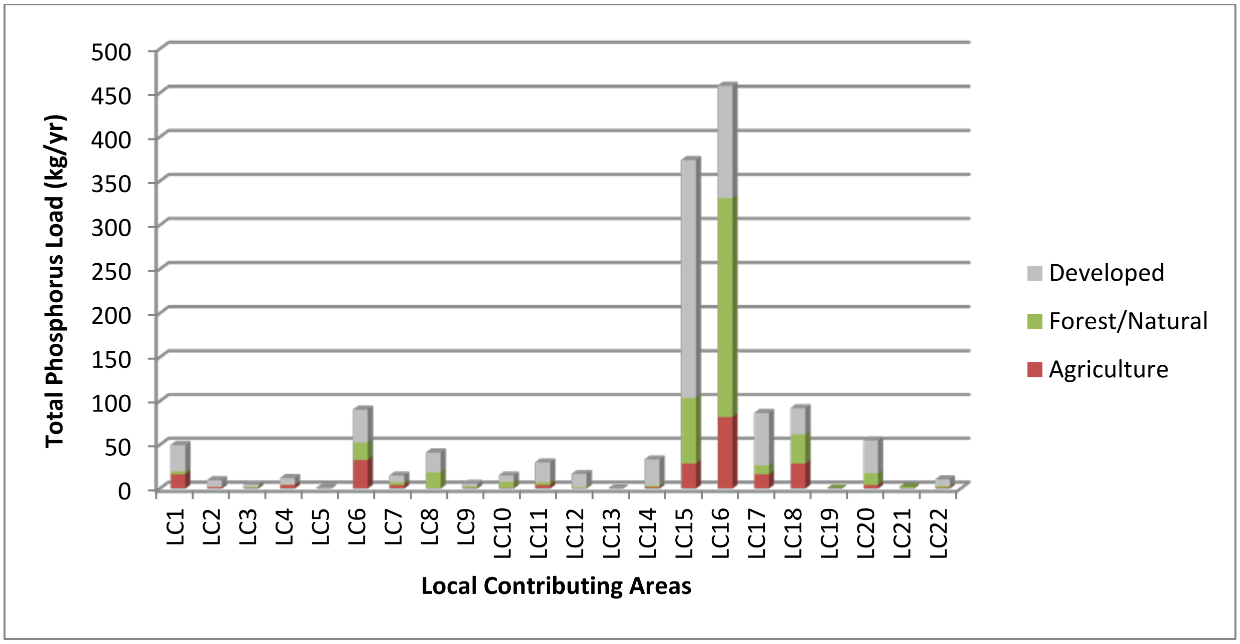


Figure 5: TP Loads Calculated by Bathtub for the 22 Local Contributing Areas at Wabamun

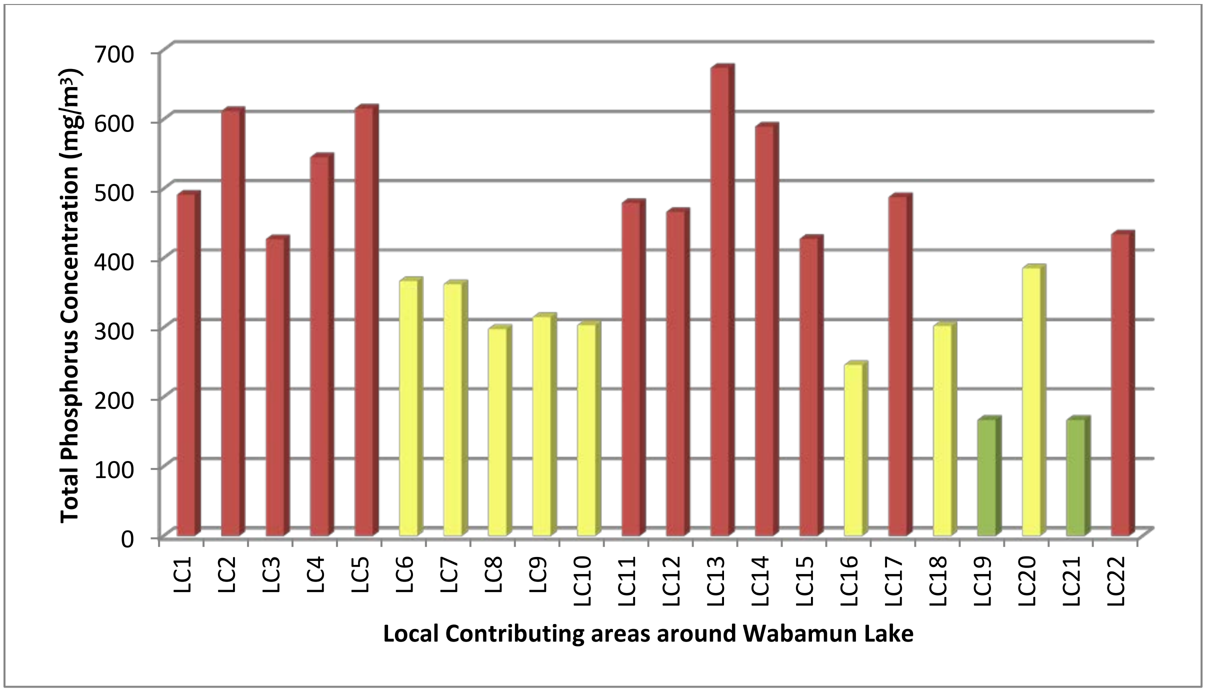


Figure 6: Flow Weighted TP concentrations for 22 local contributing areas around Wabamun

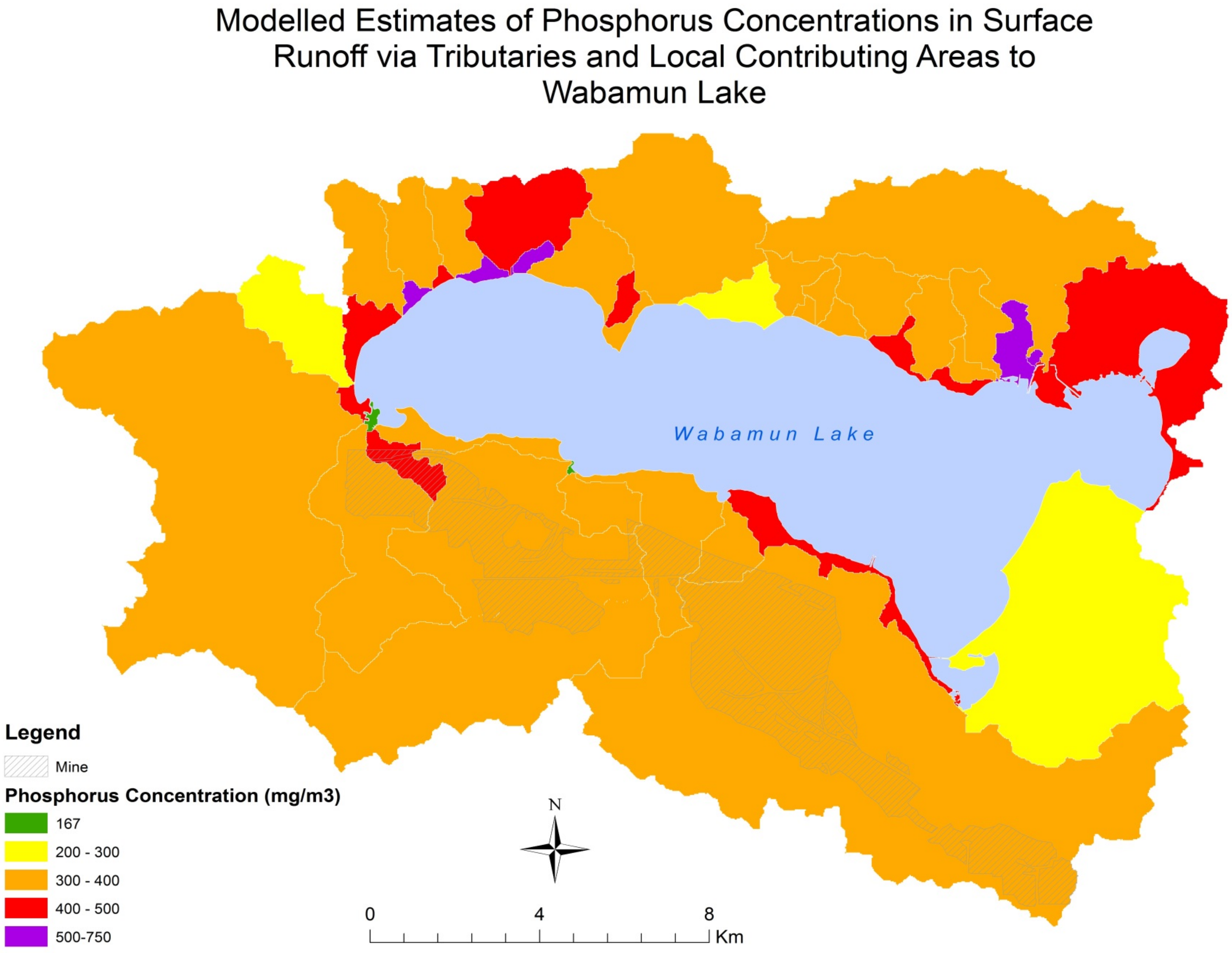
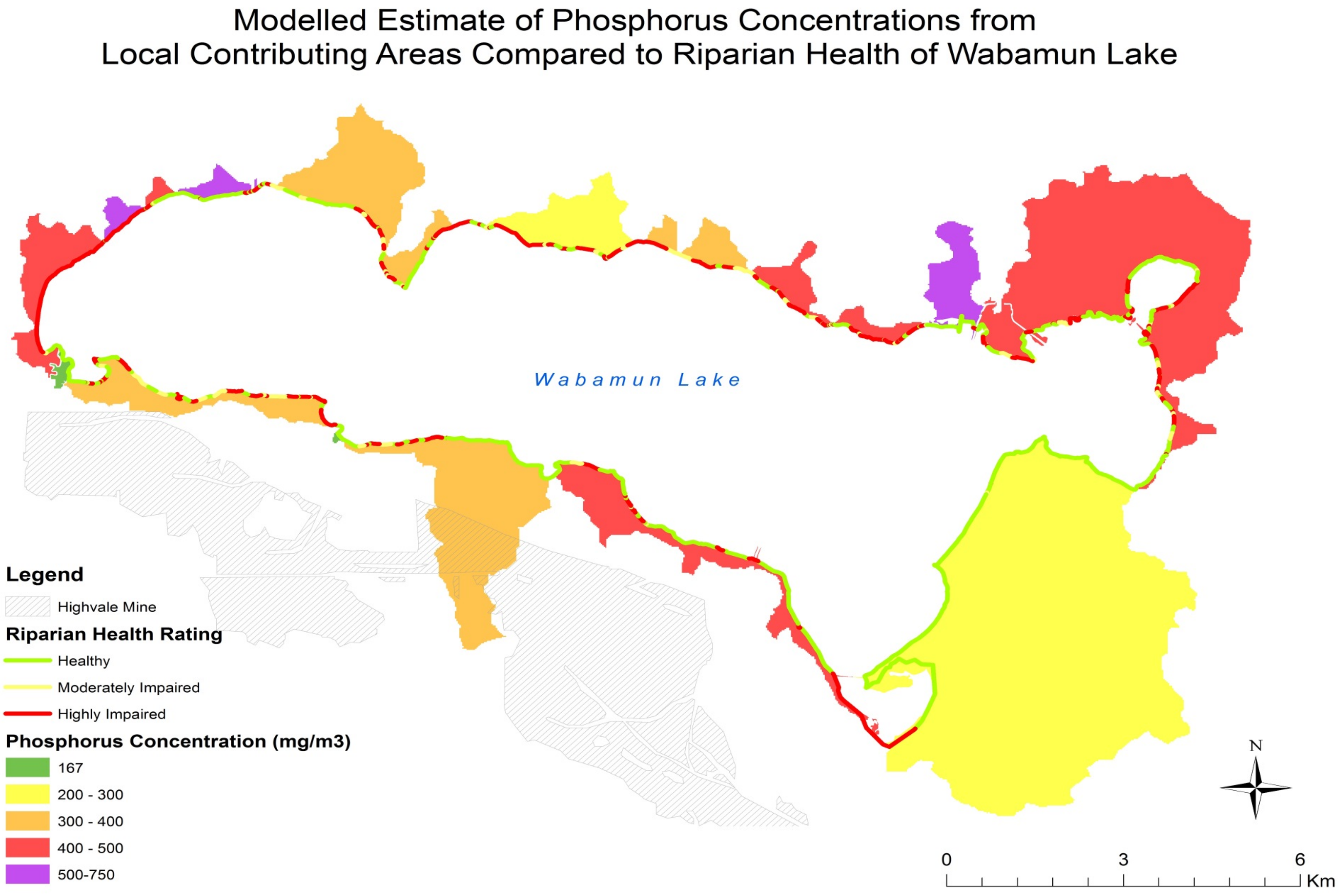


Figure 7: Flow-weighted TP Concentrations for all Tributaries and Local Contributing Areas (LC) at Wabamun Lake



Modelled Estimate of Phosphorus Concentrations from Local Contributing Areas Compared to Riparian Health of Wabamun Lake

Figure 8: Comparison of Flow-weighted TP Concentrations for Local Contributing Areas with Riparian Health Conditions at Wabamun Lake

7.3 Comparison of phosphorus loads from LC areas with Riparian Health

The phosphorus runoff analysis for LC areas was compared with an independent evaluation of shoreline riparian health at Wabamun Lake (Shain 2015). An overlay of colour coded maps from each assessment was prepared (Figure 8). The results identify areas of coincidental environmental risk, and may warrant further evaluation.

8 Future Scenarios

As described in Section 2, future development and restoration scenarios can be evaluated using the calibrated model. Note: these future scenarios should be considered as arbitrary and preliminary, and are simply intended to provide insights to support further watershed management discussions.

For Wabamun Lake, four scenario types were developed and run over three year or five year projections. In the agricultural development scenario all forested/natural land areas in each of tributaries and the (combined) LC unit were converted to agricultural land cover. In the "restoration" scenario, the agricultural land areas in each of the sub-watershed units were converted to forested/natural land cover. In the urban development scenario, the urban area was doubled for the first year and the original area is converted again for each of the ensuing two years; this expanding area is developed (subtracted) from the forest/natural land cover portion. Appropriate nutrient runoff estimates (Table 5) are applied to simulate the land cover changes.

In the mine "reclamation" scenario, the exposed land that was not included in the original model set-up was re-introduced and converted 50% to agricultural and 50% to forested/natural land, respectively. Diversions into the lake from the water treatment plant were proportionally reduced as the mine lands were incrementally reclaimed, with the assumption that hydrologic functions in mined areas were completely restored during land reclamation. Agricultural, forested and urban land cover portions in the remainder of the watershed were left unchanged in this scenario.

8.1 Agricultural Development Scenario

In the agricultural development scenario, the land cover is converted over a 5 year period. Each year 20% of the forest/natural land located in each of the tributary sub-watersheds is converted to agricultural land cover until there is 100% conversion after 5 years. This is done for each of the sub-watersheds and the LC area. The runoff value was not changed for these tributaries during the development scenario.

Calculation example: LC year 1

Current forest/natural area = 32.52 km^2
Current agriculture area = 6.50 km^2
Yearly increase = 32.52 * 0.2 = 6.5 km^2
Year 1 forest/natural area = 32.52 – 6.5 = 26.02 km^2
Year 1 agriculture area = 6.5 + 6.5 = 13 km^2
Therefore 6.5 km^2 is added incrementally to the agriculture land cover area each year.

The model is then run for the first annual time step, with the initial (Year 1) land cover data to predict a new lake concentration. For Year 2, the predicted lake TP and other nutrients from Year 1 are entered as the new "observed" lake nutrient concentrations and the land cover areas incorporate the second annual increment, etc. This process of annual adjustment is continued to achieve the cumulative change over the 5 year scenario.

The calibrated sub-watershed loading provided by BATHTUB is 6,109 kg/yr and represents 48% out of the total load of 12,709 kg/yr (Table 11). The sub-watershed loading calculated for the end of the 5 year agricultural development scenario is 8,181 kg/yr, which is 55% of the total load of 14,781 kg/yr (Table 12). The net loading increase is 2,072 kg/yr in the agricultural development scenario. The predicted lake concentration results are presented in Table 13 and illustrated in Figure 9.

Table 12: Predicted Total Phosphorus Loads in the Agricultural Development Scenario

Component	Load (kg/yr)	% Total
Precipitation	1,896.0	12.8
Internal Load	4,675.2	31.6
Nonpoint Inflow	8,181.4	55.3
Point-source Inflow	28.8	0.2
Total Inflow	14,781.3	100.0

Table 13: Predicted Lake Concentrations in Agricultural Development Scenario

Variable	Current	Year 1	Year 2	Year 3	Year 4	Year 5
TP (ppb)	29.9	30.4	30.9	31.5	32	32.5
TN (ppb)	987.7	1003	1017.9	1032.7	1047.2	1061.6
Chl-*a* (ppb)	10.7	10.9	11.1	11.3	11.5	11.6
Secchi (m)	2.2	2.1	2.1	2.1	2	2

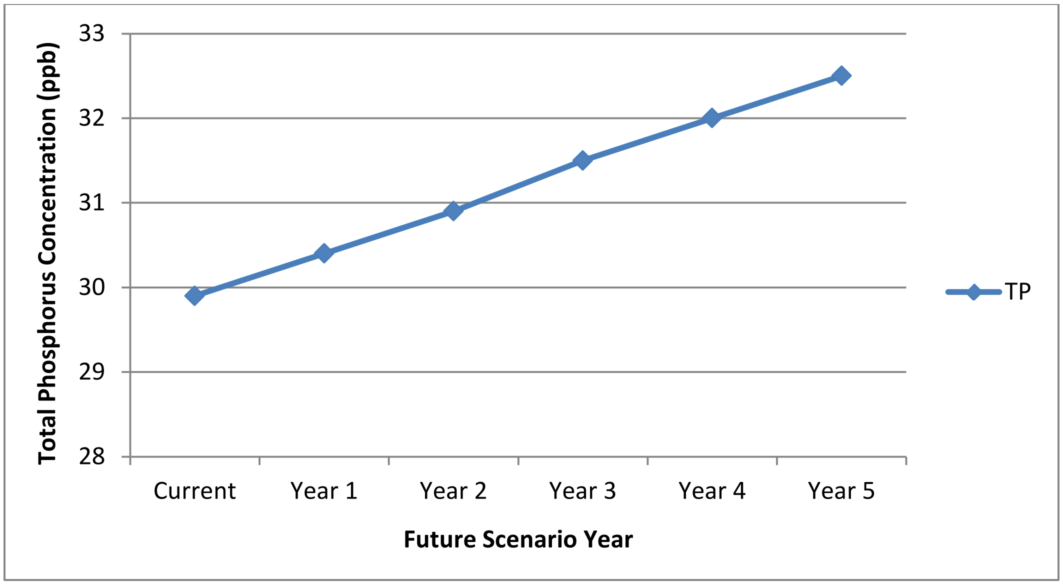


Figure 9: Predicted Total Phosphorus Trend for the Agricultural Development Scenario at Wabamun Lake

The results of the agricultural development scenario show a slight increase in predicted TP above the current observed concentration in Wabamun Lake. Almost half of the Wabamun watershed is currently forested/natural areas (48%); after the conversion the watershed becomes 85% agricultural which explains the predicted increase. However this external loading increase appears to have limited impact because internal loading is still the major contributor to the overall TP load calculation.

8.2 Restoration Scenario

In the restoration scenario, the current agricultural land cover is converted to forest/natural area over a 5 year period. Again, 20% of the agricultural land is converted to forest/natural areas each year until 100% of the land is converted for each of the sub-watersheds and the LC area.

Calculation example: LC

Current forest/natural area = 32.52 km^2
Current agriculture area = 6.50 km^2
Yearly increase = 6.5 * 0.2 = 1.3 km^2
Year 1 forest/natural area = 32.52 + 1.3 = 33.82 km^2
Year 1 agriculture area = 6.5 – 1.3 = 5.2 km^2
Therefore 1.3 km^2 is added to the forest/natural land cover area each year.

The model was run for the first annual time step, with the initial (Year 1) land cover data changed to predict a new lake concentration. For Year 2, the predicted lake TP (and other nutrients from Year 1) were entered as the new “observed” lake nutrient concentrations and the land cover areas incorporate the second annual decrement, etc. This process of annual adjustment is continued to achieve the cumulative land cover change and impact over the 5 year scenario.

The calibrated sub-watershed loading calculated by BATHTUB is 6,109 kg/yr and represents 48% out of the total load of 12,709 kg/yr (Table 11). The sub-watershed loading calculated for the end of the 5 year restoration scenario is 4,500 kg/yr which represents 40.5% of the total loading of 11,100 kg/yr (Table 14). The net loading decrease is 1,609 kg/yr in the restoration scenario. The predicted lake concentration results are presented in Table 15 and illustrated in Figure 10.

Table 14: Predicted TP Loads in the Restoration Scenario

Component	Load (kg/yr)	% Total
Precipitation	1,896.0	17.1
Internal Load	4,675.2	42.1
Nonpoint Inflow	4,500.3	40.5
Point-source Inflow	28.8	0.3
Total Inflow	11,100.3	100.0

Table 15: Predicted Lake Concentrations in the Restoration Scenario

Variable	Current	Year 1	Year 2	Year 3	Year 4	Year 5
TP (ppb)	29.9	29.4	29	28.6	28.1	27.7
TN (ppb)	987.7	975.8	963.6	951.4	938.9	926.3
Chl-a (ppb)	10.7	10.5	10.4	10.2	10.1	9.9
Secchi (m)	2.2	2.2	2.2	2.2	2.3	2.3

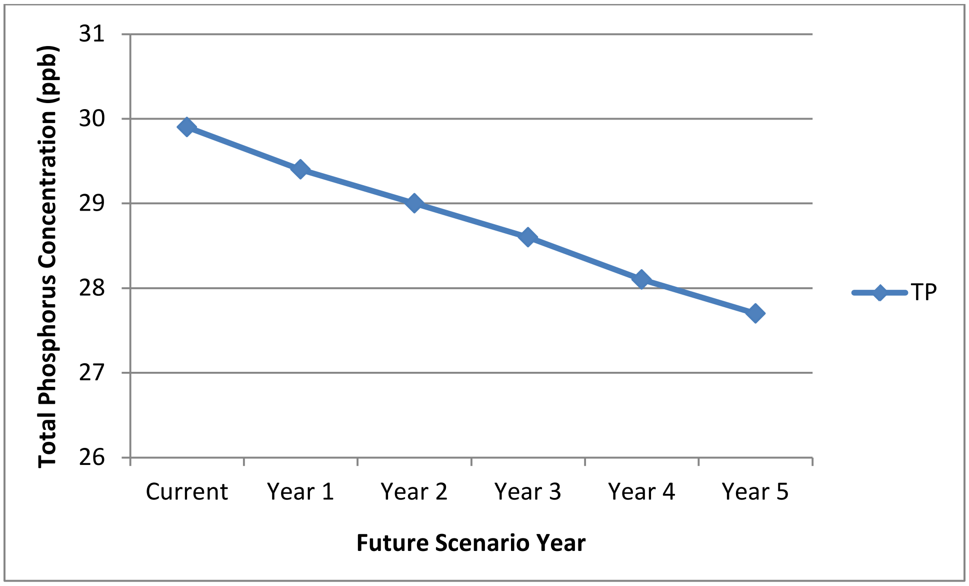


Figure 10: Predicted TP Trend Calculated for the Restoration Scenario at Wabamun Lake

The restoration scenario results in Table 15 and Figure 10 show a slight decline in the predicted lake total phosphorous concentration and this decline is relatively similar in magnitude to the lake TP increase predicted in the development scenario. Again, this may be reflective of the presence of significant internal loading and long-term retention of phosphorus in the lake. Even when the external TP inputs to the lake decrease, internal loading appears to remain significant.

8.3 Urban Development Scenario

In the "urban" development scenario, the natural land cover was changed to "urban developed" land cover over a 3 year period. For this scenario, the current urban land area was doubled in the first year of the scenario and then this same incremental increase was applied again in years two and three. The incremental area that is added to the developed land cover is subtracted from the forest/natural land cover. The agricultural land area remains constant in this scenario. In cases where there is not enough land left to remove the increment from the forest/natural areas, the net remaining area is converted and the scenario is completed for that land unit. This process is followed for each of the sub-watersheds and the LC area.

Calculation example: LC
Current developed area = 11.96 km^2
Current forest/natural area = 32.52 km^2
Yearly increase = 11.96 km^2
Year 1 developed area = 11.96 + 11.96 = 23.91 km^2
Year 1 forest/natural area = 32.52 – 11.96 = 20.56 km^2
A further 11.96 km^2 is added to the developed land cover area in Year 2.
Year 2 remaining forest/natural area = 8.6 km^2
Year 3 developed area = 35.87+ 8.6 = 44.47 km^2

The model was then run for the first annual time step, with the initial (Year 1) land cover data to predict a new lake concentration. For Year 2, the predicted lake TP and other nutrients from Year 1 are entered as the new "observed" lake nutrient concentrations and the land cover areas incorporate the second annual increment, etc. This process of annual adjustment is continued to achieve the cumulative change and predicted effect over the 3 year scenario.

The calibrated sub-watershed loading was 6,109 kg/yr and represents 48% of the total load of 12,709 kg/yr (Table 11). The sub-watershed loading calculated for the end of the 3 year urban scenario is 10,147 kg/yr which represents 60.6% of the total loading of 16,747 kg/yr (Table 16). The net loading increase is 4,038 kg/yr in the urban scenario. The predicted lake concentration results are presented in Table 17 and illustrated in Figure 11.

Table 16: TP Loads Calculated by BATHTUB for the Urban Development Scenario

Component	Load (kg/yr)	% Total
Precipitation	1,896.0	11.3
Internal Load	4,675.2	27.9
Nonpoint Inflow	10,147.2	60.6
Point-source Inflow	28.8	0.2
Total Inflow	16,747.1	100.0

Table 17: Lake Concentrations Calculated by BATHTUB for the Urban Development Scenario

Variable	Current	Year 1	Year 2	Year 3
TP (ppb)	29.9	31.8	33.6	34.8
TN (ppb)	987.7	1025.2	1060	1084.7
Chl-a (ppb)	10.7	11.4	12	12.5
Secchi (m)	2.2	2.1	2	1.9

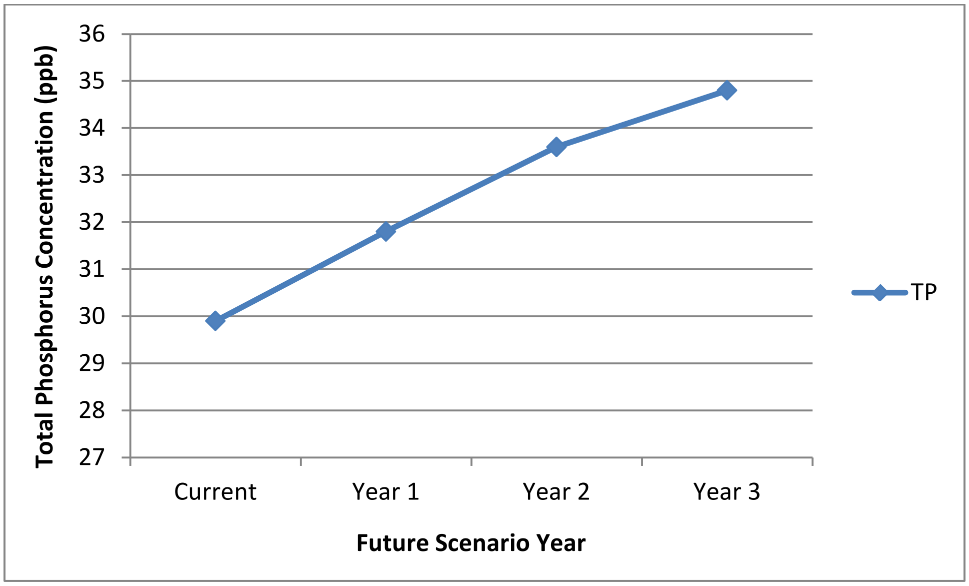


Figure 11: Predicted TP Trend Calculated for Urban Development Scenario at Wabamun Lake

The results of the urban development scenario show a slight increase in predicted TP over the agricultural development scenario. This is due to the high AFWMC used when converting forest land cover to that of “developed’.

8.4 Mine Reclamation Scenario with Water Treatment Plant Diversion Reduction

The Highvale mine areas were excluded from the restoration, agricultural development and urban development scenario model runs because the mine does not contribute hydrologically to Wabamun Lake. Some streams that originate upstream (south) from mined areas flow through the mine intact and reach the lake; those natural watershed areas south of the mine were included in the initial model set up. However, runoff within the mine site that comes in contact with mine soils is captured and sent to the cooling ponds for treatment. The water treatment plant was constructed to offset the hydrologic deficit that was created from the removal of contaminated water from the mined portion of the watershed.

In the mine “reclamation” scenario, the land cover from the current mining areas was converted 50-50 to agricultural and forested, respectively, over a 5 year period. For the sub-watersheds that were identified as having mining areas located in them (exposed land cover classification), mined areas were divided in half and that value multiplied by 20% to determine the annual increase in land being converted to each new land cover type. At the same time, the diversion from the water treatment plant into Wabamun Lake was decreased 20% annually to simulate new runoff entering the lake from the reclaimed areas. The average runoff value used throughout the modelling exercise was not changed for these tributaries, the assumption being that hydrologic function would be immediately restored.

Calculation example: LC year 1
Current mine area = 1.66 km^2
Current agriculture area = 6.50 km^2
Current forest/natural area = 32.52 km^2
Yearly increase = (1.66/2) * 0.2 = 0.17 km^2
Year 1 agriculture area = 6.5 + 0.17 = 6.67 km^2
Year 1 forest/natural area = 32.52 +0.17 = 32.69 km^2
Therefore 0.17 km^2 is added to the agriculture and forest/natural land cover area each year.
Annual water treatment plant reduction = 10.27 hm^3 * 0.2 = 2.05 hm^3
Year 1 water treatment plant flow = 10.27 – 2.05 = 8.22 hm^3

The model was then run for the first annual time step, with the initial (Year 1) land cover data and predicted a new lake concentration. For Year 2, the predicted lake TP and other nutrients from Year 1 are entered as the new “observed” lake nutrient concentrations and the land cover areas incorporate the second annual increment, etc. This process of annual adjustment is continued to achieve the cumulative effect over the 5 year scenario.

The calibrated sub-watershed loading calculated by BATHTUB was 6,109 kg/yr and represents 48% out of the total load of 12,709 kg/yr (Table 11). The sub-watershed loading calculated for the end of the 5 year mine reclamation scenario was 6,949 kg/yr which is 51.4% out of total load of 13,520 kg/yr (Table

18). The net loading increase was 811 kg/yr in the mine reclamation scenario. The predicted lake results are presented in Table 19 and illustrated in Figure 12.

Table 18: TP Loads Calculated by BATHTUB for the Mine Reclamation Scenario

Component	Load (kg/yr)	% Total
Precipitation	1,896.0	14.0
Internal Load	4,675.2	34.6
Nonpoint Inflow	6,949.4	51.4
Total Inflow	13,520.6	100.0

Table 19: Lake Concentrations Calculated by BATHTUB for the Mine Reclamation Scenario

Variable	Current	Year 1	Year 2	Year 3	Year 4	Year 5
TP (ppb)	29.9	30.2	30.5	30.8	31.1	31.4
TN (ppb)	987.7	1010.9	1034.9	1059.8	1085.7	1113
Chl-a (ppb)	10.7	10.8	10.9	11	11.2	11.3
Secchi (m)	2.2	2.1	2.1	2.1	2.1	2.1

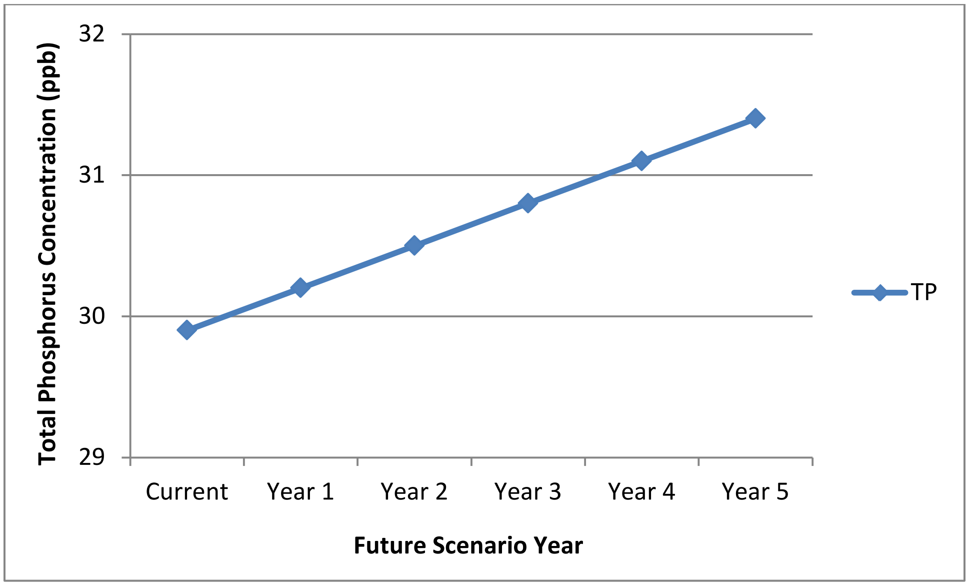


Figure 12: Mine scenario total phosphorus trend results for Wabamun Lake

The results of the mine scenario show a slight increase in predicted TP, but the lowest increase of all the scenarios applied to Wabamun Lake in this modelling exercise (note: all current land cover types in the remainder of the watershed were unchanged in this specific mine reclamation scenario - a very conservative assumption). The increase occurs because land area that had been hydrologically isolated from the watershed would slowly be re-incorporated into the lake water and nutrient budget. This “new” runoff contains TP AFWMCs that are much higher than that of the current diversion water to the lake from the water treatment plant. This scenario presumes that after mine reclamation the water treatment plant would no longer divert water to the lake, and would no longer create the dilution effect that it has been having on lake TP since it first became operational in 1997.

9 Discussion and Conclusion

The application of BATHTUB to Wabamun Lake provided an opportunity to assess the suitability of the model for this lake as well as the adequacy of current hydrologic and nutrient data available. The calibrated phosphorus and hydrologic budgets appear reasonable, given the data available and our overall knowledge of the system. Small calibration factors were needed to align predicted and observed lake TP, which provides further confidence in the overall hydrology, morphometry and nutrient loading data used to calibrate the model.

Reducing error in the water balance helps to create a more accurate phosphorus budget. Given the high year to year variability in Alberta climate and runoff data it is preferable to use longer term hydrologic data when they are available, as was the case in this project. To further improve the application of the model to Wabamun Lake, a better understanding of the long-term outflow volume and its effect on the changing lake level would be helpful.

Bathtub was applied at a coarse scale in this application. There was no attempt to segment the lake between inshore and offshore regions, or to differentiate between east and west basins. Given the large size of the system, segmentation could be considered in future modelling exercises.

Wabamun Lake has a small watershed compared to the size of the lake (4:1) and a moderate flushing rate. External loading is important, but internal loading currently plays a major role in the overall observed water quality.

The scenarios illustrated in this report are arbitrary, and intended to demonstrate predictive approaches using BATHTUB. The simple, independent scenarios involving land cover changes appeared to have modest effects on lake TP, but more complex and integrated development/reclamation scenarios could be developed; those scenarios could induce larger potential changes in lake water quality.

The recreational, urban development, agricultural and industrial pressures on this lake are significant and must be managed so that the current water quality in the lake is maintained. Good water quality is crucial to ensuring the recreational value that Wabamun currently offers to local residents and visitors. The current average phosphorus levels of approximately 30 mg/m^3 should be rigorously protected.

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