Nutrient Exports from land-use in Shuswap and Salmon Rivers and

Paleo-reconstruction of Historic Phosphorus Loading and Water Quality in Mara Lake

PROJECT SUMMARY

Megan Ludwig | Nicholas Hebda | Ian Walker | Jeff Curtis | April 2020

This Report summarizes and synthesizes the major findings from separate studies of phosphorus mass balances in the Shuswap River, of phosphorus mass balance in the Salmon River, and a paleo-reconstruction of changes in both nutrient loading from the Shuswap River and the resultant diatom community in Mara Lake. The three studies that inform this document are:

Ludwig, M and PJ Curtis 2020. Phosphorus Budget for the Shuswap River

Ludwig, M and PJ Curtis 2020 Phosphorus Budget for the Salmon River

Hebda, N, IW Walker, and PJ Curtis (in prep.) Paleo-reconstruction of historic phosphorus loading and diatom community in Mara Lake.

Raw data are available through the Shuswap Watershed Council.

Sources of Phosphorus in the Shuswap and Salmon River Watersheds

The Shuswap River contributes almost three times the amount of phosphorus to the Shuswap/Mara Lake system than does the Salmon River (7 X 10^4 and 2.5 X 10^4 kg y^{-1}, respectively). Contributions of water for the Shuswap River were more than ten times higher than that for the Salmon River (3.4 X 10^8 and 2.4 X 10^7 m^3 y^{-1}, respectively). The difference in contributions of phosphorus relative to water between these rivers was reflected in the difference in the volume-weighted average concentration (P loading, mg $year^{-1}$ divided by the annual discharge, m^3 y^{-1}). Volume-weighted average concentration was about 5 times lower in the Shuswap River than in the Salmon River (20 and 100 mg m^{-3}, respectively). In general, phosphorus levels in the Shuswap River increased with river distance from Mable Lake from the addition of water from tributary watersheds and incremental flow sub-watersheds.

Concentrations of phosphorus from undisturbed watersheds are in the concentration range 0.001-0.035 mg L^{-1}. In contrast, water bodies with concentrations of total phosphorus (TP) above 0.1 mg L^{-1} are considered at risk of eutrophication (Environment Canada, 2009). The range of concentrations for undisturbed watersheds is very large and encompasses an expected lake trophic status anywhere from very unproductive with low abundances of algae (oligotrophic) to moderately productive with moderate abundances of algae (mesotrophic, bordering on eutrophic). There is considerable variability in the response of systems to nutrient loading that depends on physical factors such as size, volume and flushing rate (Wolf and Klaiber, 2017).

The volume-weighted average TP concentration and the majority of individual TP samples from the Shuswap River (mean 0.024 mg L^{-1}, and CV 67%, at km 73) had a concentration of TP less than 0.035 mg L^{-1}, or within the reference range for TP concentration (0-0.035 mg L^{-1}) defined by Environment Canada (2009) to be indicative of an undisturbed watershed. Only two of more than one hundred samples from Shuswap River (Mara km 73) had a concentration above the 0.1 mg L^{-1} threshold for eutrophication risk.

In contrast, the volume-weighted average concentration and the majority of individual TP samples from the Salmon River had TP concentration above the reference range of 0.0-0.035 mg L^{-1} (mean 0.09 mg L^{-1}, and CV 103%, at km 66). The volume-weighted average concentration and about a third of samples from the Salmon River had a concentration above the 0.1 mg L^{-1} threshold for eutrophication risk.

Many of the samples above the 0.1 mg L^{-1} threshold in the Salmon River were at the 0 km site, and the concentration generally decreased before it reached the outlet into Shuswap Lake. This decrease was observed in part because the tributaries and incremental flow sub-watersheds diluted the P-rich water from km 0 with less P-rich water, but also there was an apparent loss of phosphorus down-stream, or a further dilution of the river by exchange with groundwater containing less phosphorus. These processes are not mutually exclusive and both may have been operating.

Phosphorus Yield

The difference in the km 0 phosphorus contribution between the rivers is especially apparent when the contribution is expressed per unit of watershed area, or phosphorus yield (kg ha^{-1} y^{-1}). Yields of phosphorus above 0 km were very low for the Shuswap (Mable Lake, 0.1kg ha^{-1} y^{-1}) relative to yields of phosphorus at 0 km in the Salmon River (Falkland, 0.425 kg ha^{-1} y^{-1}). The differences are caused by removal of phosphorus in Mabel (and Sugar) Lake for the Shuswap River, and extensive exchange with the Westwold aquifer, and land disturbance in the Salmon River above km 0.

We explored the potential for land-use change to enhance P concentration and loading for both rivers. Portions of phosphorus loading were assigned statistically to agricultural, urban and forest land use within incremental flow sub-watersheds (IFSW). Details of this analysis are described elsewhere (Ludwig, 2018). The forested component contributed 0.05 kg ha^{-1} y^{-1} of phosphorus, very similar to that from undisturbed tributaries (0.1 kg ha^{-1} y^{-1}), and considerably lower than our estimates of P yield from

IFSW. The contributions from disturbed portions of the incremental flow sub-watersheds were 2.7 and 9.4 kg ha^{-1} y^{-1} for urban and agricultural land-uses, respectively.

The yield range for urban land use varies by intensity and type, with a typical TP export range of 0.5-20.8 kg ha^{-1} y^{-1} (Reckhow et al., 1980; Johnes, 1996; Worrall & Burt, 1999; Bernald et al., 2003). Our estimates were on the lower end of the TP export range, likely due to the non-intensive urban land use. The yield range for agriculture land use depends similarly on type and intensity but is usually within the range of 0.5-15.6 kg ha^{-1} y^{-1} (ibid.). Our estimates for agriculture TP export were on the midrange for agriculture and probably reflect the combination of weighted export coefficients for different agricultural export coefficients (Figure 1).

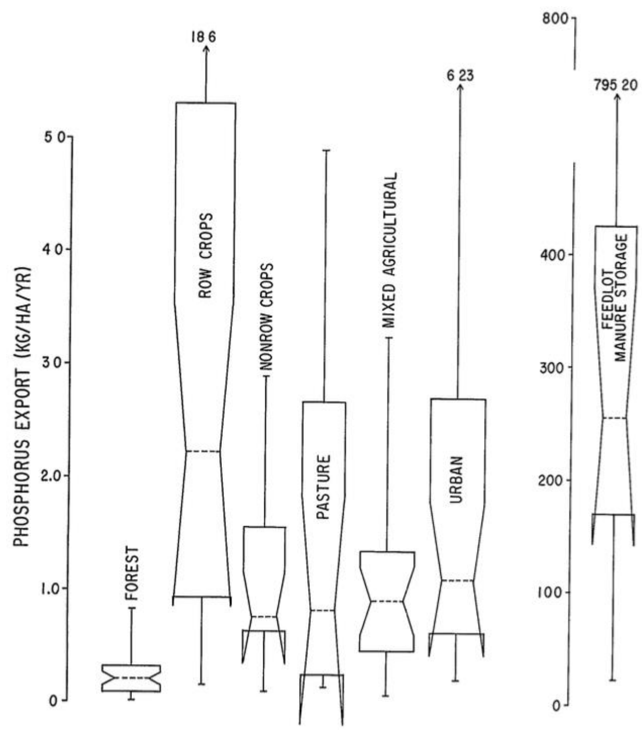

Figure 1. Box plots of phosphorus export coefficients for modelers (reproduced from US EPA, Reckow et al., 1980).

If we consider the rivers together as a source of phosphorus to the Shuswap/Mara Lake system, the volume-weighted average concentration becomes 69 mg m^{-3}, and above the range of expected concentrations for relatively undisturbed watersheds, but below the risk of eutrophic conditions (Environment Canada, 2009). This concentration is consistent with elevated productivity and potentially meso-eutrophic conditions (OECD). If we assume that pre-cultural undisturbed watershed contributed 0.05 kg ha^{-1} y^{-1}, and apply this yield to land presently in urban or agricultural land use, then the minimum volume-weighted concentration would be about 10 mg m^{-3} or 15% of the concentration today.

To evaluate the assumption that undisturbed background yields were applicable to pre-cultural yields of phosphorus from land presently in urban and agricultural land uses, we conducted a paleolimnological study of Mara Lake. This study is reported in detail elsewhere (Hebda et al., in prep). Briefly, we collected two cores and dated sections radiometrically, to reconstruct the the history of phosphorus loading and fossil indicators of changes in trophic state in Mara Lake. The first was a gravity core designed to sample surficial sediments at high resolution. This corer only penetrated sediments to 23 cm owing to the stiffness of the sediments. The second core was a percussion core intended to collect sediments dating to before significant land use changes. Percussion corers tend to liquefy surface sediments and only collect relatively stiff sediments.

Cores were sectioned into intervals (mostly 1 cm thick). The intervals were analyzed radiometrically by Flett Research. Dates were determined from 210-Pb activity by the slope regression model (Flett Research). The sediments in the first core dated from about 1980 to present. The second core provided samples that were <1860 and <1760. Subsamples of the intervals were analyzed for total phosphorus, and for microfossils of siliceous algae (diatoms and chrysophytes). Methods are described in detail elsewhere (Hebda et al., in prep). Sedimentation rates determined from radiometric dating were relatively high with an average rate of about 0.223 g cm^{-2} y^{-1}.

Phosphorus accumulation in Mara Lake sediments increases by about 20% from 1980 to the the present day (Figure 2). This is broadly consistent with the observation of increasing nutrient levels in Mara Lake (Northwest Hydraulic Consultants, 2010).

Because phosphorus accumulation depends on loading, and loading depends significantly on discharge, we tested the hypothesis that discharge increases might have caused the increase in phosphorus accumulation. Discharge over the period 1980 to present was independent of time (Figure 3; data from Water Survey of Canada). Thus, contemporary increases in phosphorus accumulation are independent of discharge.

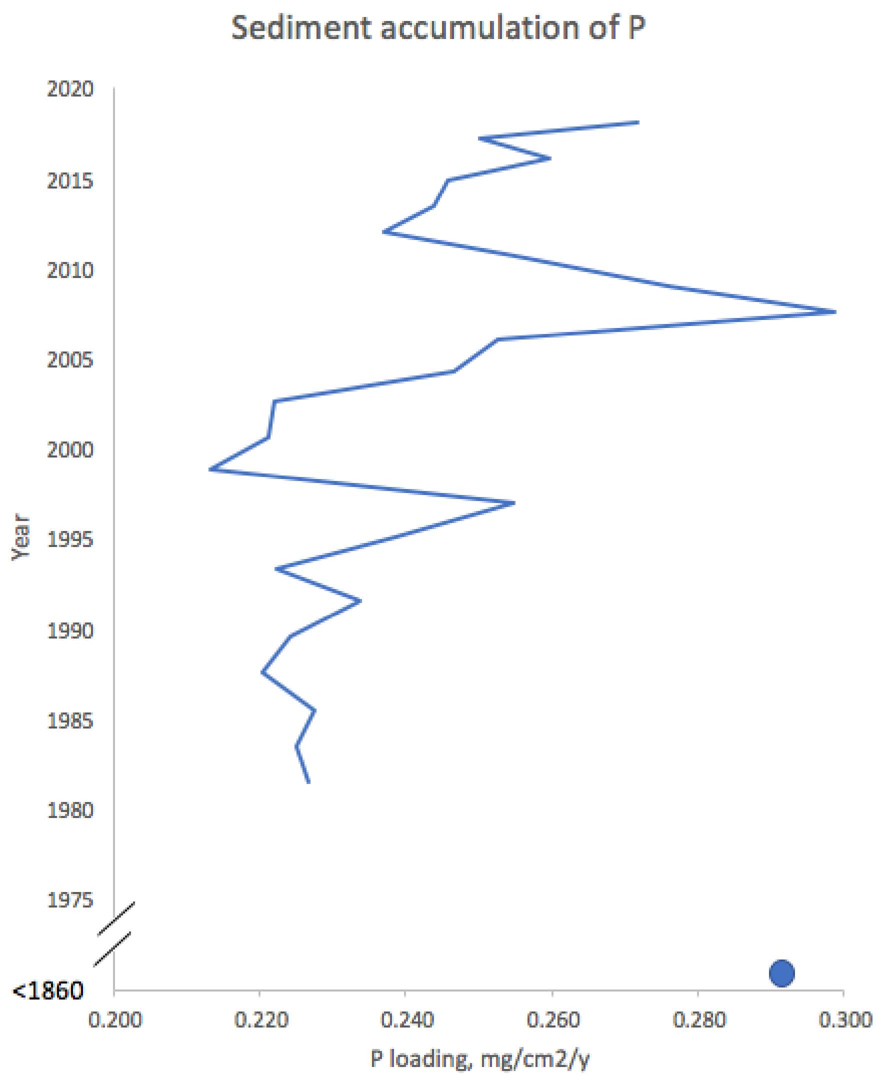

Figure 2. Phosphorus accumulation rate in Mara Lake surface sediments over time. The blue line is from the sediments collected from the gravity corer. The blue circle represents the concentration in sediments from an interval of sediment dating to before 1860.

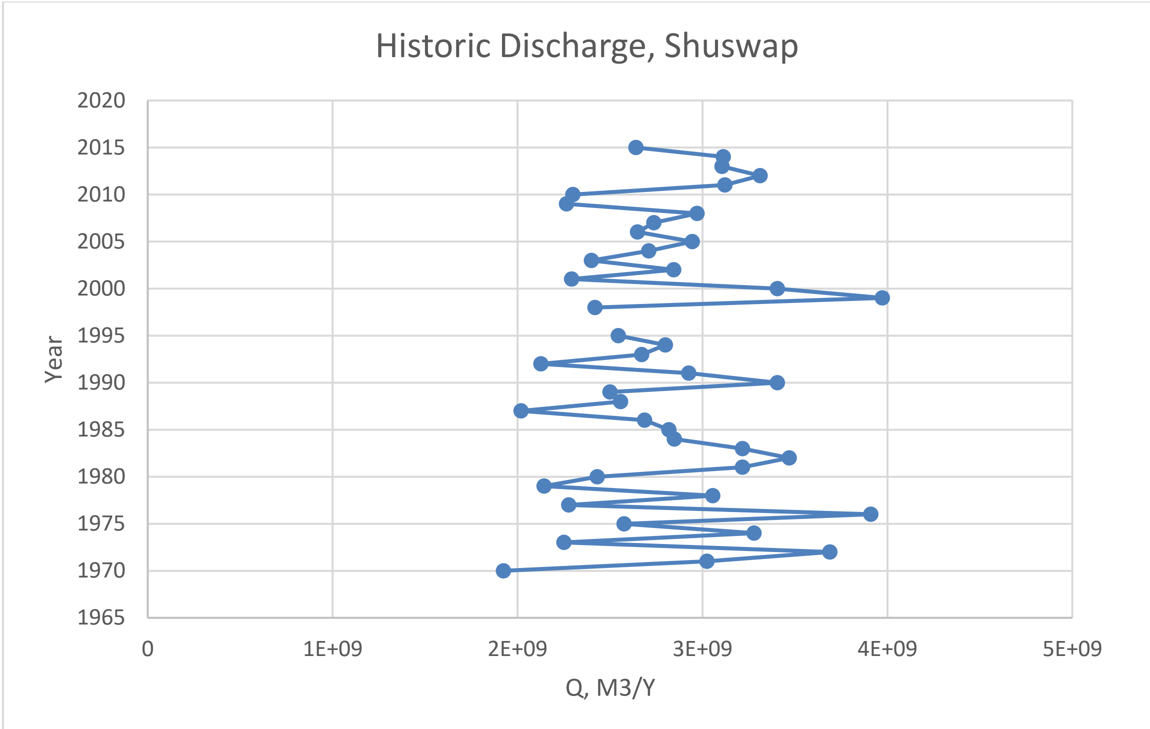

Figure 3. Historic discharge in the Shuswap River at Ashton Creek (data from Water Survey of Canada).

Phosphorus concentration in the sediment from <1860 was at the higher end of the accumulation rate. We do not have discharge data for this period, consequently the higher levels may have been from wetter conditions causing more discharge in the Shuswap River. It is also likely that erosion in the watershed and river bed were lower in the past, potentially increasing the P concentration in sediment by reducing the sediment load (dividing the phosphorus load by a smaller amount of sediment). The processes are not mutually exclusive and both may have been operating.

The inferred increase in phosphorus loading of 20% over the last 40 years (0.5% per year), represents a large potential change in the yield from the watershed. If we assume that these changes took place in the incremental flow sub-watersheds (IFSW), the yields would have been 0.18 kg ha^{-1} y^{-1} in 1980. Yields today are about 30 times higher (5.1 kg ha^{-1} y^{-1}). The theoretical yield from IFSW in 1980 is about 3.5 times higher than that from presently forested lands, probably because the land converted to urban and agricultural use is somewhat more fertile than the present forest, but still well within the undisturbed range for watersheds.

Analysis of microfossils in the Mara Lake sediments shows a change in the community structure of plankton occurring about 1998 (Figure 4). The assemblage of planktonic microfossils from <1860 more closely resembles the community from 1980-1998, than it does the community post 1998. The other significant observation in the assemblage is the large increase in chrysophytes at about the same time (Figure 5). This is consistent with the observations of blooms of chrysophytes in recent years (Ludwig, 2018).

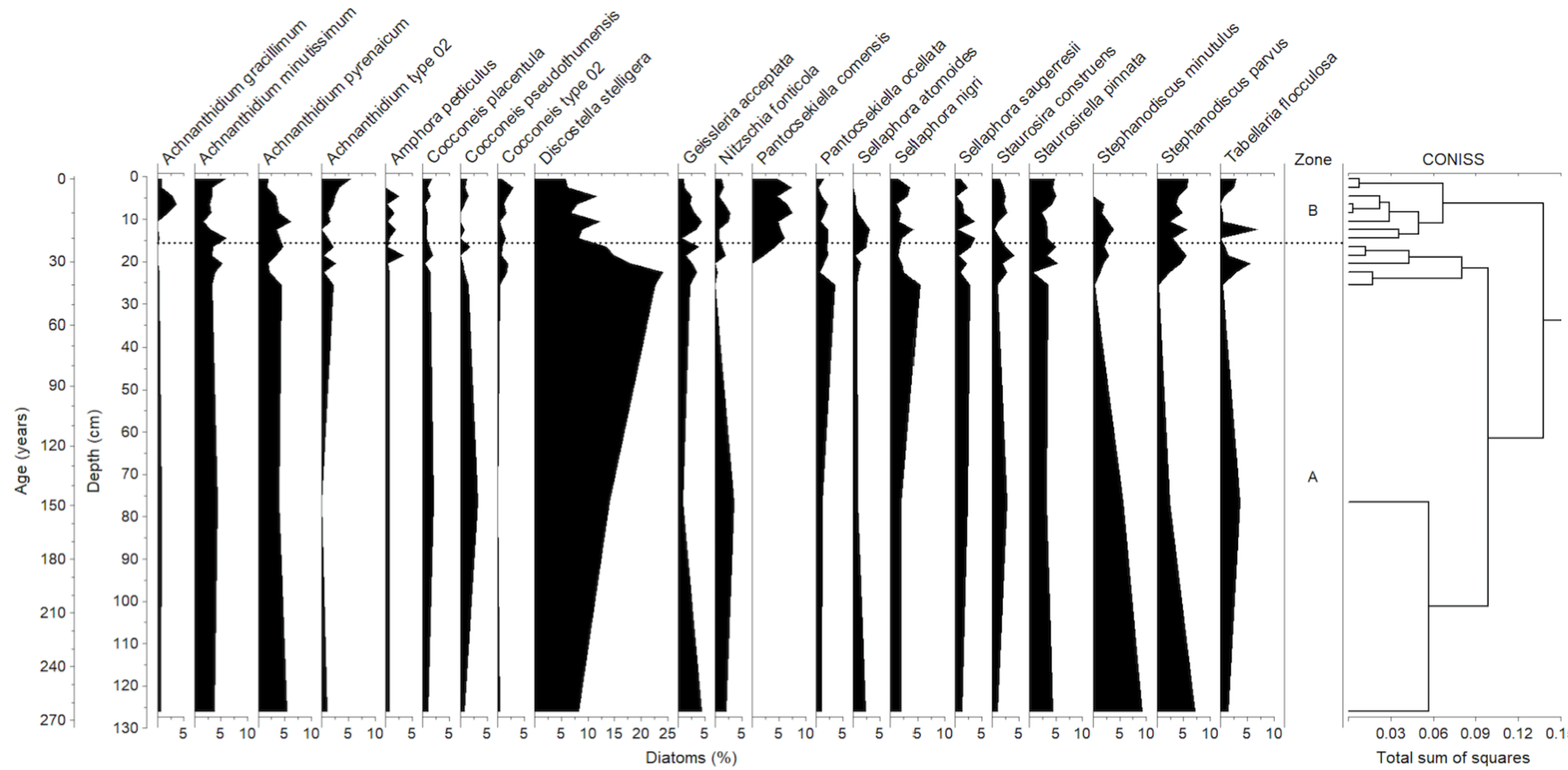

Figure 4. Depth- and Age-distribution of the microfossils recovered from sediment cores from Mara Lake. The microfossil community was analyzed by cluster analysis to reveal depth/age similarities among intervals. The main distinction among the fossil community occurred in the mid-to-late 1990s.

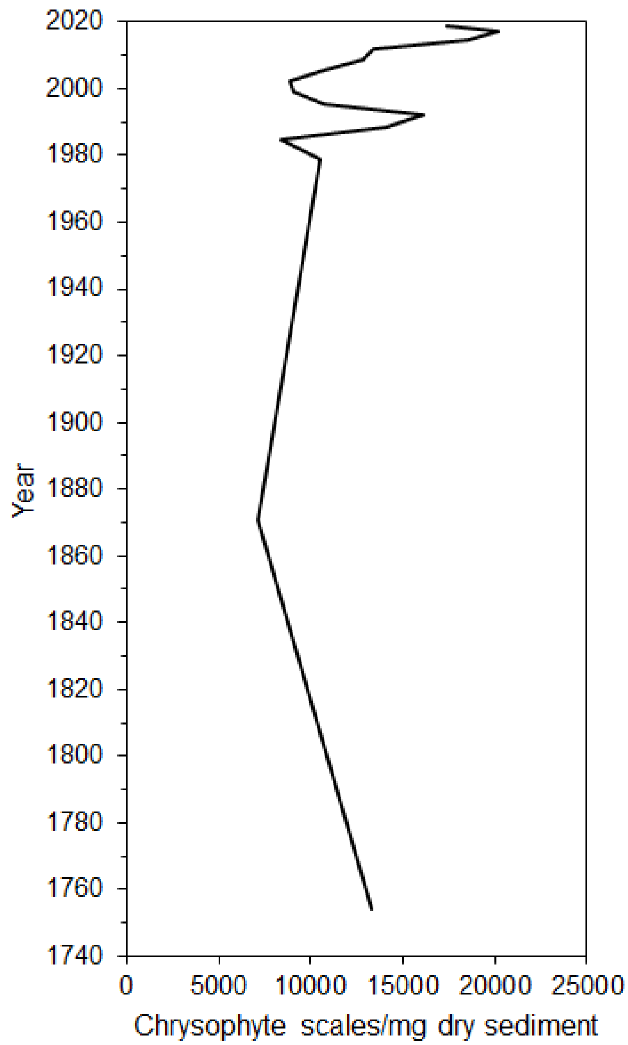

Figure 5. Historic changes in the abundance of Chyrophytes in Mara Lake.

Transfer functions were used to reconstruct historic levels of phosphorus in water from the microfossil community and are shown in Figure 6 (described in Hebda et al., in prep.). Inferred phosphorus aligns with measured values of about 11 ug L^{-1} (Jensen, 2010), and shows an increasing trend through the period 1980 to present. Inferred phosphorus <1860 is at the high end of the phosphorus range (10-15 ug L^{-1}), consistent with higher levels of phosphorus measured in sediment (Figure 2). Taken together, levels of phosphorus today are probably not unprecedented in the history of Mara Lake. In the 1980s, Mara Lake appeared to be in a state of much lower phosphorus loading but had similar algal community structure to pre-cultural conditions. As phosphorus loading increased, the plankton community changed. Because this change has taken place within the probable range of historic phosphorus loadings, it is likely that other changes over time are contributing. Possible contributors include changes to the timing of phosphorus loading, climatic change, or both.

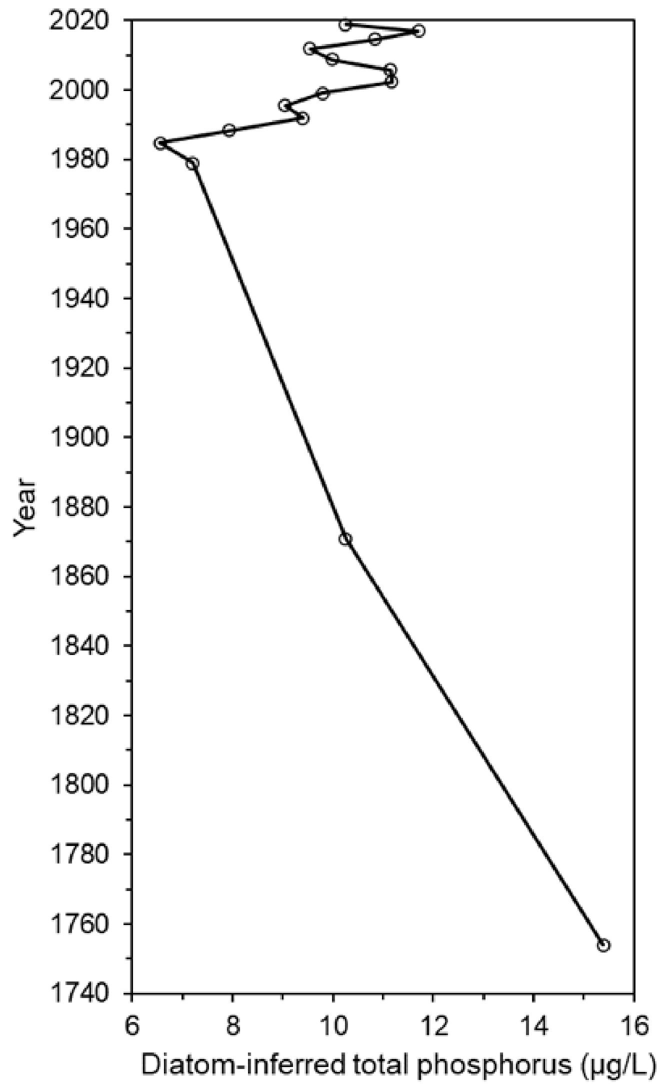

Figure 6. Lakewater phosphorus concentration inferred from the microfossil community by application of transfer functions (Hebda et al., in prep)

Paleolimnological inference of increasing phosphorus loading of about 20% and increasing abundance of bloom forming species of algae are consistent with the mass balance of phosphorus in the Shuswap watershed as land use has changed. Because the Shuswap/Mara Lakes system have had excellent water quality, it is relatively easy for that water quality to be degraded. Expectations for levels of algae (measured as chlorophyll a) from different levels of phosphorus are shown in Table 1. Note that for an oligotrophic Mara Lake (~11 ug L^{-1}), the addition of 20% more phosphorus (~2.2 ug L^{-1}) is a significant portion of the total, whereas for more productive lakes, 2 ug L^{-1} contributes negligibly to the total. This translates directly into water transparency, an important aesthetic property of lake water. For example, for an enrichment of 2 ug L^{-1}, an oligotrophic lake like Mara Lake would reduce transparency by about 60 cm, whereas an already productive lake might only lose 7 cm of transparency for the same enrichment.

Phosphorus, mg L^{-1}	Chlorophyll, ug L^{-1}	Transparency, m	Trophic state
<12	0.5-2.5	>4	oligotrophic
12-24	2.5-7.5	2-4	mesotrophic
24-96	7.5-55	2-0.5	eutrophic

Table 1. Phosphorus-based classification of lake water quality and trophic state derived and adapted from Carlson (1977).

Conclusions and Recommendations

Our analysis of the phosphorus budgets for the Shuswap and Salmon River watersheds provided the means for estimating and measuring the contribution of IFSW and inferring the anthropogenic contribution through altered land-use. Our findings are consistent with previous assessments and differ only in magnitude (Tristar, 2014). In all cases, excess phosphorus loading arises from anthropogenic land use change. Further, our findings are consistent with expectations of phosphorus export from anthropogenic land use reported elsewhere (summarized in Figure 1).

In hindsight, it is clear the Salmon River poses particular challenges related to flow path. First, much of the anthropogenic land-use effects are already apparent in the upper reaches, above our uppermost sampling site. This does not affect our estimates of land-use export coefficients because we included land use above km 0 on the Salmon

River. Second, the Salmon River loses phosphorus in our study reaches, possibly by water abstraction, by exchange of P-rich river water with less rich groundwater, and by storing phosphorus in the river bed in organic matter (dead biomass). It has been documented that abstractions of water from the Salmon River and communicating groundwater is a significant portion of the total flow of the Salmon River (Burt and Wallis, 1997). In contrast, it is unlikely that the river stores significant phosphorus in the river bed on a long-term basis (years) because high flows (esp. freshet) tend to mobilize organic matter in rivers. Taken together, the abstraction of water and exchange of river water and groundwater seem the most likely causes of net loss of phosphorus loss.

Paleolimnological analyses indicate that phosphorus concentrations in Mara Lake today are probably not unprecedented in its long-term history. However, phosphorus levels at the onset of major land-use change were likely lower than today and have increased in recent decades. If the magnitude and direction of change in phosphorus in the Shuswap and Salmon watersheds is deemed to be problematic, there are three main courses of action to reduce phosphorus loading. The target of these actions should be on excess phosphorus exported from urban and agricultural land because forested land use has low phosphorus yield that would be difficult to reduce further, and would require huge area under remediation to reduce significantly phosphorus loading.

First, and simplest, is to encourage best-practices on urban and agricultural lands. These best practices should ensure that fertilization of lands are to the required quantity and ratio for plant needs. Fertilization with excess phosphorus relative to nitrogen should be avoided. Our analyses were never intended to have the granularity to identify “hot spots” of phosphorus loading. Potential hot spots of phosphorus loading could be identified by inventorying phosphorus in soils. In aggregate, urban and agricultural phosphorus yields are higher than background, but within the range of values reported elsewhere for similar land-use (summarized in Ludwig, 2018).

Second, land-use could be changed to uses with lower export coefficients (Figure 1). For example, pasture and non-row crops tend to have lower export coefficients than row crops. For maximum effectiveness, changes should target lands that have high expected phosphorus yield or high nutrient inventory (legacy phosphorus) and that communicate closely with nearby surface water.

The third action, is to modify the flow path of water to encourage nutrient retention within the watershed. This strategy is the most commonly used mitigation technique. For example, nutrient-rich water might be directed into wetlands (or detention basins) that can efficiently retain phosphorus (mainly during the growing season). Additionally, nutrient-rich water could be identified and used preferentially for irrigation over relatively nutrient-poor water (esp. river water), effectively intercepting phosphorus and using it beneficially. This might involve irrigating from wetlands and detention basins constructed to receive nutrient-rich drainage, or it might involve irrigating with nutrient-rich groundwater that would otherwise discharge to surface waters.

For all of the actions outlined above, stakeholders should be aware that legacies of land-use take considerable time to respond to actions. Unlike point sources of nutrients (sewage outfalls, septic tanks) that can be changed immediately by improving treatment technology, land use is a non-point source that responds over decades. Thus, changes in land use alone will only be effective in the medium and far future. Flow-path modification can operate more quickly because it is the equivalent of adding treatment to urban and agricultural drainage water before it joins larger surface waters. The approaches are not exclusive of one another, and may be used in combination.

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