ATTACHMENT 2

Lake Quamichan

Overview of water and sediment quality and recommendations

Dr. Maíra Mucci, Dr. Said Yasseri, Nigel Traill
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1. Introduction

This report outlines results from a study undertaken by Limnological Solutions International at the request of the Municipality of North Cowichan on the sediments and water of Lake Quamichan in March 2022. The work was conducted to obtain more detailed information relating to sediment phosphorus concentrations so that the total pool of mobile phosphorus in the lake could be determined, a Phoslock dose defined and recommendations for future management measures made. During the sampling program, the lake was sampled for water and sediment in three locations and sediment was collected at three different sediment depths.

Sediment extractions were performed as soon as the samples arrived in Germany and laboratory analysis commenced as soon as the extractions arrived in the accredited laboratory. The sediment analyses consisted of two components: (a) an investigation to determine the mobile phosphorus pool in the three sediment layers of each location and (b) a determination of the physical and chemical sediment characteristics in terms of dry weight, density, organic content and other parameters. After the analyses were completed, the data were collated so that recommendations to improve water quality at Lake Quamichan could be made.

2. Sampling

Intact sediment core samples were taken using a UWITEC "Mondsee corer" at three locations in the lake on the 2nd of March, 2022 (Figure 1 and Table 2). Around six sediment cores were collected at each location. The sediment cores were sliced onsite to depths of 0 to 5 cm, 5 to 10 cm and 10 to 20 cm. Composite samples for each sediment depth were then created by mixing the six sediment samples from the same location and same sediment depth. Three composite samples from each zone were processed according to the phosphorus fractionation procedure at our labs in Bremen, Germany (Psenner et al., 1984). Following the extractions, the water and sediment samples as well as the Psenner extracts were sent to the accredited lab Chemisch -Technisches Laboratorium Luers GmbH & Co. KG in Bremen, Germany, for further analysis. The samples were analysed for the parameters described in Table 1.

In addition, water samples were collected from the surface in each zone and the following parameters were measured onsite at location 1: Secchi depth, temperature, electric conductivity, pH, redox and dissolved oxygen.

Figure 1: Sampling location at Lake Quamichan Map from google Earth.

Table 1: Analysed water and sediment parameters with the analytical method.

Water parameters	Methods
Secchi depth (SD)	ISO 7027-2:2016
Temperature (T)	DIN 38404- C4:1976-12
Electric conductivity (EC)	EN 27888- C8:1993-11
pH	DIN 38404- C5:1984-01
Dissolved oxygen (DO)	EN 25814- G22:1992-10
Total phosphorus (TP)	ISO 6878- D11:2004-09
Total nitrogen (TN)	ISO 11885- E22:2009-09
Dissolved organic carbon (DOC)	EN 1484 (H3): 1997-08
Ammonium-nitrogen (NH4-N)	ISO 11732- E23:2005-05
Nitrite-nitrogen (NO2-N)	ISO 13395- D28:1996-12
Nitrate-nitrogen (NO3-N)	ISO 13395- D28:1996-12
Ortho-phosphate-phosphorus (PO_4-P)	ISO 6878- D11:2004-09
Aluminium (Al)	ISO 11885- E22:2009-09
Lanthanum (La)	ISO 11885- E22:2009-09
Calcium (Ca)	ISO 11885- E22:2009-09
Iron (Fe)	ISO 11885- E22:2009-09
Sediment parameters	**Methods**
Dry weight (DW)	ISO 11465/EN 14346
Loss on ignition 500°C (LOI 550°C)	EN 15169: 2007-05
Density	Lab method
Total nitrogen (TN)	ISO 16948:2015-09
Total phosphorus (TP)	ISO 11885-E22:2009-09
Calcium (Ca)	ISO 11885-E22:2009-09
Iron (Fe)	ISO 11885-E22:2009-09
Manganese (Mn)	ISO 11885-E22:2009-09
Lanthanum (La)	ISO 11885-E22:2009-09
Aluminium (Al)	ISO 11885-E22:2009-09

3. Results

3.1 Water

Lake Quamichan is a 314 ha lake (max depth 8.2; average depth 4.4) used for recreational purposes. The lake has received high inputs of nutrients over many years from the surrounding agricultural and urban areas. The lake also receives inflows from several creeks with the main contributors to nutrient concentrations being McIntyre Ck and the Stamps Road ditch (Preikshot, 2019). The lake has an outflow (Quamichan Creek), however residence time is higher during the dry season (summer) when the outflow is dry. The creeks that flow into the lake are surrounded by agricultural fields, which have been the main contributor to nutrient pollution for the past 100 years (Preikshot, 2019). As a result, Lake Quamichan is currently considered eutrophic (average summer chlorophyll-a between 2004 and 2018 was 300 ug/l and total phosphorus 0.3 mg P/l).

The lake was not stratified during our sampling; oxygen concentrations were between 14.8 and 15.7 mg O_2/l and conductivity was between 169 and 173 µS/cm (Figure 2). pH in the water column was relatively high (8.76) for the time of the year (Table 2). Total phosphorus (TP), total nitrogen (TN), ortho phosphate phosphorus (PO_4-P) and ammonium (NH_4-N) concentrations were similar to values found in May 2018 (Preikshot, 2019); however, nitrate (NO_3-N) and nitrite nitrogen (NO_2-N) were higher in March 2022 than in May 2018. At location 1, closer to McIntyre Ck, TP, TN, PO_4-P and dissolved inorganic nitrogen concentrations were higher than in the other two locations, which may have been caused by the nutrients entering the lake from McIntyre Ck (Table 2). Based on the lake volume calculated by Preikshot (2019) (18.3 million m^3) and the average P concentration measured during our sampling, the phosphorus mass in the lake's water column is currently around 2.6 tonnes.

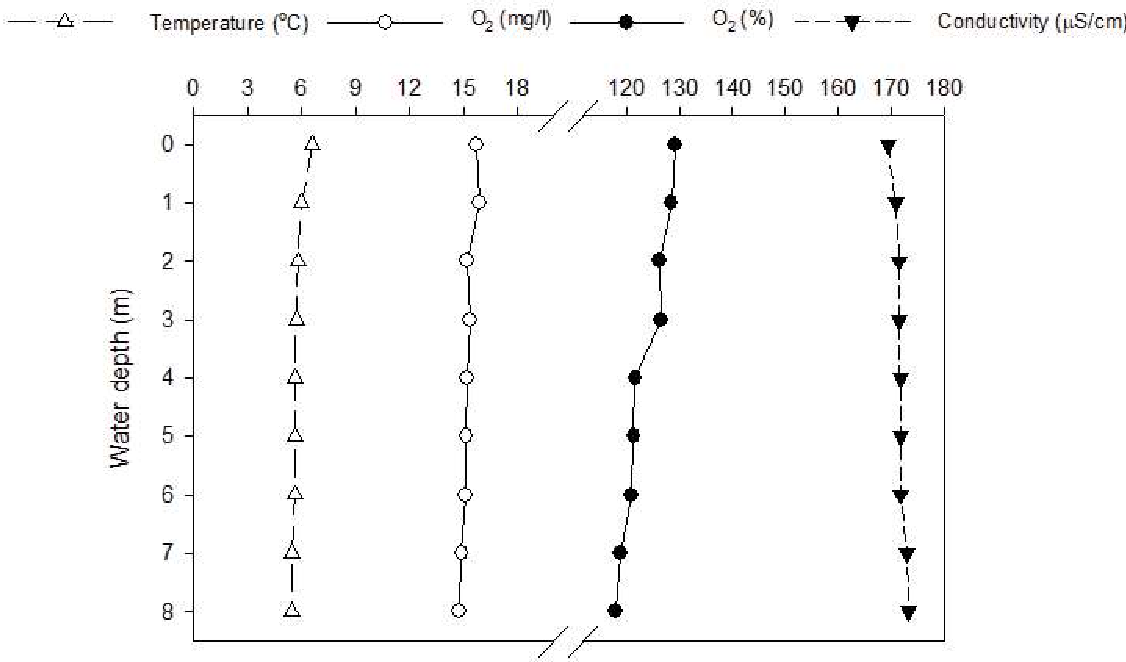

Figure 2: Profile of oxygen (concentration and saturation), temperature, and electrical conductivity measured at each depth at location 1.

Table 2: Water characteristics from three sampling locations at Lake Quamichan

Parameters	Units	Location 1	Location 2	Location 3
Coordinates	(degrees, decimal minutes)	48°48.3023`N 123°39'.1418`W	48°47.6599`N 123°39'.8402`W	48°47.7369`N 123°40'.5055`W
Water depth	m	8.2	7.8	6
Secchi depth	m	1	1	1
pH	-	8.74	-	-
Total Phosphorus	mg/l	0.17	0.13	0.13
Total Nitrogen	mg/l	1.8	1.4	1.3
DOC	mg/l	11	6.8	11
PO4-P	mg/l	0.03	0.009	0.006
Nitrate-N	mg/l	0.17	0.00	0.00
Nitrite-N	mg/l	0.025	0.002	<0.002
Ammonium-N	mg/l	0.062	0.086	0.044
Total Iron	mg/l	0.011	<0.01	<0.01
Total Calcium	mg/l	19	19	20
Total Aluminium	mg/l	<0.05	<0.05	<0.05
Total Lanthanum	mg/l	<0.005	<0.005	<0.005
Acid binding capacity	mmol/l	1.75	1.12	1.08

3.2 Sediment

The sediments sampled at the three locations in Lake Quamichan had extremely low densities (between 1.085 and 1.030 g/cm^3), even at a sediment depth of 20 cm (Figure 3). The sediment also had low dry weight and around 93 to 96 % of the sediment is water, which suggests that the sediment layer interacting with the water column could be deeper than 20 cm. Lake Quamichan sediments are rich in organic matter even in the deeper layers (Table 3). This is evident from the high LOI 550°C values (suggesting between 40 and 49% of the sediment is organic material) and also from our observations when we dried the samples which smelt similar to pure manure.

Figure 3: Around 45 cm of intact sediment sampled from lake Quamichan (left panel), first layers of the sediment (middle panel), soft, rich -organic sediment even at deeper layers (~30cm). Photo taken by Sarah Grieves.

The sediment from Quamichan is also high in total phosphorus and sulphur. The Fe:P ratio (w/w) is between 10 and 28, while the Fe:S ratio (w/w) is low at between 0.9 and 1.9. In 1992, Jensen et al. suggested that internal-P loading is well controlled in sediments with a Fe:P ratio above 15 (w/w). In Lake Quamichan, most of the sediment analysed is below this ratio (Table 3). Nevertheless, the conclusion of Jensen *et al.* was based solely on field surveys of 15 lakes in Denmark which were undertaken at a point in time when it was not well known that the formation of insoluble iron sulfide (FeS) can reduce the availability of Fe to bind P. Nowadays, the importance of not only Fe:P ratios, but also S concentrations, in controlling internal P loading has been well established. Wang *et al.* (2018) recently proposed that Fe:P ratios that are higher than 30 and Fe:S ratios that are higher than 6 can greatly suppress sediment P-release, however the correlation between organic degradation and the release of P, Fe and S in lakes with rich organic sediments such as Lake Quamichan requires further study. Most of the studies that have been undertaken in this field until now have considered Fe, P and S concentrations in pore water in order to determine ratios, however in our study we have analysed the total Fe, P and S content in the sediment. Nevertheless, our data still suggest that the sediments of Lake Quamichan may not have enough Fe to bind the releasable P and that the high S concentrations in the sediment might reduce the natural binding capacity of the sediment for P by acting as a sink for Fe (and causing the formation of FeS). The fact that phosphate concentrations are relatively high when the lake is not stratified (between 0.13 and 0.256 mg P/l) also indicates that the sediment in Lake Quamichan has a low capacity to retain phosphorus.

Table 3: Sediment characteristics from three sampling locations in Lake Quamichan.

		Location 1			Location 2			Location 3		
		Sediment depth (cm)			Sediment depth (cm)			Sediment depth (cm)		
Parameter	**Unit**	**0-5**	**5-10**	**10-20**	**0-5**	**5-10**	**10-20**	**0-5**	**5-10**	**10-20**
Density	g/cm^3	1.030	1.072	1.084	1.047	1.066	1.094	1.045	1.061	1.085
Dry weight	% (m/m)	3.64	4.50	5.03	3.66	4.28	4.89	3.72	4.71	6.36
LOI 550°C	% DW	43.9	44.0	43.5	41.9	41.5	42.1	48.7	40.9	39.8
Total phosphorus	mg/kg DW	2600	1600	1600	1900	1700	1600	2200	1600	1200
Total nitrogen	mg/kg DW	3600	4200	4900	3100	2900	4100	4200	3600	4200
Iron	mg/kg DW	28000	23000	26000	21000	23000	24000	21000	36000	34000
Manganese	mg/kg DW	1300	890	750	910	710	580	570	600	600
Calcium	mg/kg DW	14000	11000	12000	10000	11000	11000	11000	11000	11000
Aluminium	mg/kg DW	30000	26000	30000	26000	32000	30000	24000	27000	27000
Sulphur	mg/kg DW	15000	14000	16000	12000	11000	13000	23000	27000	24000
Lanthanum	mg/kg DW	8.40	7.5	7.30	6.20	6.80	7.10	6.60	6.80	6.70
TFe:TP (w/w)	-	11	14	16	11	14	15	10	23	28

In our study, the potentially available phosphorus pool was analysed by exposing Lake Quamichan sediment to different reagents. The available P is the amount of P released from the sediment under natural conditions (e.g. during anoxic events and microbiological activity). The release of phosphorus from sediments can play an important role in pond and lake water quality. As expected, due to the high organic matter and bad odour during drying, the organic P bound in detritus, humic substances and microorganisms was the most significant P form present in the sediment from all the three locations (Figure 4). On average, 43% (± 6) of the total P in the sediment is organic bound P (Figure 4 and Table 4). The residual phosphorus, considered inert under natural conditions, was the second most significant form of P present in the sediment (37 ± 9%) (Figure 4). Fe/Mn bound P was around 8 ± 4% of the total phosphorus in the sediment and P in Al/Fe-oxides around 12 ± 4%. The releasable P is usually considered to be the sum of pore water P, redox-sensitive P and organic bound P (Table 4), however in high pH lakes, P contained in Al/Fe-oxides can also be considered releasable P. The releasable P concentrations in the top 5 cm of the Lake Quamichan sediment were similar in all three locations (ranging from 1240 to 1491 kg P/g DW) and higher than in deeper sediment layers (Figure 4). Nevertheless, a significant amount of releasable P was found (439 to 794 kg P/g DW) even in the deepest layer of sediment (10 to 20 cm) (Table 4, Figure 4).

Table 4: Results of Psenner Sequential Phosphorus Extractions on Sediments collected from three locations and different sediment depths at Lake Quamichan.

		1. Released in oxygen-free Aqua bidest	**2.Released in Bicarbonate-Dithionite**			**3. Released in NaOH**		
		labile P (pore water)	Fe/Mn bound P, labile in anoxic conditions		organic P, labile in reductive conditions	base labile P in Al/Fe-oxide		organic P bound in detritus, humic substances and microorganisms
		TP	SRP	TP	NRP	SRP	TP	NRP
	Sediment depth	mg/kg DW	mg/kg DW			mg/kg DW		
Loc 1	0-5cm	4.4	261.0	359.3	98.3	296.2	1423.8	1127.6
	5-10cm	6.1	60.1	99.4	39.3	309.3	883.6	574.3
	10-20cm	7.4	65.4	99.1	33.7	183.1	792.9	609.7
Loc 2	0-5cm	5.2	180.0	252.2	72.3	244.3	1227.1	982.7
	5-10cm	5.7	62.5	97.6	35.1	173.6	918.5	744.9
	10-20cm	6.1	54.6	91.2	36.6	164.6	861.4	696.8
Loc 3	0-5cm	0.0	123.6	205.0	81.3	259.2	1388.4	1129.2
	5-10cm	3.0	46.0	84.7	38.7	177.9	847.1	669.2
	10-20cm	3.3	21.8	34.3	12.5	132.4	533.8	401.4

During sampling, the pH at the surface was 8.7, and according to Preikshot (2019), at the bottom of the lake (5 to 6 m) the pH is never higher than 8-8.1 (Figure 28 from Preikshot, 2019). However, pH can be high near the surface (0 to 4 m), increasing from 7.5 up to 10 during summer. Thus, there is still a risk that the aluminium phosphate bond will weaken due to an excess of hydroxide ions (OH^-) and the possibility that P may also be released from the aluminium bound P fraction in the sediments cannot be excluded. The aluminium bound P pool should therefore be considered potentially releasable. It is also important to define the sediment depth that communicates with the water column. Normally, in deeper lakes such as Quamichan, the top 5 or 10 cm of the sediment is considered as the layer from which P may be released. However, the Lake Quamichan sediment is extremely soft, even in the deeper layers (20 cm) (Figure 3) and we therefore recommend that at least the top 20 cm of the sediment should be considered as the “active sediment layer” for the purposes of developing management measures. Consequently, in our report, we choose to define “releaseable P” for Lake Quamichan as the sum of pore water P, redox-sensitive P, organic bound P and P in Al/Fe oxides contained within the top 20 cm of the sediment.

The samples collected from all three sampling areas contained similar amounts of releasable P per ha (108, 103 and 96 kg per ha at locations 1,2,3 respectively) (Figure 5) and we therefore used an average for the three locations (102 kg P/ha ± 6) to calculate the total mass of releasable P. Based on a lake area of 314 ha, the sum of total releasable phosphorus in the first 20 cm of sediment for the whole lake amounts to 32.2 tonnes.

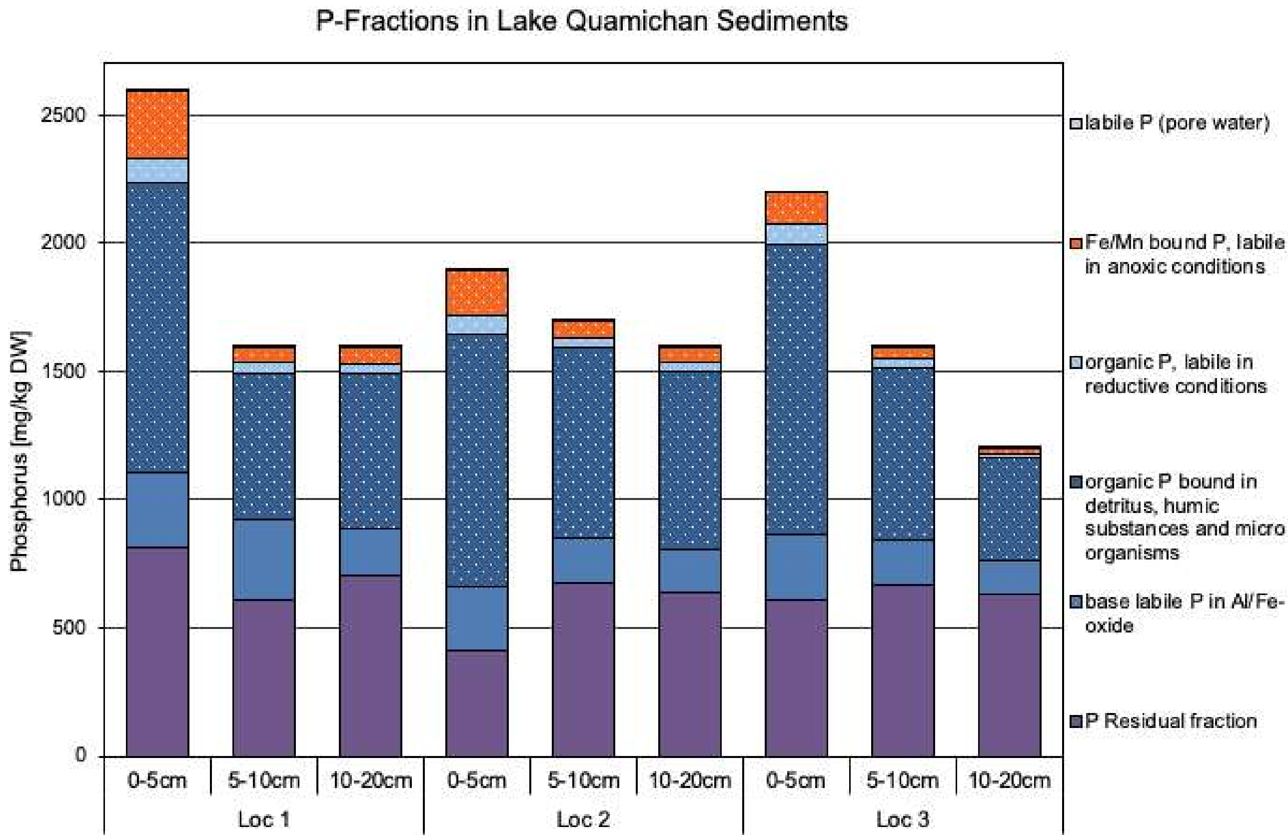

Figure 4: Different phosphorus fractions measured in sediments at three sites monitored in Lake Quamichan.

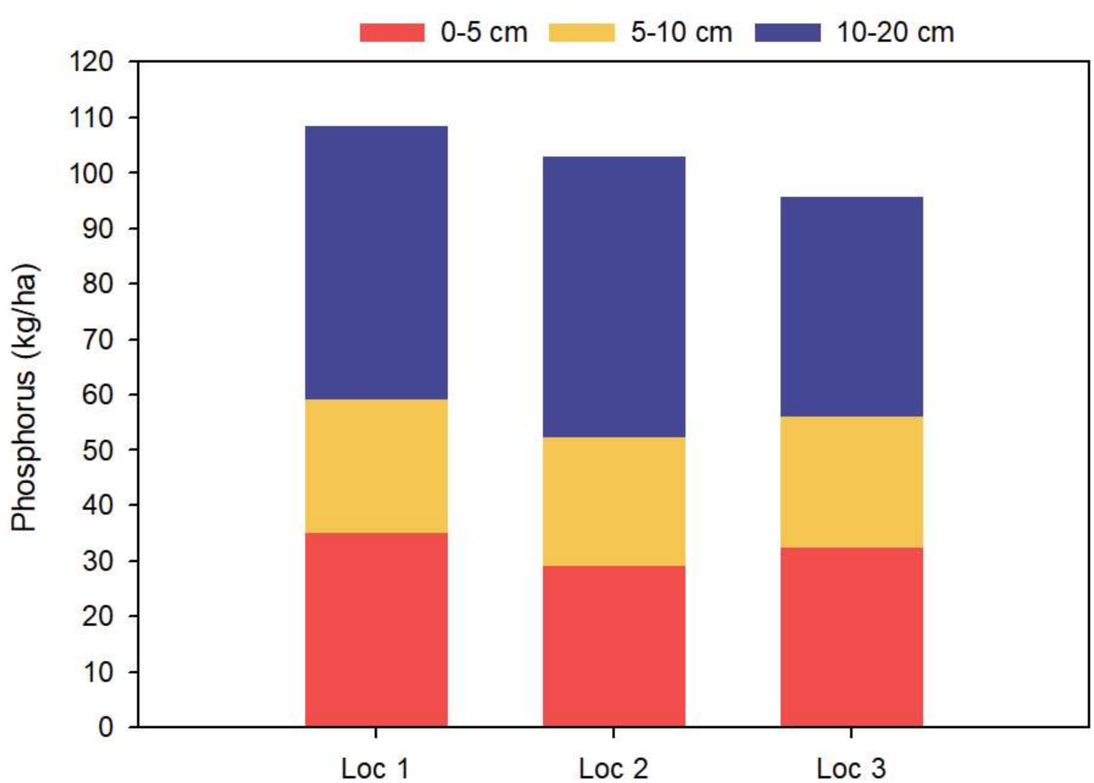

*Figure 5: Releasable total phosphorus loads (*sum of the redox-sensitive P, organic bound P and P in Al/Fe-oxide*) of Lake Quamichan per sediment depth and in each location.*

4. Recommendations

The nutrient concentrations in Lake Quamichan should be reduced to improve water quality. The sediment is rich in P, and it is likely that this P pool is a key driver of the lake's poor water quality. Thus, it is important to increase the P binding capacity of the sediments. A number of measures that target nutrients in the sediment could be considered for Lake Quamichan. In this section, we introduce several of the measures which appear to offer the most promise based on the characteristics of the lake. Ineffective measures that are being marketed without any scientific underpinning (e.g. ultrasound, effective microorganisms (Lürling and Mucci, 2020)) and measures that directly target algal blooms (e.g. algaecides) are not considered.

4.1. Dredging

The removal of nutrient-rich sediment has been undertaken for many years, primarily for water transport purposes and to allow shipping in canals or rivers. Dredging can also be and has also been used to improve water quality and restore lost recreational amenities. Nevertheless, dredging does not always result in the desired effects as, even if a few centimetres of sediment are removed, the sediments below (that remain following the dredging) are normally also rich in P. For instance, in 1988, about 220,000 m^3 sediment was removed from 47 ha in the 178 ha shallow Lake Binnenschelde (the Netherlands). Internal P release was reduced from 4.1-6.8 to 1.4 mg P m^{-2} day^{-1} during the first year after dredging, but returned to pre-dredging levels in the following years. No effects on water column P concentrations were observed (https://edepot.wur.nl/4702). Recently, Yin *et al.* (2021) compared dredging with an in-situ adsorbent inactivation (Lanthanum modified bentonite-LMB) and found that, whilst both LMB inactivation and dredging can reduce mobile P concentrations, the impact of LMB in reducing mobile P was more prolonged than that of dredging.

Prior to commencing any dredging program, it is important to determine the pool of potentially releasable P so that an assessment can be made as to how many cm of sediment need to be removed in order to reduce P release significantly. Lake Quamichan, for instance, contains a layer of rich organic sediment that is up to 45 cm deep (Figure 2) and therefore at least 45 cm of sediment would need to be removed (~1,413,000m^3 of sediment) from the entire lake. In addition, it is not certain that the sediment below those 45 cm contains significantly less releasable P. Normally, releasable P concentrations in deeper sediment layers can be expected to be lower, however Lake Quamichan has received such huge inputs of organic matter in the past decades that a substantial pool of "legacy P" has developed in the sediments. Apart from this uncertainty, dredging is extremely expensive compared to other measures. Other disadvantages of dredging include the need to remove fish prior to dredging and the disturbance to the water column and sediments which can result in increased P release into the water column and spills (Figure S1). Finally, a plan for the disposal of the dredged sediments needs to be formulated and care needs to be taken to ensure that this plan is compliant with the Canadian legislation in respect to heavy metals and nutrients. Dredged sediments should not be placed next to the lake (even for dewatering which has occurred in several cases) as nutrients will be leached again into the lake.

Based on our analysis of the sediments, we do not believe that dredging would be suitable for Lake Quamichan due to the quantity of sediment that would need to be removed, the high costs and uncertain efficiency.

4.2. Artificial mixing, aeration or oxygenation

Artificial mixing or circulation aims to eliminate stratification in aquatic systems and transport air to deep waters. In deeper systems with sufficient oxygen and iron, this may reduce sediment P release and reduce nutrient concentrations in the deep waters. Artificial mixing should, however, be avoided in shallow areas as it may cause sediment resuspension and could even stimulate rather than control cyanobacteria (Visser *et al.*, 2016). According to Visser *et al.* (2016), destratification or whole water column mixing is only likely to be effective in water bodies that are deeper than 15 to 20 m. Artificial mixing can be generated by aeration with compressed air or pure oxygen. Speece cones have also been installed in many lakes with the aim of injecting pure oxygen to deeper water layers and reducing hydrogen sulfide (e.g. Horne et al., 2019). The majority of these systems have been installed in deep reservoirs to prevent the release of ions from sediments (e.g. manganese, iron, phosphate, ammonium and calcium) and to avoid precipitation and clogging in pipes in hypolimnetic extraction systems. These systems are fed by pure oxygen which makes operations expensive due to the need for continuous supply. Oxygen is fed into the cones to achieve optimal enrichment and avoid the formation of large bubbles that disturb stratification. Higher oxygen concentrations in the hypolimnion improve the habitat for many oxygen-dependent organisms (e.g. zooplankton and fish) and may also avoid fish kills. Higher oxygen concentrations closer to the sediment may also reduce sediment P release if a high P percentage in the sediment is normally bound to Fe. Nevertheless, even in sediments with relatively high Fe concentrations, it is possible that the sediment does not contain enough Fe to bind all the P present. In some case studies, a reduction in total P concentrations was not observed after artificial mixing and hypolimnetic oxygenation, possibly due to an increase in the mineralization of P containing organic matter (Bormans *et al.*, 2016).

Based on the above-mentioned points, destratification by aeration or other methods (e.g. propellers) may not be suitable for Lake Quamichan. Firstly, Quamichan is too shallow (average 4.4 m) for artificial mixing and, instead of preventing excessive growth in algae, the introduction of an artificial mixing system to Lake Quamichan may have the opposite effect (Visser *et al.*, 2016). Secondly, the density of the Quamichan sediments is low and the installation of a mixing system (consisting of pumps, pipes and mixers) may result in the continual resuspension of sediments. This would increase the depth of the “active sediment layer”, thereby increasing nutrient release. Thirdly, the mixing of water layers may bring higher pH water close to the sediment, which, in turn, could cause the solubilization of iron and aluminium phosphate complexes and increase P release from the sediment even further (Seitzinger, 1991). In addition, most of the releasable P in the sediment of Lake Quamichan is organic P and therefore increasing oxygen in deeper water layers through artificial aeration could increase the mineralization rate as well as the release of P bound to organic matter. Finally, Lake Quamichan does not have a favourable Fe:P and Fe:S ratio to significantly reduce P flux, even if the conditions (redox and pH) are favourable.

4.3. Hypolimnetic withdrawal

This measure aims to remove nutrient-enriched water in deep, stratifying lakes and has been used successfully in several water bodies (Nürnberg, 2007). During late summer or early autumn, when the highest nutrient concentrations in the hypolimnion occur, discharge of hypolimnion water through a pipe to downstream water will remove those nutrients from the lake, although extra measures may also be necessary in order to prevent negative impacts on downstream water (Nürnberg, 2020).

Lake Quamichan is unfortunately not suitable for hypolimnetic withdrawal. The lake is not deep enough and, crucially, phosphate concentrations near the surface (0 to 4m) are sufficiently high (≥ 0.17 mg P /l) to allow excessive algal growth, even when the lake is stratified. A larger difference in nutrient concentrations between surface and bottom water layers than that that is observed in Lake Quamichan is necessary for hypolimnetic withdrawal to improve water quality.

4.4. Phosphorus binders

Another way to mitigate eutrophication is via chemical inactivation of phosphorus using metals to bind phosphorus. A literature search for materials that can bind phosphorus suggests that around a hundred such materials have been developed, however only a few of these are available commercially and have been adequately studied scientifically. These include aluminium salts (e.g. aluminium sulphate or polyaluminium chloride), iron salts (e.g. iron chloride) and modified clays (e.g. Lanthanum modified bentonite – known as Phoslock and aluminium modified zeolite – known as Aqual-P). The commercial availability of Aqual-P is currently uncertain however Phoslock has been manufactured and sold worldwide since the early 2000s. All of the commercially available P binders are able to bind phosphorus in the water column and reduce sediment P release, however the choice of the most appropriate P binder will depend on the physio-chemical conditions of a particular lake. The application of a phosphorus binder to the surface of Lake Quamichan could be expected to improve water quality in the lake as it would both reduce phosphate concentrations in the water column and prevent the release of P from sediments (e.g. Epe *et al.*, 2017; Huser *et al.*, 2011).

The application of an iron-based P binder is not recommended for Lake Quamichan, as P bound to iron is unlikely to remain bound due to the potential for anoxic events in the lake. Additionally, aluminium-based P binders are also not recommended due to the high pH events. Aluminium salts adsorb P over a more limited pH range (6 to 8) than La based P binders and can be harmful to aquatic organisms when the pH falls outside this range. Therefore, the use of Al salts should be avoided in situations when pH values of less than 6 or more than 8 are to be expected (Gensemer and Playle, 1999; Poléo, 1995; Wauer *et al.*, 2004; D'Haese *et al.*, 2019; Kennedy and Cooke, 1982). Furthermore, if pH is higher than 8, there is a risk that P bound to Al will be desorbed (e.g. Reitzel *et al.* 2013b and Anderson and Berkowitz 2010). Despite its higher cost, in our opinion, lanthanum modified bentonite (commercially known as Phoslock) would be a better fit for Lake Quamichan.

Lanthanum, the active ingredient of Phoslock, is not redox-sensitive and can bind P over a wider pH range than Al compounds. Theoretically, La can bind P between a pH of 4 to 13 based on chemical equilibrium modelling. However, when pH is higher than 9, the binding of PO_4^{3-} will require more time due to the possible kinetic interference by OH^- ions. Once bound, the Phoslock-P bond will not be desorbed unless the pH drops below 4 or increases to above 12 (D'Haese *et al.*, 2019), conditions which are extremely unlikely to occur naturally (Wetzel, 2001). Another advantage of Phoslock is its capacity to increase sediment stability (Egemose *et al.*, 2010). This may be particularly advantageous in a lake such as Lake Quamichan where the sediments are exceptionally soft and fluid. In addition, Phoslock will not affect the pH nor the conductivity of the water (Spears *et al.*, 2013), thereby eliminating the need to use any other compound (such as buffers) and avoiding stress on aquatic organisms as a result of pH change (which may occur with aluminium and iron salts).

Lanthanum has a straightforward theoretical La:P molar ratio of 1:1, which means that 4.48 g of La can capture 1 g of P as rhabdophane (which is a naturally occurring mineral). This has also been shown through chemical equilibrium modelling and experimentally by Dithmer *et al.* (2015). According to the manufacturers, Phoslock Environmental Technologies Ltd of Australia, Phoslock contains around 5% La (www.phoslock.eu/what-is-phoslock), which means 89 g of Phoslock can bind 1 g of P, although La content may vary between 4% and 5% depending on the batch (Gibbs *et al.*, 2011; Haghseresht *et al.*, 2009; Mucci *et al.*, 2018; Reitzel *et al.*, 2013a). Thus, the manufacturer recommends that a Phoslock and P ratio of 100:1 be used, which means 100 g of Phoslock can bind 1 g of P. This ratio of 100:1 (g/g) has been used in most of the applications undertaken until now (e.g. Epe *et al.*, 2017; Lürling and Oosterhout, 2013; Waajen *et al.*, 2016).

The total pool of releasable P at Quamichan is 34.8 tonnes (32.2 tonnes in the sediment and 2.6 tonnes in the water column). Thus, a dose of 3,480 tonnes of Phoslock would be required to inactivate the releasable P in the top 20 cm of the sediment and the water column. So far, there is not a method available to calculate exactly how much of the sediment is in contact with the water and based on the soft sediment in Quamichan there is a chance that the "sediment water communication" layer is deeper than 20 cm and 3,480 tonnes may be an underdose. Nonetheless, we recommend targeting the 20 cm first and monitoring the lake to evaluate Phoslock distribution in the sediment to shed light on the sediment communication layer.

Phoslock has been applied in many lakes around the world (e.g. Copetti et al., 2016; Lürling and Van Oosterhout, 2013; Meis et al., 2012; Nürnberg and LaZerte, 2016), and dosages have ranged from 1.4 to 10.5 tons per ha depending on the amount of available phosphorus and the targeted sediment depth. The recommended dose of 11.6 tons per ha for Lake Quamichan is comparable to dosages applied to a number of Dutch lakes (e.g. Kralingse Plas (10 tons per ha) and Lake de Kuil (10.5 tons per ha). For both Dutch lakes, the targeted sediment depth was only 10 cm because the sediment density is higher than in Quamichan; however, for Quamichan, we expect that phosphorus is being released from a deeper sediment layer. As a result, more releasable phosphorus should be inactivated and a higher dose of the phosphorus binder should be used (e.g. Phoslock).

Phoslock Environmental Technologies Limited (PET) advise that the current price of Phoslock (ex factory) is around USD 1,900 per tonne. This price does not include freight from the factory to Lake Quamichan or the cost of applying the product (both of which would need to be quoted separately), however PET advises that the cost per tonne would be negotiable due to the large quantity of Phoslock that would be required.

4.5. Other recommendations

In addition to applying a P binder to increase sediment capacity to retain P, we also recommend measures be undertaken to reduce the external P load. For instance, two creeks appear to be the major source of the external P load to the lake, while most of the nutrients entering the lake seems to come from the runoff of fertilizers used on the surrounding agricultural land.

A dephosphatisation plant could be built to reduce the external P load from these creeks, although this would be extremely expensive.

Worldwide, the reduction of diffuse pollution such as agricultural runoff is exceptionally challenging and, frequently, in situ measures are likely to be necessary if water quality that meets societal demands is to be achieved (Lürling and Mucci, 2020).

Often, if the external load is not completely reduced, a re-application of any P-binder from time to time will be needed, although the time between re-applications will depend on how much phosphorus is still entering a system annually (e.g. Epe *et al.*, 2017; van Oosterhout *et al.*, 2021).

Birds can also be an important source of nutrients (Verstijnen et al., 2021), and feeding them can further contribute to eutrophication (Sven *et al.*, 2017). Lake Quamichan is populated by ducks, geese and swans, which are fed by the visitors to the lake, despite the presence of a sign urging the public not to do so (Figure 6). Feed can be a significant P source and the introduction of a program to educate the local community about the problems caused by bird feeding, together with clearer signage, may be initiatives that are worth considering.

In addition to nutrient problems, Lake Quamichan also suffers from high concentrations of *Escherichia coli* (pers. communication with Dave Preikshot). Ingesting *E. coli* can be harmful to human health, often causing diarrhoea and more severe symptoms depending on the strain. Reducing the abundance of *E. Coli* will also be essential if water quality is to be sufficiently improved to allow recreational use of the lake. The Canadian limit for *E. coli* in recreational waters is ≤ 200 E. coli /100 mL (average of a minimum of five samples) (Health Canada, 2012). We are not aware of the actual figures for *E. coli* concentrations in the lake; however, we recommend evaluating *E. coli* numbers in recent years and checking if there is an upward tendency. The North Cowichan municipality is aware that the *E.coli* comes from the birds, so it is to be expected that if people stop feeding them, the *E.coli* abundance might reduce in the lake. However, the lake is also surrounded by houses, so it is also important to investigate if any septic systems are directly discharging to the lake and contributing to *E. coli* concentrations. There are no in-lake measures that can be applied to reduce *E. coli* other than decreasing *E coli* loads on the lake, however this can only be achieved if sources are known and quantified.

Figure 1: Birds at Lake Quamichan. Photo Taken by Maíra Mucci

The municipality of North Cowichan already undertakes monthly monitoring of the lake and frequent monitoring of the creeks, however we recommend that this monitoring program be continued so that the system can be further understood.

5. Key Points and Conclusions

In summary, the key points from our study and our recommendations for future management measures are as follows:

- Lake Quamichan has received nutrients for decades from the creeks that feed it. This has resulted in a huge legacy of nutrients in the sediment.
- The water column from Lake Quamichan contains around 2.6 tonnes of phosphorus.
- The sediment is an important nutrient source with a total releasable P pool of 32.2 tonnes in the first 20 cm. Most of this is organic P.
- The sediment is soft (low density and dry weight) and has a low natural capacity for retaining P (the Fe:P and Fe:S ratios are low)
- Phosphorus concentrations in the water column and the sediment P-release should be reduced to improve water quality
- While effective in some situations, dredging, aeration and hypolimnetic withdrawal would not be suitable measures to improve water quality in Lake Quamichan
- The application of a phosphorus binder may be a suitable measure for Lake Quamichan, however Al or Fe based binders are unsuitable due to the high pH and anoxic events observed in the lake.

- Lanthanum-modified- bentonite (known as Phoslock) would be a more suitable P binder for Lake Quamichan, although it is potentially more expensive than other P binders
- 3,480 tonnes of Phoslock should be applied to inactivate the phosphorus in the water column (2.6 t) and in the sediment (32.2 t).
- The reduction of the external phosphorus load from the creeks is needed to assure longevity of any in-lake measures (e.g. P binder application).
- Local residents and visitors to the lake should be discouraged from feeding the ducks. Food for waterfowl is a source of nutrients and the birds are a source of *E.coli.* An educational program may help increase awareness among the community in relation to the risks associated with feeding the birds.
- *E.coli* sources in the lake should be better investigated and reduced to ensure the lake's recreational use.
- The monitoring program being implemented by the municipality of North Quamichan should continue so that the lake and its condition and its condition are better understood.

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7. Supplementary Information

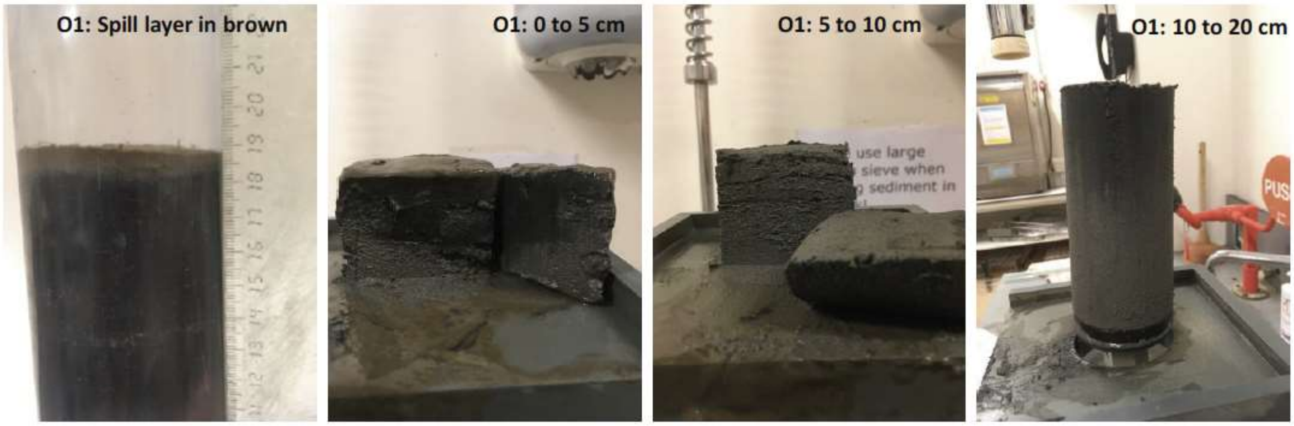

Figure S1: Sediment sampled in a lake in the Netherlands after dredging. We can see less than one cm of a brown spill after the dredge, and the rest is original sediment from the lake (a mix of solid clay and sand). In this project, the dredging company did a great job and did not leave many spills while dredging; however, in other dredging projects, there are several cm of fresh organic-rich sediment left behind in the lake. Sample intact sediment cores before and after dredging is a good way to evaluate dredge efficiency. Pictures were taken by Maíra Mucci in 2020.