Moses Lake Water Quality, Dilution Effectiveness, Internal Loading, Sediment History and Inflow Nitrogen

Prepared for Moses Lake Irrigation and Rehabilitation District

By

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Introduction

This report is a collection of short reports during 2020 that analyzed past and recent data on the lake's condition and likely causes.

The lake has been diluted with low phosphorus Columbia river water (CWR) for 44 of the past 45 years. Continued dilution of external and internal phosphorus loading has largely maintained greatly improved lake quality over the lake's predilution state (Welch et al., 2019). Nevertheless, blue-green algae continue to dominate in summer with *Microcystis aeruginosa* becoming the principal species. While microcystin concentrations were recently measured, that toxic product of *Microcystis* has been in the lake all along, but apparently increased in the 1990s. Reasons for that change may include increased water temperature and nitrogen-to-phosphorus ratio. Nevertheless, reducing the blue-green fraction of algae and alga toxins, requires lowering lake total-P at least in half.

Report Summary

Water Quality: The lake had slightly more phosphorus and algae, in terms of chlorophyll (chl) during May-September in 2020 than during 2017-2019. Total P and chl averages, as well as the summer maximum TP, were higher than in 2017-2019, despite 90% more Columbia River dilution water (CRW). Also, average TP, chl and transparency in lower Parker Horn and South Lake were about the same as during 1986-1988, which had 40% less CRW than in 2020.

Increased TP during summer, well above the volume-weighted inflow from surface and groundwater inputs, was due to internal loading from sediment-P recycling. While CRW input has not always produced the expected proportional dilution effect, whole-lake, volume-weighed lake TP, which averaged 78 ppb in 2020, would be about double the current level without CRW.

Dilution water to Rocky Ford Arm: The transport of CRW well up into RFA was realized at the start of dilution in 1977-1978. That process, aided by wind, was confirmed by specific conductance (SC), which could be used as a conservative tracer of low-SC CRW. That process has continued with about half of upper Rocky Ford Arm (RFA) reaching half CRW and nearly two-thirds half way up RFA by July 2020, as well as in 2018 with less CRW. However, the effectiveness of CRW was diminished by internal loading. The modeled internal loading, with 2017-2019 data, was enough to add 58 ppb to water column TP, or a doubling of the May concentration by mid-summer

Effect of Rocky Coulee Wasteway: Rocky Coulee Wasteway (RCW) has contributed to the inflow TP to Parker Horn. The total inflow from lower Crab Creek averaged 39 ppb the past four years. That was higher than the calculated inflow TP during May-September 2017-2019 of 23 ppb, including 100,000 AF of CRW. Total P in RCW was probably around 80 ppb based on past data and would have contributed about 5 ppb to the calculated inflow of 23 ppb. Nevertheless, the large spring, early summer CRW input held TP in lower Parker Horn and South Lake to a May-September average of 34 ppb diluting out that half-lake volume. The lake TP should have been around 30 ppb without RCW. Also, continuous input of CRW during spring and summer would have probably lowered average inflow TP closer to the calculated 23 ppb average rather than the observed 39 ppb.

Internal loading: Recycling of sediment phosphorus, or internal loading, represents a large source to the water column in summer causing algal blooms. Internal loading contributed 39% of the total (external and internal) during May-September, 1984-1988 after wastewater diversion, and is similarly important now. For example, the average flow-weighted inflow TP concentration during May-September, 2020, including 193,000 AF of low-P CRW, was 32 ppb. That inflow concentration would have produced a volume-weighted, whole-lake TP of around 21 ppb after settling of particulate P. Yet, whole-lake TP was 78 ppb, with the difference coming from internal loading.

Another indication of internal loading was the increase in TP concentration between lows in May and highs in June-July, +41, +48, +63 and +75 ppb at sites TS 5/6, TS 15, TS 11 and TS 12. Inflow concentrations in Crab and Rocky Ford Creeks were relatively constant over that period, so the increases came from in-lake.

Internal loading in lower Parker Horn and South Lake was estimated by calculating sediment-P release rates from the 1970s-1980s data, as well as laboratory core determined rates in the mid-1980s. Average May-September lake TP concentrations estimated from these rates, along with external inputs, were 36 and 48.5 ppb. Those expected concentrations are similar to the observed TP during 2017-2019 of 37 ppb. Without 100,000 AF during those years, average lake TP would have been 63 ppb. These estimates of lake TP omitted effects of carp, which add to internal loading through excretion and sediment disturbance.

Internal loading can be effectively reduced by inactivating mobile sediment-P with alum, as shown with data from over 200 lake treatments worldwide. There was no net internal loading during the DOE study in 2001, when whole-lake average TP was only 28 ppb and blue-green algae represented < 5% of biomass in lower Parker Horn and South Lake and 30% in Rocky Ford Arm. During 2018, blue-greens averaged 82% at those sites and whole-lake TP was 67 ppb, despite 106,000 AF of CRW. The difference was no net internal loading in 2001.

The cost for treating a large lake like Moses Lake is large. So, one approach may be to treat the areas that go anoxic and have high sediment-P release rates. Treating the 400 or so acres below 5 m in South Lake and lower Parker Horn could decrease lake TP by about 35%.

Sediment core analysis: Three cores were collected by HABS personnel in March 2020 and analyzed for total P concentrations. The largest core (64cm) was analyzed for microcystin as well. The average sedimentation rate using the termination of leaded gasoline as a marker (1972), was 0.73 cm/year, comparing closely with 0.625 cm/year by USGS. The core data indicate that sediment-P has decreased since dilution began, possibly due to lowered lake TP concentrations and, therefore lower rated of deposition.

Microcystin was present before irrigation began, assuming a constant rate of sedimentation, but has increased since around the mid-1990s. There was a switch in blue-green algal dominance from *Aphanizomenon* during the 1960s – 1980s to currently *Microcystis*, the producer of microcystin. The switch may be related to higher nitrogen and lower phosphorus, favoring the non-nitrogen fixing Microcystis, as well as an increase in lake temperature of 4.5F during July-August in 2017-2020, compared to 1986-1988.

Inflow nitrate: Nitrate-N concentrations in Crab Creek have increased markedly since 1969-1970 and especially in the last four years. Nitrate-N also increased the past two years in Rocky Ford Creek, but less so than in Crab Creek. Total P remained unchanged in Rocky Ford Creek, but decreased in Crab Creek. While the resulting total N–to-total P ratio in the lake has increased, algal biomass has remained controlled by phosphorus as indicated by chl:TP ratios around the usual average of 0.35. However, increased TN:TP may be favoring *Microcystis.*

Pelican Spring: which enters lower Pelican Horn, is a source of nitrate-N, which has doubled since 1977-1988. The springs high sodium content indicates the high nitrate may come from wastewater. While the volume is relatively small – 7.4 cfs -, the source may indicate changes in near-lake groundwater inputs. Other groundwater inputs sampled in 2001 had nitrate-N concentrations similar to those in 1977-1988 that were half the current levels. Higher ground water nitrate may be contributing to increased lake TN:TP ratio.

Water quality

Water quality in 2020 was slightly worse than the May – September average of the last four years in both the lower lake and Rocky Ford Arm (Table 1). The three indicators of trophic state, TP, chlorophyll and Secchi disc transparency (SD) were nearly the same in lower Parker Horn and South Lake as in 1986-1988 despite 68% more Columbia River water (CRW) in 2020. Total P averaged much lower (23 ppb) during 2002-2016 with 37% more CRW on average than in 2020 (Welch et al., 2019). Lower Parker Horn and South Lake are currently eutrophic (TP>30 ppb) and Rocky Ford Arm is hypereutrophic (TP>50 ppb). Sampling sites are shown in Figure 1.

Table 1. Average May-September TP and chlorophyll (chl) in ppb, transparency (SD) in meters, and % cyanobacteria (2017 and 2018 only) at TS5/6 (lower Parker Horn and South Lake) and TS11/12 (mid and upper Rocky Ford Arm) during 2017-2020. Eutrophic boundaries for TP and chl are 30 and 10 ppb, and transparency 2.0 meters. Hypereutrophy are 100, 30 and 1.0, respectively.

		TP		chl	SD	% cyanobacteria
TS5/6	2017	25	13-48	7	1.4	43
	2018	41	13-65	18	1.4	87
	2019	30	15-60	14		
	2020	41	20-74	22	1.6	
	4-year Average	34	15-62	15		
TS11/12	2017	58	37-69	15	1.0	75
	2018	83	59-119	49		79
	2019	101	52-137	51		
	2020	99	52-175	63	0.9	
	4-year Average	85	50-125	45		

The seasonal average values do not reflect the effect of internal loading. Total P concentrations typically increase in summer, well above the inflow concentrations, as indicated by maximums in Table 1. In 2020, Crab Creek inflow TP increased only 3 ppb from 45 ppb in May to 48 in June-July and Rocky Ford Creek decreased from 220 to 166 ppb. However, lake TP averaged for those months in lower Parker Horn and South Lake increased from 18 ppb to 59 ppb, while Rocky Ford Arm TP increased from 35 to 83 at TS15, 36 to 99 at TS11 and 91 to 166 at TS12. Maximum TPs were even higher at TS 5/6 (74 ppb) and TS 11/12 (175 ppb; Table 1). Those increased TPs were due to internal loading and not to increased inflow because inflow concentrations were largely unchanged during the summer. The effect of internal loading on lake TP was estimated by two procedures, as will be discussed.

Enhancing the effect of dilution water input through Parker Horn into Rocky Ford Arm

Columbia River low-P dilution water (CRW) entering Parker Horn reaches well up into Rocky Ford Arm (RFA) propelled by wind. This was observed in 1977-1978 at the start of dilution and led to abandonment of plans to pump dilution water from Crab Creek to upper RFA (Welch and Patmont, 1980). Observations the past 4 years, using specific conductance as a conservative tracer, as in 1977-1978, has verified that process. The fraction of CRW half way up RFA at TS11 (Connelly Park) was 37, 46, 65 and 60% in May, June, July and August 2020, respectively. There was less CRW in upper RFA (TS12) for those months: 12, 21, 57 and 53%. Although CRW was slower to reach upper RFA, the lake water was more than half CRW by mid-summer. The pattern for those months was similar in 2018; 41, 44, 62 and 61% at TS11, and 26, 35, 55 and 53% at TS12 with less CRW (106,000 AF in 2018 vs 193,000 in 2020). During 2011-2016, CRW averaged 249,000 AF and averaged 74% at TS6 and 67% at TS11 for the summer months.

Total phosphorus (TP) concentrations increased in RFA during summer despite the presence of CRW. The last four-year average TPs at TS11/12 combined for May, June, July and August were 57, 78, 114 and 92 ppb, respectively. The increase was due to internal loading, or recycling of sediment P, into the water column. A similar increase in 2017-2019 gave a calculated summer sediment-P release rate for the whole RFA of 4 mg/m^2 per day (Tetra Tech, 2020). At that rate and mean depth of 6.2 m, 58 ppb of TP was added to the water – a doubling of the May concentration. The summer increase in TP was not due to Rocky Ford Creek inflow, which was rather constant. Also, the relatively low May TP of 57 ppb, before the summer increase began, was probably due mostly to Rocky Ford Creek, which was 32% of total loading to RFA in 2017-2019, while internal loading contributed 64% of total load, including carp excretion (Tetra Tech, 2020).

These data indicate that while CRW reached well up into RFA, its dilution effect on the high TP entering from Rocky Ford Creek was diminished by the high rate of internal loading. If internal loading were reduced by inactivating sediment-P, CRW currently transported to Parker Horn via Rocky Coulee wasteway and Crab Creek would have a much greater effect diluting the inflow from Rocky Ford Creek and lower TP concentration in RFA.

Effect of Rocky Coulee Wasteway on inflow phosphorus

Total P concentration in the inflow to Parker Horn the past four years was surprisingly high with an average 39 ppb and an average range of 20 to 56 ppb - despite large inputs of Columbia River water (CRW; Table 2). That average was only 20% less than the average TP in upper Crab Creek (TS2) of 53 ppb. The average inflow TP for 2020 was lowest of the last four years at 29 ppb, due to 90% more CRW (193,000 AF).

The calculated average expected inflow TP for 2017-2019, with about 100,000 AF of CRW, was 23 ppb, volume-weighted from the four inputs; Crab Creek (47 ppb), RCW (77 ppb), CRW (7 ppb) and groundwater (57 ppb). Total P in RCW was 153 ppb in 1969-1970 with minimal CRW, 77 ppb in 1986-1988 and 87 ppb in 2001, both during no CRW input.

Thus, RCW itself, at around 80 ppb, had an apparent effect of adding about 5 ppb to the input TP concentration to Parker Horn. Nonetheless, CRW input held average lake TP (34 ppb) below the average inflow TP (39 ppb) during the past four years (Table 2). That is because the large spring-early summer CRW input, with 7 ppb TP, diluted out the lake volume and that lower lake TP concentration persisted due to the 14-day residence time of CRW. However, the average lake TP of 34 ppb should have been lower (around 30 ppb), due to uptake of P by algae and settling out of particulate P from the water column. Also, internal loading added to the lake TP concentration, as indicated by the average maximum of 62 ppb, which was double the average inflow, due to recycling of sediment P (Table 2).

If 100,000 AF of CRW were delivered continuously during April to September at an average of 270 cfs, instead of most entering during April to June, inflow TP may have been lower than 39 ppb and closer to the calculated inflow of 21 ppb. That assumes there were no other inputs that contributed to the CC average of 39 ppb. Lake TP concentration may also have been lower than 34 ppb.

Table 2. Average TP concentrations during May-September for the respective sampling sites and periods. Sites TS2 and TS3 are, respectively, upstream and downstream of Rocky Coulee Wasteway (RCW)

	Crab Cr. up TS2	Crab Cr – down TS3	Rocky Coulee Wasteway	Lake TS5/6 0.5 m
1969-1970	111	No data	153	152
1986-1988	46	37	77	41
2017-2020	53 (36-79)	39 (20-56)	No data	34 (15-62)

Internal Loading

Methods to determine internal loading

Internal loading, or recycling of bottom sediment phosphorus into the water column, is usually the principal source producing summer algal blooms in many lakes. Release of phosphorus from sediments is highest in summer as water temperature increases promoting microbial activity that lowers oxygen in bottom water.

Moses Lake, having a large surface area and wind fetch is highly susceptible to the effect of internal loading. It's deep enough (11 m) to stratify allowing DO below about 5 m to deplete and sediment P to release at relatively high rates. Also, it's shallow enough for wind to mix the water column from time-to-time entraining high TP that is mostly soluble (SRP) from bottom water to the surface that can stimulate algal growth. If the lake were deeper and with less wind fetch, high P water would tend to stay locked below the 5 m level and unavailable for algae for most of the summer, as is the case for strongly stratified lakes. However, Moses Lake is polymictic, so internal loading, including sediment resuspension and entrainment of high-TP bottom water, leads to higher surface TP concentrations during summer and higher algal production. Therefore, substantial reduction of algal biomass in summer is unlikely without reducing internal loading.

Internal loading averaged 39% of total phosphorus loading during 1984-1988, after wastewater diversion. Also, internal loading was highly correlated with weakened density stratification due to wind during 1977-1988. Recent analysis of cores shows that sediment phosphorus concentrations have not changed since the 1980s and most of the water column phosphorus in lower Parker Horn and South Lake during summer originates from internal loading

Internal loading has been and still is an important source of phosphorus causing algal blooms in Moses Lake. Internal loading can be determined by several methods including: 1) as a net result of loss/gain to/from the sediment calculated in a mass balance of inputs and outputs; 2) direct measurement of sediment release in the lake or in sediment cores in the laboratory; and 3) calibrating a mass balance model to inputs, outputs and the observed change in lake TP concentrations. No. 1 was applied to Moses Lake during 1977-1988 (Welch et al., 1989), No. 2 for Moses Lake in the mid-1980s and recently No. 3 for Rocky Ford Arm (Tetra Tech 2020). Each has strengths and weaknesses.

Net internal loading from mass balance (No. 1) averaged 9,345 kg during 1984-1988 (Welch et al., 1989). Sediment core release rates determined in sediment cores in the laboratory in 1984 (No. 2) were used to calculate 7,013 kg from oxic and anoxic areas of the lake (Okereke, 1987). Although carp excretion contributed to the higher net internal loading determined by mass balance, the similar magnitude of estimates by the two methods indicate that sediment release is a major source.

An alternative indication of internal loading

Another way to view the relative importance of internal loading is to compare the lake TP concentration predicted from the flow-weighted inflow concentration with the observed volume-weighted (v-w) whole lake concentration.

Average inflow TP during May-September, 2020, was 46 ppb in Crab Creek, 161 ppb in Rocky Ford Creek and 8.7 ppb in Columbia River dilution water (CRW). Total P in ground water and Rocky Coulee Wasteway base flow were assumed at 59 ppb and 87 ppb, respectively, from earlier investigations (Carroll, 2006).

The flow-weighted inflow concentration to the lake from those principal external sources was 32 ppb using past average flows, except for CRW, which was higher in 2020 at 193,000 AF than the past four years. That 32 ppb would have been the average v-w whole-lake TP concentration before loss through sedimentation. Predicted v-w whole-lake TP from that inflow of 32 ppb, minus sedimentation loss, as a function of water residence time, would have been 21 ppb. In fact, the observed v-w whole lake TP was 78 ppb, including lower Parker Horn (TS 5, 48 ppb), South Lake (TS 6, 63 ppb), Cascade (TS 15, 60 ppb) and Upper Rocky Ford Arm (TS 11/12, 99 ppb). Higher TP concentrations at depth, due to constant anoxia, were included at TS5/6. Temporary anoxia at the sediment surface occurred in Rocky Ford Arm.

Combining the sites and their respective lake volumes for a whole-lake TP concentration is reasonable, because tracing with specific conductance shows that CRW is nearly as prevalent in upper Rocky Ford Arm (RFA, TS11/12) as in the lower lake (TS 5/6) by midsummer. Percent CRW reached 60% in upper RFA in 2020 with CRW input at 193,000 AF, as well as in 2018 with 106,000 AF of CRW. From 2011-2016, CRW input averaged 249,000 AF while the CRW fraction averaged two thirds of total volume at TS 11 and nearly three fourths at TS 6. The 193,000 AF of CRW in 2020 represented 1.6 whole-lake volumes with an average whole lake replacement rate of 0.9%/day.

Source of high TP concentrations in June/July in 2020

These large increases in lake surface TP concentrations indicate the source was internal loading from bottom sediment in the lake and not from surface inflow, because TP concentrations in Crab Creek and Rocky Ford Creek were essentially constant and could not have increased lake concentrations by 50-70 ppb (Table 3). The low lake concentrations in May, averaging 41% lower than June-July, partly reflect dilution from the 135,000 AF of CRW entering Parker Horn and extending part way up Rocky Ford Arm. The subsequent increased TP by 57% reflects the increase from internal loading.

The lake TP increases in June/July were likely not due to ground water either, because ground water TP concentration and flow would not be expected to increase sufficiently in only one-two months. Also, the ground water TP concentration used by DOE to calculate loading in 2001 was 59 ppb and 50 ppb was used by UW in 1977-1988; both well below June-July lake TP concentrations. Ground water was estimated at about 4% of TP input to RFA (Tetra Tech. 2020).

Table 3. Change in inflow total P in ppb and the lake at 0.5 m in 2020. TS5/6 represents Lower Parker Horn/South Lake, TS15 is lower Rocky Ford Arm, TS11 is the Connelly Park area, andTS12is upper Rocky Ford Arm.

site	May	June/July	+/-
Crab Cr.	51	45	-6
TS5/6	18	59	+41
RFCr.	172	175	+3
TS 15	35	83	+48
TS11	36	99	+63
TS12	91	166	+75

Another indication that increased TP concentrations came from sediment release is that TP at 0.5 m above bottom at TS5/6 in July was 122 ppb and DO was less than 1 mg/L, indicating anoxia, which allows high release rates that were found to be ten times the rate from oxic sediments (Okereke, 1987). Bottom water TP usually increases during summer as anoxia persists. Bottom water with high P may become entrained into surface water, available to algae, with wind mixing events and low water column stability (Welch et al., 1989).

The same pattern of increased TP, in excess of the concentration in Crab Cr., existed in the previous three years, but not to the extent as in 2020 (Table 4).

Table 4. Change in average total P at 0.5 m in 2017-2019
At TS5/6, TS11 and TS12.

site	May	June/July	+/-
TS5/6	16	35	+19
TS11	43	68	+25
TS12	67	105	+38

Internal loading in Parker Horn and South Lake during 2017-2019

Internal loading is the continual recycling of phosphorus originally deposited from external inputs. Release rates from sediment are greater in the absence of oxygen (anoxic). Areas of Moses Lake with depths greater than 5 meters usually go anoxic during thermal stratification of the water column in summer. Anoxic release rates were ten times greater than from oxic sediments observed in sediment cores in the laboratory (Okereke, 1987).

Internal loading can be determined by mass balance if inputs to and from the lake are known (method No. 1). Internal loading determined from 1984 to 1988 (after wastewater diversion) showed the internal fraction averaged 39% of total external plus internal and varied by 17% from year-to-year (Welch et all, 1989). Anoxic sediment release rate can be determined by the increase in phosphorus in the bottom water layer (hypolimnion) during summer, as well as in sediment cores incubated in the laboratory (Okereke, 1987). Wind-caused resuspension of sediment can also be important in shallow lakes, as can aerobic release and carp excretion. All processes are included in a mass balance.

Table 5 shows sediment P release rates recently calculated using total phosphorus (TP) concentrations from South Lake bottom water during 1977-1978 and 1986-1988 (data from Welch et al., 1989).

Table 5. Calculated sediment-P release rates (internal inputs) from 1970s-1980s data, laboratory core release rates from Okereke (1987), and resulting lake TP concentrations from those rates, in areas (%) of lower Parker Horn and South Lake during May-September.

Source of data	area, acres	%	oxygen	Sed-P release mg/m^2 per day	lake TP ppb
This analysis	326	20	anoxic	4.1	15.6
Okereke 1987	519	32	anoxic	10.0	30.8
This analysis	1311	80	oxic	2.0 w/ carp	5.4
Okereke 1987	1118	68	oxic	1.2 w/ carp	2.7

Table 6 and subsequent explanations illustrate the importance of internal loading to lake TP concentration during the spring-summer period during 2017-2019. Internal loading can often deliver more phosphorus for algal production than from external loading during summer and is probably the case in Parker Horn and South Lake, shown here, as well as most of Rocky Ford Arm.

Using the release rates in Table 5 calculated for anoxic water of 4.1 mg/m^2 per day and the oxic release rate of 1.0 mg/m^2 per day from Okereke (wo/ carp) gives an area-weighted, total sediment release rate (wo/ carp) for lower Parker Horn and South Lake of 1.6 mg/m^2 per day. The daily net rate from mass balance during 1977-1988 (wo/ 1980 ashfall year) gave the same whole lake areal May-September rate of 1.6 mg/m^2 per day. This indicates that release rates determined by different methods can give similar results. Rates determined from sediment cores in the laboratory have agreed closely with rates determined by TP increase in the hypolimnion in other lakes. Sediment cores from the 1980s and recently show that sediment TP has decreased by 22% (Table 7), so the average sediment release rate now may be slightly less than observed in the 1970s-1980s of 1.6 mg/m2 per day.

The observed sediment-P release rate from five years in the 1970s-1980s is an average and rates vary from year-to-year depending largely on weather. Internal loading calculated by mass balance during eight years (1977-1988) varied by 100% depending mostly on water column stability affected by wind.

Table 6. Expected May-September average lake TP concentrations in South Lake and lower Parker Horn from internal inputs (anoxic+oxic sediment release) compared and combined with external inputs w/ and wo/ low-TP Columbia River water (CRW) at 100,000 AF, expected resulting lake TP concentrations (ppb), and observed lake TP concentrations. Water residence time (T) in half the lake = 0.59 years wo/CRW and 0.19 years w/CRW. Lake TP estimated by TP lake = TP inflow/(1 + √T) from Brett and Benjamin (2008).

Expected lake TP concentrations from internal inputs (ppb):	lake
Internal input: This analysis 15.6 + 5.4	21.0
Internal input: Okereke 1987 30.8 + 2.7	33.5
Expected lake TP concentration from external inputs (ppb):	
External input: Crab Cr.+groundwater+RCW = 48	27.0
External input: Crab Cr.+groundwater+CRW+RCW = 21	15.0
Expected lake TP concentration form internal plus external inputs:	
Internal+external: this analysis (21 + 15)	36.0
Internal+external: Okereke 1987 (33.5 + 15)	48.5
Observed lake TP, lower Parker Horn & South Lake 2017-2019	32.0 at 0.5 m
Estimated lake TP adjusting for higher deep-water TP	37.0 water column
Estimated lake TP from external (27) + internal (36) wo/ CRW	63.0 water column

These estimates of internal loading in lower Parker Horn and South Lake during 2017-1019 show that internal loading (21-33.5 ppb) would have added more (1.4-2.2-fold) to lake TP concentration (21-33.5 ppb) during summer than external loading (15 ppb) and that internal loading plus external loading (35-48 ppb) approximated observed lake TP (37 ppb). Also, without dilution from CRW, estimated lake TP would have averaged 63 ppb with a much larger maximum. The lower expected lake TP concentrations than entering the lake from inflow are due to water residence time that allows settling loss. CRW input of 100,000 AF was about the quantity that entered the lake in 2017, 2018 and 2019.

Control of Internal Loading.

The most effective method to reduce internal loading is to inactivate sediment phosphorus with alum (liquid aluminum sulfate), which is distributed by barge and metered in proportion to depth delivering the prescribed dose determined by sediment mobile -P concentration. Recent analysis of over 200 lake alum treatments world-wide found that properly dosed treatments effectively lowered lake phosphorus and lasted ten years on average (Huser et al., 2016). While alum floc layers tend to gradually sink through the soft bottom sediment, aluminum continues to sorb and inactivate sediment phosphorus enhancing treatment longevity (Welch et al., 2017). Alum is dosed to inactivate mobile phosphorus in usually the top 4 inches of sediment, but sometimes the top 8 inches.

A possible cost-effective approach for Moses Lake may be to start by alum treating the areas deeper than about 5 m that go anoxic and produce high rates of sediment-P release, which are 10 times those from oxic sediments shallower than 5 m. The anoxic area in South Lake and lower Parker Horn is about 400 acres. A detailed bathymetric map is needed to accurately determined those areas. An applicator can treat an area deeper than 5 m with GPS and auto depth recording. Using the estimates in Table 6, treating the 400-acre area should reduce internal loading by 80% and result in lowering TP in South Lake and lower Parker Horn from an average of 37 ppb to 24 ppb, or 35%. That assumes 100,000 AF of CRW (Table 6). Accuracy can be much improved with a calibrated mass balance TP model and detailed bathymetry.

Effect of reducing internal loading

What are the prospects for improved water quality if whole-lake TP were reduced by sediment inactivation? The DOE study in 2001, in which a TP mass balance showed no net internal loading, suggests a possibility. Whole-lake volume-weighted (v-w) TP in 2001 was 28 ppb and 17 ppb in South Lake (TS6) and lower Parker Horn (TS5). Blue-green algae were not dominant, representing < 5% of algal biovolume in lower Parker Horn and South Lake, and 30% in RFA (TS 11) during May-September with CRW input at 230,000 AF (Carroll, 2006). In contrast, percent blue-greens averaged 82% at TS 5, 6, 11 and 12 and whole-lake TP was 67 ppb in 2018 with CRW input at 106,000 AF.

Lake TP was low in 2001 because there was no net internal TP loading as determined by mass balance, in addition to the large input of CRW (Carroll, 2006). Why there was no net internal loading is unclear. There was also no net internal loading in 1980 when Mt. St. Helens' ash covered bottom sediment with a four-inch layer and the input of CRW was only 27,000 AF. Internal loading was substantial in 10 of the other 11 years during 1977-1988 after dilution began and averaged 39% of total loading during 1984-1988 after wastewater was diverted (Welch et al., 1989).

Dilution with CRW is essential for acceptable water quality even if internal loading were markedly reduced. Without 193,000 AF in 2020 and no internal loading, v-w inflow TP would have been 82 ppb instead of 32 ppb, and estimated v-w whole lake TP at equilibrium after sedimentation loss would have been 37 ppb instead of 21 ppb. In fact, v-w, whole-lake average TP was 78 ppb, with the 41-ppb difference due to net internal loading.

Phosphorus, lead and microcystin in sediment

Table 7 shows sediment total phosphorus (TP), lead (Pb) and microcystin results from three cores collected by personnel from HABS (alum applicating Co.) in March, 2020 at TS5, TS6 and TS15, with the deepest at TS6 (South Lake). Microcystins were analyzed by King County and lead and phosphorus by IEH.

Table 7. Concentrations of TP and Pb from the top 30 cm are from all three cores and concentrations below 30 cm are from the 64 cm core at TS6. Microcystins are from the 64 cm core only. Concentrations for TP and Pb are in mg/kg as dry weight and microcystins are in µg/kg or parts per trillion.

	TP	Pb	microcystins	
0-4 cm	733 ± 72	1.43 ± 0.38	0.391	
4-10	728 ± 61	1.56 ± 0.35	0.542	
10-20	645 ± 76	1.51 ± 0.34	0.315	1993-2006
20-30	616 ± 90	1.68 ± 0.32	0.128	
30-40	598	1.77	0.087	1965-1979
40-50	839	2.57	0.113	
50-64	898	2.56	0.117	1933-1952

Lead and sedimentation rate

Table 7 shows lead concentrations in lake sediment that were used to estimate sedimentation rate assigning 1972 as a marker that was roughly the end of using leaded gasoline. Lead from exhausts entered lakes via atmospheric deposition to the lake surface and runoff from the watershed. These lead concentrations have not returned to near zero before leaded gasoline probably due to continued runoff from land. Lead concentration decreased in Moses Lake between 30-40 and 40-50 cm, so assuming about 35 cm as a marker for 1972 would give a sedimentation rate of 0.73 cm/yr (35/48), or 0.29 inches/yr. The USGS calculated 0.625 cm/yr or 0.25 inches/yr, using the 1980 Mt. St. Helens ash layer as a marker. Those sedimentation rates are about double the rate for Lake Sammamish. At 0.73 cm/yr, the depth of 50 - 64 cm represents 68 and 87 years ago or about 1952 and 1933. Those dates are before the Columbia Basin irrigation project. At 0.625 cm/yr 50-64 cm represent 1940 and 1918. Using 0.73 cm/yr, 40 cm represents the mid-1960s, which is realistic given that the use of leaded gasoline ceased around 1972.

Phosphorus

The corresponding TP data indicate that sediment TP has decreased since dilution started in 1977 and diversion of wastewater in 1984. At 0.73 cm/yr and TP concentrations below 40 cm, which was about 1965, gives an average content of 869 mg/kg and an average of 680 above 30 cm, or about 1979, for a decrease in TP of 22% since dilution began. That percent would be more accurate if more frequent core intervals had been sectioned. Nevertheless, these data do show a noticeable decrease in sediment TP. The decrease in TP may indicate that sediment-P release rates (i.e., internal loading) have also decreased since dilution started. Much lower lake TP concentrations (53-78%) since dilution began would have resulted in lower TP deposition rates and, thus, lower sediment TP concentrations.

Microcystins

Microcystins increased above a depth of 20 cm, which was around the mid-1990s. Earlier, microcystins were present but in lower concentrations. The increase may be related to *Microcystis* becoming the most dominant blue-green alga, which represented 78% of blue-green biovolume in July-September at TS5,6,11,12 in 2017-2018. *Aphanizomenon,* which produces neurotoxins, but not microcystin, was by far the dominant blue-green from 1969 to 1988 and in 2005; Bergoon, 2006). For example, *Aphanizomenon* was 95% of blue-green biovolume and *Microcystis* only 3% in July 1986. Why Microcystis has become the most dominant blue-green may be related to temperature and nitrogen. Two possibilities are: 1) surface water temperature was 4.5F warmer during July-August in 2017-2020 than in 1986-1988, and 2) nitrogen:phosphorus ratios have been much greater in recent years due to reduced phosphorus in the lake and higher nitrate in Rocky Ford Creek and Crab Creek (Welch et al., 2019). Unlike *Aphanizomeno*n, which was the dominant blue-green until recently, *Microcystis* does not fix atmospheric nitrogen – an advantage for *Aphanizomenon* in high phosphorus low nitrogen lakes. Thus, the decrease in TP and increase in nitrogen relative to phosphorus, as well as the increase in temperature, may have favored *Microcystis.*

Future cores

The sectioned depth intervals are sufficiently narrow to see decadal changes, but the range is too great to be certain of more specific dates related to events and their implications. Also, sedimentation rates vary year-to-year, so an average long-term sedimentation rate may not be realistic. To increase accuracy of past events, two replicate cores to 60-70 cm should be collected at TS6 and T15 and analyzed for TP, lead and microcystin at 2-cm intervals. For more year-to-year accuracy, dating with lead-210 can be used.

Increased inflow nitrate

Inflow stream nitrate concentration

Table 8 shows that nitrate-nitrogen has increase significantly in Rocky Ford Creek and Crab Creek inflows to the lake the last few years, while total P has remained rather constant in Rocky Ford Creek and decreased in Crab Creek. Data from USBR and MLIRD were in relatively close agreement, given that the year-to-year variation in inflow nitrate was around ±30%. Nitrate-N during 2017-2018 (1245 ppb) was similar to concentrations during earlier years in Rocky Ford Creek, but average concentrations increased the last four years in Crab Creek (including 1187 ppb in 2017-2018), as well as since dilution began. As a result of increased N in the inflow and decrease P in the lake due to dilution, the total nitrogen-to-total phosphorus ratio (TN:TP) has increased in the lake.

Table 8. Average concentrations in ppb of nitrate-nitrogen and total phosphorus during May-September in Crab Creek, Rocky Ford Creek and Pelican spring for the time periods indicated. Sampling frequency for MLIRD and UW was usually twice monthly May-September and for USBR usually four times during spring-fall. Pelican spring data are from 1979-1987 and 2017-2020.

	1969-1970 UW	1977-1988 UW	2003-2018 USBR	2019-2020 USBR	2019-2020 MLIRD
Crab Creek					
Nitrate-N	542	929	794	1140	1437
Total P	93	62	48	45	49
Rock Ford Cr.					
Nitrate-N	1346	1125	1200	1534	1735
Total P	185	151	164	161	155
Pelican spring					
Nitrate-N		6292			12871
Total P		80			119
Lake TN:TP ratio	7.5	7.3	19.6	16.9	no TN

Increased TN:TP in the lake has probably favored the blue-green alga *Microcystis* (MA), which is a non-N-fixer, and is the prime producer of microcystin. The other major blue-green, *Aphanizomenon* (APH), which dominated previously before and after dilution, is favored by low TN:TP ratios, because it can supply its N via fixation of atmospheric N. Algae have a N:P ratio in their cells of about 7.2, so in-lake ratios <7.2 favor N fixers. Thus, when N is in low concentration relative to P, APH has the advantage and dominates. The sediment core analysis showed that microcystin has increased in the lake since the 1990s, which may be due to the raised N:P ratio favoring MA.

Is this recent increase in inflow nitrogen due to increased use of fertilizer or increased atmospheric deposition? Atmospheric deposition of N tripled from pre industrial times to the 1990s. The recent increase in inflow nitrate-N is probably not due solely to increased atmospheric deposition.

While increased inflow nitrogen and TN:TP ratio in the lake may be related to the shift in dominant blue-greens and the increase in microcystin observed in the sediment core, phosphorus has determined the magnitude of total algal mass, as is usually the case in world-wide lakes. The average chlorophyll:TP ratio for world lakes is 0.35. That ratio the past four years in Moses Lake averaged 0.32 in lower Parker Horn and South Lake and 0.43 in Rocky Ford Arm, demonstrating the dependence of algal biomass on phosphorus.

Pelican Spring

Nitrate-N concentration in the constant flow ground water source entering the lake on the east side of lower Pelican Horn has doubled since 1977-1988. Also, nitrate-N in the spring (MLIRD) was about eight times the content of Rocky Ford Creek and Crab Creek in 2019-2020 and six times the creek inflows during 1977-1988 (Table 8).

These very high concentrations indicate either fertilizer or human wastewater as a source. The recent high sodium content in the spring water (65 ppm) is close to that of Moses Lake wastewater in 1982 (82 ppm), before diversion, indicating the source is wastewater. Spring water sodium and nitrate-N are much higher now than in in the past; 2.6 and 6.3 ppm, respectively in 1986-1988 versus 65 and 12.9 ppm (12871 ppb) now. Sodium content in lower Parker Horn and South Lake was 12-16 ppm in recent years, having been diluted with Columbia River water with 2.4 ppm sodium.

Sodium is conservative, i.e., it stays in solution and not sorbed by soil particles. Using sodium as a tracer showed that ground water flow from the east side of lower Pelican Horn has not changed much; 9.1 cfs in 1982 and 7.4 cfs in 2017; Welch, 2018). Thus, that ground water source is not a large contributor in itself of phosphorus and nitrogen to the lake. On the other hand, it may indicate changes in nutrient content of ground water in other areas around the lake. Its TP content is larger than was used to estimate external loading to the lake from ground water in 1977-1988 (50 ppb), and in 2001 (59 ppb; Carroll, 2006).

The large increase in spring nitrate-N may indicate that nitrogen loading to the lake from ground water in other areas has increased. Ground water sampled with piezometers along the east side of Rocky Ford arm (2 sites), Lewis Horn (2 sites) and the east side of Pelican Horn (2 sites) showed an average nitrate-N concentration of 6.61 ppm (6610 ppb) during May, July and October, 2001 (Pitz, 2003). That is close to the average concentration (6.29 ppm) in Pelican Spring during 1977-1988, which doubled in 2017-2020 (12.9 ppm). Thus, ground water nitrate-N may have increased in other parts of the lake, as well as in Pelican spring, and contributed to the increased TN:TP ratio in the lake.

Recommendations

1. Continue twice-monthly monitoring of the lake's water quality from May through September. Add the collection of samples for algae analysis according to procedures used in 2017-2018. Samples should be collected at least monthly at sites TS5, 6, 11 12 and 15. Knowing the changes in the blue-green fraction of algae and that of *Microcystis*, the microcystin producer, is important for management of the lake's water quality.
2. Develop a calibrated mass balance model to predict whole-lake TP. The model will allow evaluating effects on lake TP of reducing external and/or internal sources of phosphorus.
3. Digitize the existing bathymetric map of the lake to determine areas and volumes of depth contours. Those data are needed for model development and delineating given depths for treating internal phosphorus sources.

4. Determine the additional on-site household septic drain fields installed near the lake since the DOE ground water study in 2001. Estimate the magnitude of nitrate and soluble P that may enter the lake from these sources. Has the input of N and P from nearshore ground water sources changed since 2001? Data from Pelican spring indicate that ground water nitrate has doubled since the 1970s-1080s and the DOE ground water study in 2001. Increased nitrate in inflow streams and ground water may be favoring the dominance of *Microcystis*.

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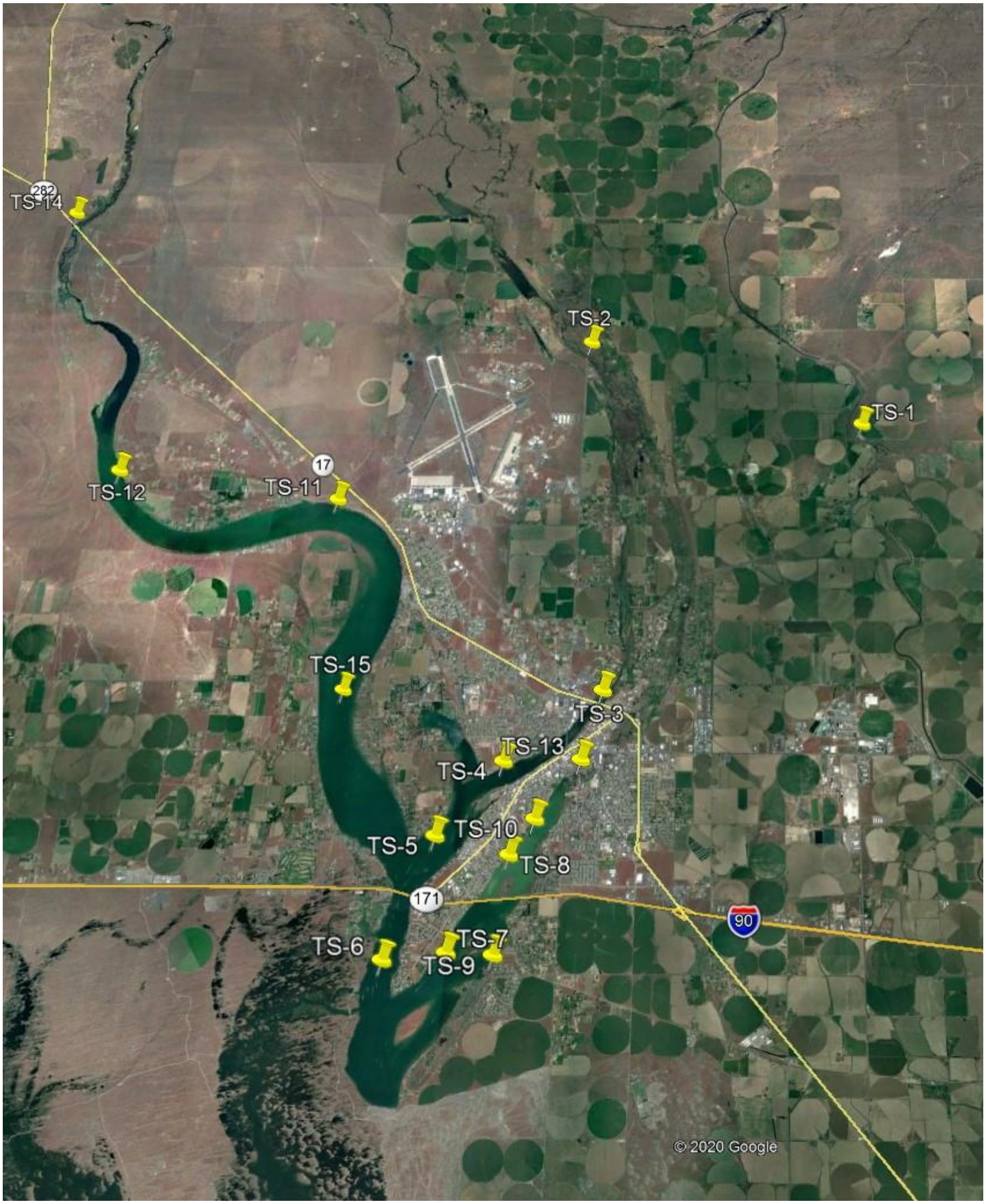

Figure 1. Location of sampling sites in the inflows and lake. These sites are the same as sampled during 1969-1970 and 1077-1988.