Moses Lake Water Quality:
Effects and Benefits of Columbia River Dilution Water

Prepared for Moses Lake Irrigation and Rehabilitation District

By

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Introduction

This report is a collection of analyses and short summaries that describe the lake's water quality during 2021, as well as in recent and past years and probable causes for year-to-year changes in water quality.

The lake has been diluted with low phosphorus Columbia River water (CRW) for 45 of the past 46 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., 1989; 2019). Nevertheless, blue-green algae dominated in most summers and *Microcystis* has become the principal blue-green species. While excessive microcystin concentrations were determined recently, that toxic product of the algal species *Microcystis aeruginosa* was in the lake before dilution began, but the species' dominance may have started in the 1990s. Reducing algal biomass, blooms of blue-greens and their fraction of total algae, require lowering lake surface (0.5 m) total P to around 20 ppb. Results from the large amounts of CRW in 2001 and 2021 show that such a goal is possible because the May-September average TP was, respectively for the two years, 19 and 20 ppb in the lower lake and 36 and 42 ppb in Rocky Ford Arm (RFA). Also, blue-greens were not the dominant algal group in either year.

Methods

Water Sample Collection and Analysis

Water samples were collected by MLIRD personnel with a Van Dorn bottle twice per month in 2021, as in past years, at a depth of 0.5 m at nine lake sites during May-September (Figure 1). Samples were collected through the water column in 2020 and 2021. Inflows were sampled at two sites on Crab Creek (TS2, TS3), and one each at east low canal (TS1), Rocky Ford Creek (TS14) and a ground water source (TS9).

Samples were shipped on ice to IEH Analytical Laboratories, Seattle, WA, for analysis of total P, total N and nitrate-N (NO_3-N). Chlorophyll was determined in the same lake samples on residue following filtration in the laboratory. Analytical procedures were according to standard methods (Eaton et al., 2005). Specific conductance (SC), dissolved oxygen (DO) and temperature were determined *in situ* at all lake sites coincident with water sampling.

Water samples for algae identification and enumeration were also collected from the Van Dorn bottle water, coincident with the sample for other constituents. Samples for algae were collected during regular monitoring events in June, August and September in 2021. Algal abundance was determined as cells/ml and also expressed as biovolume in mm^3/L based on measured cell volumes of individual species observed. Samples were analyzed by Algae Analytical Services.

Water column stability, or resistance to mixing by wind is defined by RTRM – relative thermal resistance to mixing: RTRM = $(D_{bottom} - D_{surface})/(D_4 - D_5)$ where D is water density at the surface and bottom and at 4C and 5C.

Specific conductance (SC) was used to trace CRW in the lake and determine % lake water or % CRW according to Welch and Patmont (1980). SC, in µS/cm, is much lower in CRW (142) than in Crab Creek (491) and Rocky Ford Creek (371), which allows tracing of CRW.

$$100 [(LW – ELCW) / (CCW – ELCW)] = \% LW$$

$$(\% CRW = 100 - \% LW)$$

Improved lake water quality in 2021

Lake water quality in 2021 was much improved over that in 2017-2020, probably due to more low-P Columbia River dilution water (CRW): 2017 - 75,456; 2018 – 105,758; 2019 – 119,077; 2020 – 186,813; 2021 – 230,003 AF. The trend has been for more CRW each year averaging 28%/year. Average TP and algal biomass (chl) were lower and transparency greater in 2021 than during past years (Table 1).

Table 1. May-September average total phosphorus (TP), chlorophyll (chl), both in µg/L or ppb, and % cyanobacteria of total algal biovolume in water sampled at 0.5 meters, and Secchi disc transparency during 2017-2021. TS5/6 = Lower Parker Horn/South Lake and TS11/12 = middle and upper Rocky Ford Arm. NS = not sampled. Chl* = chlorophyll estimated from chl/TP ratios, 0.32 at TS5/6 and 0.26 at TS11/12 for the 2 months wo/ lab analyses. Sampling usually twice monthly by the MLIRD crew and samples were analyzed by IEH Laboratory in Seattle.

Site	year	TP		chl	SD	%BG	days	AF CRW
TS5/6	2017	25	13-48	7	1.4	43	50	75,456
	2018	41	13-65	18	1.4	87	76	105,758
	2019	30	15-60	14	NS	NS	67	129,077
	2020	41	20-74	22	1.6	NS	93	186,813
	2021	**20**	**10-49**	**7***	**3.0**	**16**	**163**	**230,003**
5-year	Average	31	14-59	14				
TS11/12	2017	58	37-69	15	1.0	75		
	2018	83	59-119	49	NS	79		
	2019	101	52-137	51	NS	NS		
	2020	99	52-175	63	0.9	NS		
	2021	**42**	**25-88**	**11***	**1.9**	**24**		
5-year	Average	77	41-118	38				

There was actually more CRW early in 2020 (ave. April 981 cfs, May 1280 cfs) than in 2021 (ave. April 730 cfs, May 1112 cfs). However, CRW was more effectively transported throughout the lake in 2021. Lake water was over half CRW earlier in 2021 than previous years. CRW was 80% in Lower Parker Horn/South Lake and 60% in middle Rocky Ford Arm in June 2021. CRW had usually reached 50-60% of lake water in Lower Parker/South Lake (TS5/6) by mid-summer in the past four years, and later in Rocky Ford Arm (RFA, TS11/12). Prevailing wind from the south effectively distributes CRW throughout the lake, as determined in the 1970s-1980s (Welch and Patmont, 1980; Welch et al., 1982).

Total P concentrations were much lower in 2021 than during the previous four years, accounting for less algal biomass (chl) and greater transparency, which is a function of the concentration of algae (Table 1). The fraction of algal biomass represented by blue-greens (cyanobacteria) was also much less in 2021 due directly to lower TP concentrations. There were no cyanobacteria in June and they were not dominant even in August. *Microcystis*, the microcystin producing species, was still the dominant blue-green, as it was in 2017 and 2018. Algae were not sampled in 2019 and 2020. Algal biomass (chl) did increase in September and October in 2021 and cyanobacteria increased to 30-41% of total algal biovolume.

The five-year average TP of 32 µg/L in Lower Parker Horn/South Lake was below the action criterion of 35 µg/L set by DOE for Columbia Basin lakes. If TS7 and 15 (Lower Pelican Horn and lower RFA) were included the average TP was 34 µg/L. That concentration was still less than the action criterion and represents half of the lake's area at 3,370 acres. However, to minimize cyanobacteria, maintaining a May-September average concentration of around 20 µg/L observed this past year would most likely achieve the observed 2021 water quality conditions. Cyanobacteria were < 5% in Lower Parker Horn/South Lake in 2001 and 30% in RFA when CRW was 230,433 AF, while TP was 19 ppb at lower Parker Horn/South Lake, 36 ppb in RFA and there was minimal net internal loading (Carroll, 2006). Low TP persisted at South Lake through 2016 at an average of 23 ppb (USBR data) as CRW averaged 263,000 AF/year (Welch et al., 2019).

Total P in RFA was usually more than the lower lake, but still maintained relatively low average TP and chl concentrations and higher transparency in 2021, compared to 2017-2020. Also, percent cyanobacteria was lower than in past years, as was observed in the lower lake.

Internal loading was the principal source of TP contributing 50% and 55% of the total load to the lake in 2020 and 2021, respectively, and 60% to RFA in 2019 (Tetra Tech, 2020, 2021, 2022). Total P increased in late September 2021 to 33 µg/L in lower Parker/South Lake and 71 µg/L in RFA, from 15 and 33 µg/L, respectively, in the previous months. That increase was due to internal loading. Nevertheless, the May-September average in 2021 was lowest of the last five years at 20 and 42 µg/L, at lower Parker/South Lake and RFA, respectively, indicating that there was more effective transport of CRW throughout the lake and dilution of internal loading in 2021.

Internal loading to the lake was consistently high averaging 39% of total loading during 1984-1988, after wastewater was diverted from Middle Pelican Horn, and varied 17% from year-to-year. Large inputs of CRW may tend to minimize the effect of internal loading by diluting phosphorus recycled from sediment. There were large inputs of CRW in 2020 (186,813 AF) and 2021 (230,003 AF) and 50% and 55% of total loading was from internal sources, yet surface and whole-lake TPs in 2020 were double those in 2021 (Table 1; Tetra Tech, 2021, 2022). Dilution was apparently more effective in 2021 as %CRW occurred earlier and was larger in 2021 than 2020.

Wind mixing has a positive effect on summer internal loading by destratifying the water column density gradient, indicated by RTRM – relative thermal resistance to mixing - and entraining high-P bottom water. Thus, internal loading was inversely related to the water column density gradient (RTRM) during 1977-1988 (Welch et al., 1989). Greater RTRMs deterred internal loading. That process apparently had a greater effect on internal loading during that 12-year period than the variable amount of CRW. Warm surface water at around 81F increased RTRMs during early summer 2021 and RTRM did not decrease until September when surface temperatures were 65-70F. Some of the differences in lake TP between 2020 and 2021 may have been due to RTRMs, which were greater throughout the lake during July-September in 2021 than in 2020, and spring-summer TP was much lower in 2021.

Goal for phosphorus concentration

Lowering phosphorus is the key to achieving acceptable water quality. The long history of improving Moses Lake quality with increasing inputs of low-phosphorus CRW provides evidence for setting a phosphorus goal.

The average May-September TP concentration at lower Parker/South Lake during 1969-1970, before the Clear Water Project began, was 152 ppb. The goal set then to improve lake water quality was 50 ppb. The average input of CRW was 95,600 AF during 1977-1984 after the project began and average May-September TP was 74 ppb. During 1986-1988, after wastewater diversion from middle Pelican Horn, average CRW input was 114,200 AF and TP decreased to 41 ppb (Welch et al., 1989; 2019). Thus, 50 ppb was a reasonable goal with around 100, 000 AF of CRW. However, blue-greens were 81% of total algal biovolume in 1986-1988 with 41 ppb TP, and 43-87% in 2017 and 2018 with 25 and 41 ppb TP with about that much CRW (Table 1).

The goal of 50 ppb was continued following the DOE study in 2001 (Carroll, 2006). While the large input of CRW in 2001 (230,433 AF) resulted in an average TP of 19 ppb at lower Parker/South Lake (TS5/6) and 36 ppb in RFA (TS11), there was uncertainty about the continuation of such large inputs of CRW. However, CRW inputs continued through 2016 at an average of 263,000 AF producing an average TP of 23 ppb at South Lake.

Total P during 2001-2016 was similar to that in 2021 with an input of 230,003 AF of CRW and a TP of 20 ppb at lower Parker/South Lake and 42 ppb in RFA (TS11/12; Table 1). Moreover, the blue-green fraction of total algal biovolume was < 5% at lower Parker/South Lake in 2001 and 16% in 2021 with the large inputs of CRW and TPs of 19 and 20 ppb. Thus, there is good evidence that a much lower goal of 20 ppb, with less dominance of blue-green algae, is achievable at lower Parker/South Lake and 40 ppb in RFA.

The goal of 50 ppb was set by DOE because a lower concentration was considered unachievable unless internal loading were reduced (Carroll, 2006). Net internal loading was relatively low in

2001 (250 kg), as determined by mass balance. The results from 2001 and 2021 indicate that a much lower TP concentration of 20 ppb is achievable without internal load reduction if CRW input is around 230,000 AF. Total P concentrations would be even lower if internal loading were reduced and the lake received that much CRW.

Transparency, phosphorus and CRW inflow in June 2021

Transparency in June was markedly greater in 2021 than the past four years at all four sites. The increased transparency was associated with dilution water (CRW) distribution throughout the lake earlier in 2021 (Table 2). Rocky Ford Arm (RFA) had usually reached about 60% CRW at TS11 and 50% at TS12, but not until mid-summer. Lower Parker Horn/South Lake (TS5/6) was already 80% CRW in June 2021 and middle Rocky Ford Arm was 60% CRW.

Input of CRW during April-June in 2021 was more than in 2017-2019, but not greater during those months than in 2020. Early input of CRW in 2020 was similar to that in 2021 but transparency was much greater at all sites in 2021 (Table 2). Thus, the magnitude of CRW through June 2021 may not alone account for the early high percent of CRW in the lake and the high transparency.

Wind is effective at transporting CRW throughout the lake. That effect was recognized at the beginning of dilution in 1977-1978 (Welch and Patmont, 1980; Welch et al., 1982). Consequently, piping CRW from Rocky Coulee Wasteway to RFA was abandoned. However, wind apparently does not explain the faster distribution of CRW throughout the lake in 2021 because average wind speed was similar the past five years (Table 2). However, the higher surface temperature may have allowed colder CRW to disperse more at depth.

Table 2. Columbia River water (CRW) input through June, transparency as SD (Secchi disk depth in meters) and percent CRW in the lake at four sampling sites during June: TS5 (lower Parker Horn), TS6 (South Lake), TS11 Rocky Ford Arm at Connelly Park, and TS12 (upper Rocky Ford Arm). Percent CRW was determined by specific conductance, which measures inorganic ion content and is used as a tracer of low-SC CRW. Average wind speed is in mph at Moses Lake for April-June. Total P concentrations are in (ppb).

	2017	2018	2019	2020	2021
CRW AF to June 30	58,940	91,550	119,000	153,200	151,229
SD TS5 June, m	1.4	2.6	2.9	1.2 (74)	4.0 (12)
SD TS6 June, m	2.2	2.6	3.6	4.0 (52)	4.8 (17
SD TS11 June, m	0.9	2.3	2.3	1.4 (117)	3.8 (39)
SD TS12 June, m	1.0	1.2	1.7	0.8 (124)	2.6 (52)
% CRW TS5/6	54	52	71	65	80
% CRW TS11	46	43	53	46	61
% CRW TS12	43	35	31	23	43
Ave. wind speed	8.0	8.2	8.2	8.1	8.2

Low TP concentrations during June 2021 were the indirect cause for the high transparency (Table 2). There was less TP, less algae and less particulate matter to inhibit light transmission. Total P was much lower in 2021 at all four sites than in 2020, and TP in 2020 was higher than the previous three years. The lower TP in 2021 may be partly explained by greater surface temperature that reached 81.8F (and less density) resulting in larger RTRMs – relative thermal resistance to mixing. Average RTRMs were 112 and 154 at TS5 and TS6, respectively, in June 2021, versus 67 and 110 in 2019. Larger RTRMs would have produced greater water column stability and less vertical mixing and less entrainment of high-P bottom water. There was only one observation of vertical temperature measurements in June 2020, but three in 2019 and 2021, so RTRM in 2021 was compared with that in 2019.

Wind-caused mixing of the water column in shallow lakes can affect water quality is several ways. High RTRMs favor less mixing and low bottom water DO and buoyant blue-green algae, while low RTRMs favor water column mixing and discourage blue-greens. Liberty Lake near Spokane had higher RTRMs (ave. 72.7) during summers with blue-green blooms and lower RTRMS (ave. 44.8) in non-bloom summers. RTRMS for the five worst bloom summers averaged 92 (Brattebo et al., 2019). Wind also affects DO in shallow lakes. Maximum daily wind speeds in Upper Klamath Lake, Oregon during July-August in 1990-2001 were strongly related to water column DO and RTRMs ranging from 50-120 and (Kann and Welch, 2006).

Water temperature

Temperature is important because world warming is, according to some, stimulating an increase in cyanobacteria blooms. Average daily maximum air temperature during May-September at Moses Lake increased from 80±1.9F during 1949-1965, to 82.8±1.7F during 1997-2013, to 84.4±1.1F during 2014-2021, an overall increase of 4.4F. There was no record from 1966-1996.

Lake surface temperature has increased by only about 2F since 1977-1988, 11 years (only 5 shown here) during which the July-August average in Lower Parker Horn and South Lake (TS5/6) was 74.4F (± 3%), versus 76.4F (± 3%) during 2017-2021 (Table 3). Except for 2021 (79F), the increase was only about 1F. Thus, surface water temperature does not appear to have increased significantly over the past 45 years, that is, above the year-to-year variation.

Increasing CRW input threefold in 2021 had no apparent effect on average May-September or July-August surface water temperature. Temperature during July-August varied only 1.5% over the 5 years, regardless of a three-fold difference in CRW input.

Average temperature of CRW during May-September 1986-1988 was 56F, 20F less than the average July-August lake temperature in 2001 and 2017-2020. Even the large CRW input in 2001 (230,433 AF), with inputs from March-October and every month except July, did not affect the July-August surface lake temperature of 76.2F. Thus, solar heating apparently had more effect on lake surface temperature during any year than the magnitude and distribution of CRW input, despite its low temperature. The large input of CRW in 2001 and 2021 (230,000 AF) exchanged the lake volume at only 0.56%/day during May-September. That low rate would allow ample time for solar heating to dominate lake surface temperature.

Table 3. Average surface temperature in lower Parker Horn and South Lake for different periods during spring-summer over a range of Columbia River dilution water (CRW) during 1977 and 1979 (164,760 to 209,150 AF) and 1986-1988 (66,020 to 207,280 AF). Sampling frequency during 1977-1988 was twice-monthly as the past five years.

Ave. surface (0.5 m) temperature TS5/6					
Year	CRW, AF	May-June	July-Aug	September	May-Sept
2017	75,456	67.2	77.6	70.5	70.5
2018	105,758	66.2	75.4	67.0	69.5
2019	119,077	71.0	75.3	64.5	70.3
2020	186,813	66.7	74.5	67.2	69.5
2021	230,003	67.2	79.0	67.8	72.0
Column averages		67.7	76.4	67.4	70.1
1977/79	186,950	64.9	75.9	65.8	69.5
1986-88	114,500	64.5	72.6	66.5	68.1

From these data, there seems to be little advantage to reducing mid-summer water temperature by spreading CRW input throughout the summer. While the large CRW input in 2001 reduced May-June temperature to 59.4F, well below the average of 67.7F in 2017-2021, the July-August 2001 temperature of 76.2F was no different from recent years, despite CRW input every month except July (Carroll, 2006). However, the input of large volumes of cool CRW almost every year since 1997 may have reduced the effect of long-term air temperature rise.

Factors that account for lower TP in 2021

Thermal resistance to water column mixing (RTRM) was greater in 2021 than 2020 (Table 4). Low RTRMs allow deeper water with higher TP from internal loading to increase surface TP concentration. June RTRM was higher at South Lake in 2021 (154) than in 2019 (110). The higher RTRM in 2021 was due to greater difference between surface and bottom temperature and density. Also, the fraction of CRW dilution water was greater at the surface and bottom in 2021, probably diluting internal loading, which was similar in 2020 and 2021.

Off-bottom dissolved oxygen (DO) was at least as prevalent in 2021 as in 2020. Low off-bottom DO < 2 mg/L represents anoxia in the sediment and immediate overlying water. Anoxia resulted in a ten-fold increase in phosphorus release from sediment, or internal loading, from Moses Lake sediments (Okereke, 1987). Thus, sediment-P release was probably as great in 2021 as 2020, but higher RTRMs in 2021 and dilution from the greater fraction of CRW at surface and bottom probably reduced the contribution of internal loading to lake TP concentrations.

Table 4. July-September averages in 2020 and 2021 for: 1) thermal (density) resistance to water column mixing (RTRM); 2) surface-to-bottom temperature difference; 3) off-bottom (0.5 m) DO (dissolved oxygen); and 4) % Columbia River Water input. Averages from TS6 (South Lake), TS15 (Cascade/lower Rocky Ford Arm) and TS11 (Rocky Ford Arm, Connelly Park).

Characteristic	2020	2021
Thermal (density) resistance to mixing RTRM	56	73
Surface (0.5 m)-to-0.5 m off-bottom temperature difference	3.5	4.7
Off-bottom (0.5 m) DO in mg/L	4.5	3.8
% CRW Surface (0.5 m)/bottom (0.5 m above bottom)	66/59	79/75

Internal loading

Internal loading of phosphorus occurs when the release of P from lake sediment exceeds inputs from external sources and sedimentation loss in the lake. That process results in an increase in lake TP concentration. The largest source of internal loading is from anoxic (anerobic) bottom water overlying sediment in deep areas, as noted on p. 8. Phosphorus is also released from shallow oxic (aerobic) sediment, but at a much lower rate (Okereke, 1987). The result is increased lake TP concentration during summer in excess of inflow concentrations.

Internal loading of phosphorus in Moses Lake was strongly inversely correlated with RTRM in the 1970s-1980s, with an average RTRM of 113 and a range of 73-172 at South Lake (TS6). Internal loading was 57% of total loading in 1985, TP during May-September at TS5/6 was 102 ppb and RTRM was very low at 56, indicating that the low water column stability favored internal loading (Welch et al., 1989). The positive effect of wind and RTRM were apparently greater in 1985 than the effect of CRW, which was relatively high at 159,012 AF.

Internal loading occurred in 2021 (similar to 2020) despite the lower average May-September TP concentrations than in the previous four years (Table 5, Tetra Tech 2022). Surface TP at South Lake (TS6) and middle Rocky Ford Arm (TS11) increased more in 2021 than in 2020 even though May-September whole-lake TP in 2021 (36 ppb) was half that in 2020 (77 ppb). The lower average TP in 2021 was likely due to greater effectiveness of dilution by CRW at surface and depth (Table 4). Also, RTRMs were high in June (112 and 154 at TS5 and 6), as well as later during July-September (Table 4).

Total P in inflow streams declined during summer in 2021, as in the previous four years (Table 6). Thus, increased lake surface TP during summer 2021 came from internal and not from external sources, as was observed in 2017-2020 (Table 5). Rocky Ford and Crab Creeks contributed 25% of total loading in 2021 while 55% came from internal (Tetra Tech, 2022). Lake TP concentration exceeding inflow TP concentration has been a persistent pattern from year-to-year.

Table 5. Average May and June-September TP in ppb at TS6 (South Lake) and TS11 (Rocky Ford Arm, Connelly Park) combined during 2017-2020 versus 2021. Increased lake TP concentration during the summer indicates internal loading, even in 2021 despite more CRW and lower TP.

	May	June-September	Increase
2017-2020	28	50	22: +79%
2021	16	36	20: +125%

Table 6. Average May and June-September TP in ppb at TS2 (Crab Creek) and TS14 (Rocky Ford Creek). Increased lake TP during summer was not due to inflows because stream TP concentrations decreased.

		May	June-September	Decrease
2019-2020	Crab Cr.	56	47	-9: -16%
2019-2020	Rocky Ford Cr.	201	149	-52: -26%
2021	Crab Cr.	65	55	-10: -15%
2021	Rocky Ford Cr.	181	151	-30: -17%

Internal loading in 2020

The large increases in lake surface TP concentrations that occurred throughout the lake in 2020 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 7). Total P loading from those two inflows contributed 30% in 2020 (Tetra Tech 2021). The low lake concentrations at TS5/6 in May 2020, averaging 41% lower than during June-July, partly reflect dilution from the 185,103 AF of CRW entering Parker Horn and extending well into Rocky Ford Arm. The subsequent increased TP by 57% in RFA reflects the increase from internal loading. Net internal loading was 8,318 kg in 2020, similar to the average during 1984-1988 of 9,346 kg (Tetra Tech, 2021; Welch et al., 1989).

The lake TP increases in June/July were likely not due to ground water either, because ground water TP concentration and flow would not have increased sufficiently in only one-two months. Also, the ground water TP concentration used by DOE to calculate loading in June-July 2001 was 59 ppb (Carroll, 2006). A ground water TP concentration of 50 ppb from a spring inflow (TS9) was used to calculate loading during 1977-1988 (Welch et al., 1989). Those concentrations are both well below lake TP concentrations during June-July. Ground water was estimated at about 7% of total TP loading to the lake in 2020 (Tetra Tech, 2021).

The increased TP during summer in 2020 was due to internal loading and confirmed by the TP mass balance, which showed that source accounted for 50% of the May-September TP load to the whole lake. The same pattern of increased lake TP, in excess of the concentration in Crab Cr., existed during previous years (Tables 5 and 6).

Table 7. 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, and TS12 is 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 2020 was 122 ppb and DO was less than 1 mg/L, indicating anoxia, which allows high release rates that 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 – low RTRM (Welch et al., 1989).

Table 8. 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

Observations of DO extremes during July, 2020

As sampling time increased during the day in July 2020, DO at the surface (1 m) increased from near or a little above saturation (9 mg/L at 68F) to super saturation. Supersaturation results from high rates of algal photosynthesis that exceed respiration. Photosynthetic rates that produce supersaturation during the day are followed by continued high respiration rates at night without oxygen added from algal photosynthesis.

At depth (5 m), DO was usually undersaturated, especially in late July, because 5 m and deeper were well below the lighted zone (about 0-3 m) where respiration exceeded photosynthesis or there was no photosynthesis. At 1 m deeper (6 m), DO was nearly exhausted. Between 6 and 9 m at TS6, anoxia prevailed allowing high rates of sediment P release. Anoxia would have prevailed to the maximum depth of 11.5 m. The lake area at 5 m depth with potential anoxia is 2924 acres, which is 43% of the total lake area.

The undersaturated DO of 5.4 mg/L observed at 1 m at TS15 and 6:44 AM on July 8 suggests that predawn surface DO was probably well below 5 mg/L, because respiration had proceeded to lower DO during the night. Thus, anoxic water overlying shallower areas may have produced high sediment-P release rates as well.

The minimum DO for fish growth and activity is 5 mg/L. Low DO restricts habitat, especially for cold and even cool water species, such as trout, smallmouth bass and walleye that prefer lower water temperature than at the surface. Temperatures at TS6 were 78.6F at 1 m and 70F at 6 m on July 22, and the difference was same at TS15. Thus, some fish species may not have sought refuge at depth from surface temperature higher than their optimum or preferred temperature due to low DO.

Table 9. Dissolved oxygen (DO) in mg/L (ppm) at surface (1 m) and depth (5 and 6 m) and percent saturation (%) of DO at three sampling sites in Moses Lake during July, 2020.

site	7/8, 6:20 -6:55	7/14, 8:30 -9:40	7/22, 8:00 -10:20
TS6	1 m: 6.8, 97% 5 m: 0.7, 9%	1 m: 9.6, 133% 5 m: 5.1, 68%	1 m: 10.9, 161% 5 m: 3.9, 58%
TS 15	1 m: 5.4, 76% 5 m: 5.2, 74%	1 m: 10.9, 150% 5 m: 6.6, 89%	1 m: 14.3, 210% 5 m: 1.3, 27%
TS11	1 m: 8.1, 119% 5 m: 7.9, 116%	1 m: 11.0, 154% 5 m: 6.6, 55%	1 m: 14.8, 223% 5 m: 0.8, 12%
TS6/15	6 m: 0.3/0.8	6 m: 0.3/5.4	6 m: 1.8/0.7

Distribution of CRW

Most CRW has entered the lake in the spring and early summer. An average of 81% of the total during 2017-2021 entered by June 30. Would the effect of dilution have been greater, i.e., produced lower spring-summer TP, if CRW inflows were distributed equally throughout the spring-summer?

Predictions with a TP mass balance model calibrated to 2020 data, show little difference in the May-September whole-lake average TP concentration if most of the CRW inflows in either 2020 or 2021 had entered the lake early, as actually occurred, or were evenly spread out throughout the spring-summer period (Tetra Tech, 2021; Figure 2). While whole-lake TP actually decreased slightly in September as CRW inflow resumed in 2020, May-September average whole-lake TP was about the same at 67 ppb whether inflows were continuous or were concentrated in spring and early summer as usual (Figure 2). That is because the water exchange rate from normal inflows is very low, so entering low-P CRW in the spring tends to remain throughout the lake whether added mostly in spring/early summer or continuously throughout spring-summer.

Summary

1. Water quality during spring-summer markedly improved in 2021, compared to the previous four years. Total P and chl were lower by 40-75% throughout the lake and transparency was more than double, averaging 3 m at lower Parker Horn and South Lake (TS5/6) and 1.9 m in Rocky Ford Arm (RFA, TS11/12). Phosphorus and chlorophyll were still greater in RFA than the lower lake, but much lower than the previous four years and the percent blue-greens was 2/3 to 3/4 less. The five-year, spring-summer average TP of 32 ppb in the lower lake is less than the DOE action level of 35 ppb for Columbia Basin lakes.
2. Factors causing the improved water quality were: 1) percent Columbia River water (CRW) was higher throughout the lake earlier than in past years, 2) water column density gradient, indicated by the relative thermal resistance to mixing (RTRM), was 30% higher early and through summer and 3) %CRW at surface and bottom was 20-27 % higher than in 2020. These factors probably minimized the effect of internal loading through greater dilution earlier and at depth and less entrainment of high-TP bottom water. Sediment-P release still occurred during summer, indicated by lake TP concentration increase and bottom water had low DO, indicating anoxia.
3. Dilution water (CRW) input increased 28% per year on average during the past five years. The response of lake TP (20 ppb) to 230,000 AF in 2021 was similar to that during 2001-2016 with an average TP of 23 ppb and average CRW of 263,000 AF/year. Those average spring-summer TPs were from the lower lake. These results indicate that 200,000 to 250,000 AF of CRW is needed to largely overcome summer internal loading and hold May-September TP to around 20 ppb in the lower lake and around 40 ppb in RFA. That quantity should also minimize the percent of total algae composed of blue-greens (cyanobacteria), as occurred in 2001 (Carroll, 2006) and 2021.
4. The results from 2001 and 2021 indicate that a goal of 20 ppb average TP concentration during May-September is achievable in the lower lake, and 40 ppb in RFA, if CRW input were over 200,000 AF. Earlier goals of 50 ppb, set prior to the start of dilution in 1977 and following the DOE study in 2001 (Carroll, 2006), are too high to minimize the fraction of blue-green algae, which was low with the large CRW inputs in 2001 and 2021. A lower goal than 50 ppb was considered unachievable unless internal loading was reduced. However, the results from 2001 and 2021 indicate that lower goals are achievable if CRW input were over 200,000 AF.
5. Sediment-P release, or internal loading, occurs mostly from deep anoxic (DO < 2 mg/L) areas, but also at a slower rate from oxic (aerobic) sediment in shallower water.

Internal loading occurred in 2021 during summer as usual but resulting TP concentrations were lower, probably due to dilution as shown by higher bottom water % CRW than in 2020. Surface TP actually increased during summer more in 2021 than in 2020 and previous years, but beginning TP in May-June was much lower resulting in lower average surface (0.5 m) and whole-lake TP during May-September. Whole-lake (including all depths) TP was 77 ppb in 2020 and 36 ppb in 2021. Net internal loading determined by mass balance was 8,318 kg in 2020 and 10,281 kg in 2021 (Tetra Tech, 2021. 2022), similar to the average of 9,346 kg during 1984-1988 (Welch et al., 1989).

6. Internal loading is the major source of phosphorus during May-September due mostly to low DO in deep areas (> 5 m) of South Lake (TS 6), Cascade (TS 15; lower RFA) and middle RFA (TS 11). Internal loading accounted for 60% of May-September total loading to RFA in 2019 and 50% and 55% to the whole lake in 2020 and 2021, as determined by mass balance (Tetra Tech, 2020, 2021, 2022). Reducing TP in stream inflows would have little effect on lake TP during late spring and summer when internal loading has dominated, as determined by increased TP relative to inflow TP and predicted by mass balance models. Reducing internal loading will require inactivation of sediment P, especially in deep areas that are prone to anoxia. Alum is preferred because the floc removes (strips) soluble and particulate P from the water column and has a long record of effectiveness and longevity.
7. Surface temperature in Moses Lake was 3.3F higher in 2021 than in the past four years. Surface temperature reached 81.8F in 2021 and averaged 79F during July-August. However, except for 2021, the increase in July-August was only about 1F during 2017-2020 compared to that period in 1977-1988. While spring-summer average maximum air temperature has increased 4F over the past 70 years, the response of lake temperature over the past 45 years has been slower. The year-to-year July-August surface temperature was unrelated to the amount of CRW, but the slower long-term response to increased air temperature may be due to the annual input of cool CRW.

Recommendations

1. Continue monitoring twice monthly during May-September as during the last five years with water sample collection through the water column at deep sites. Include temperature and SC at TS1 (East Low Canal) and samples for TP in Rocky Coulee Wasteway base flow on two or three occasions during summer without CRW.
2. Plan to inactivate sediment P in deep areas greater than 5 m (2924 acres). Rocky Ford Arm contains about 60% of the deep area. Those areas go anoxic and account for most of the internal loading. That treatment is predicted to reduce whole-lake, volume-weighted TP from about 74 to 47 ppb and surface (0.5 m) TP at TS5/6 from 40 to 26 ppb (Tetra Tech, 2021). Alum is recommended to inactivate P because it removes (strips) particulate as well as soluble P through the whole water column. Portions of the deep area could be treated in yearly stages as funds become available. Resulting aluminum-P in sediments would remain bound and probably continue to sorb P added externally and diffused from deeper sediment subsequent to treatment.

3. Determine the effect of a 5-foot water level drawdown on phosphorus input due to freeze-dried exposed sediment. Sample transects at two sites over the course of water level rise.

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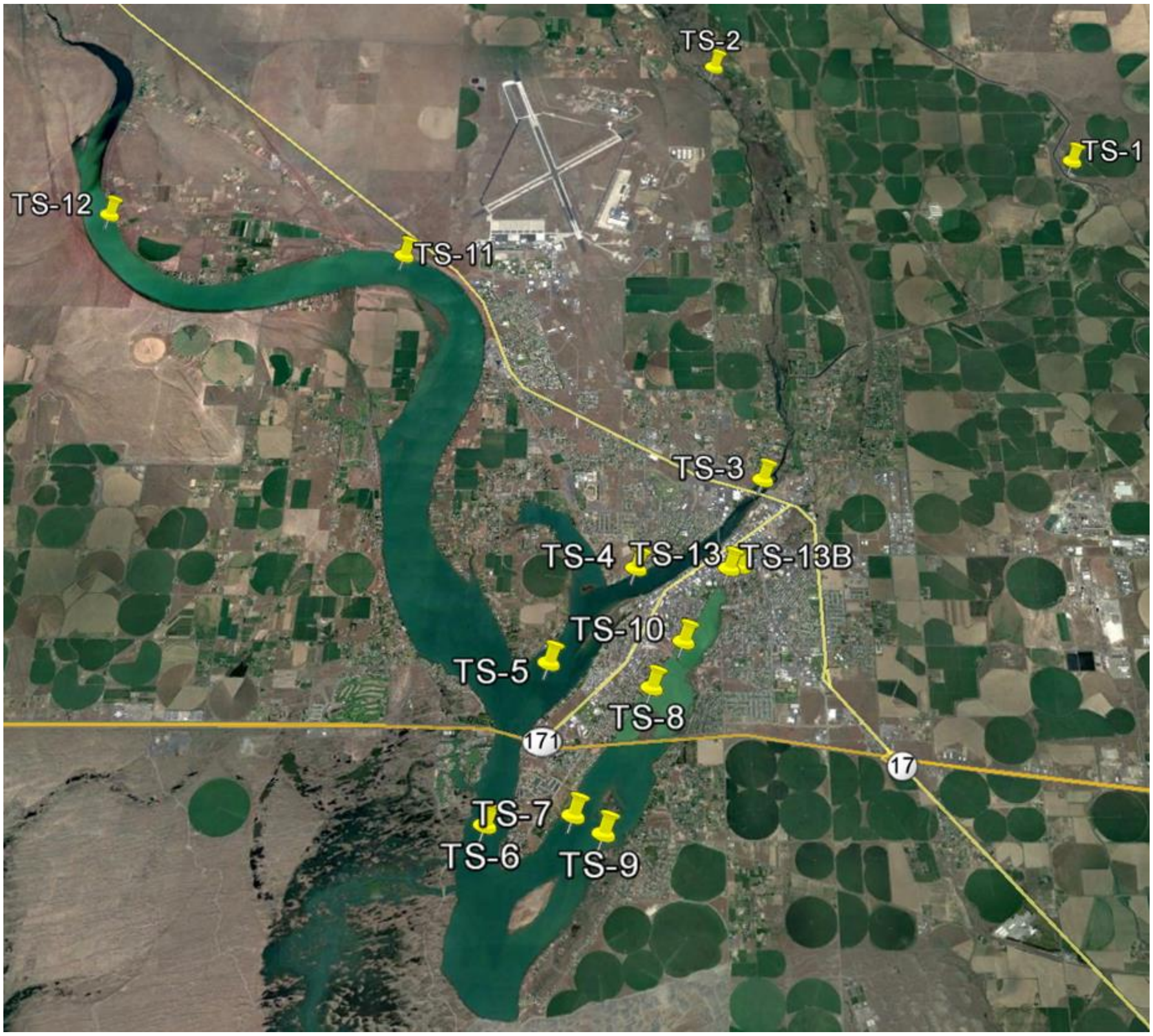

Figure 1. Sampling sites by MLIRD during 2017-2021. Most sites are similar to those sampled by UW, Civil and Environmental Engineering, during 1969-1970 and 1977-1988 (Welch et al., 1989).

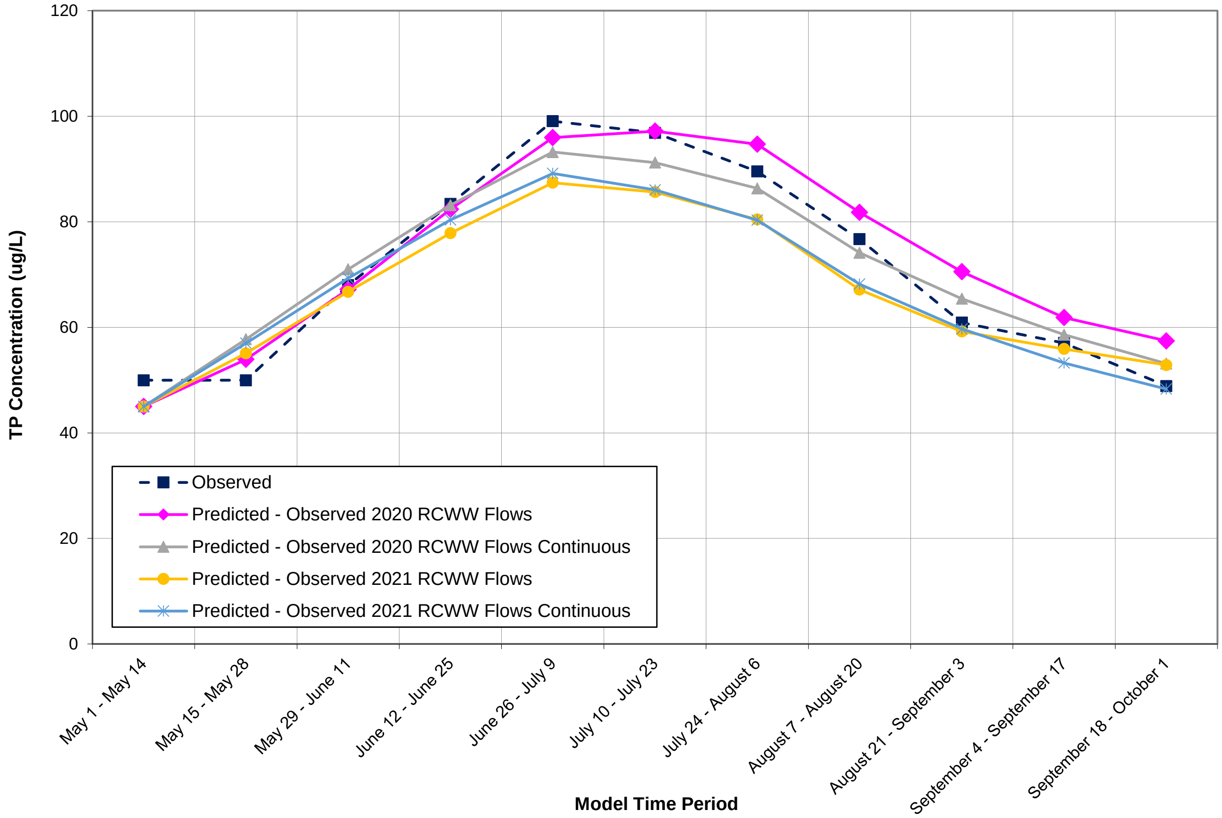

Figure 2. Observed whole-lake TP predicted using a mass balance model calibrated to 2020 data showing the effect of CRW inputs as occurred in 2020 and 2021 compared to continuous inflow through spring-summer or mostly in the spring as recorded. CRW inflows were 185,103 AF in 2020 and 230,003 AF in 2021.