Moses Lake Water Quality:
Effects and Benefits of Columbia River Dilution Water
2017-2023

Prepared for Moses Lake Irrigation and Rehabilitation District

By

Eugene B. Welch

Consulting Limnologist and

Prof. Emeritus, University of Washington

and

Shannon K. Brattebo

Tetra Tech, Spokane, WA

May, 2024

Introduction

This report describes the improvement in lake quality during the past seven years that MLIRD personnel have monitored water quality constituents. Lake quality is characterized by concentrations of total phosphorus (TP) and chlorophyll (chl), which is directly related to TP, and water transparency, which is inversely related to chl. The fraction of blue-green algae (cyanobacteria) of total algae, is also an important indicator of lake conditions, and that characteristic has declined. The reduction of chl and blue-greens and increase in transparency was due to reduced TP concentration, which in turn was due to increased input of Columbia River water (CRW) by 85% on average between 2017-2019 and 2020-2023. Also, CRW input started at a lower lake surface elevation the past four years at an average of 1042.1 feet, which represents 64% of full pool volume. Adding CRW to a smaller lake volume enhances dilution of lake TP. Over half the lake averaged 74% CRW at the surface (0.5 m) the past four years and the long-term (40 years) data set shows TP is inversely related to %CRW.

Internal loading was still a substantial fraction of TP loading the past four years as indicated by increased lake TP during the summer, while there was little or no change in stream inflow TP concentrations. Nevertheless, average spring-summer lake TP was 30 µg/L at five sites representing 74% of lake area the past four years. Without CRW input, lake TP would average about 150 µg/L at those sites, due largely to internal loading.

Although middle and upper Rocky Ford Arm (RFA) usually have more TP and chl than the lower lake, CRW nevertheless dilutes that area as the diluted lower lake mixture is transported up the arm by wind. That was demonstrated in 1981 when predicted %CRW at distances up RFA with a diffusion model agreed with the observed CRW fractions.

These observations of improved lake quality related to increased CRW inputs and resulting %CRW in the lake are described in more detail in the following report sections. The sediment core analysis, showing the history of microcystin in the lake, was in the 2020 report, but repeated here to emphasize that toxin's occurrence in the lake is not new.

Water Sample Collection and Analysis

Water samples were collected by the Moses Lake Irrigation and Rehabilitation District (MLIRD) personnel with a Van Dorn bottle twice per month the past seven years, at a depth of 0.5 m at nine lake sites during May-September (Figure 1). Samples were also collected through the water column in 2020 - 2023. Inflows were sampled at two sites on Crab Creek (TS2 and 3), and one each in the east low canal (TS1) and Rocky Ford Creek (TS14). Samples were shipped on ice to IEH Analytical Laboratories, Seattle, WA, for analysis of total phosphorus (TP) using the method 4500PI with detection to 2 µg/L. Chlorophyll was determined in the same lake samples on residue following filtration in the laboratory with detection to 0.1 µg/L. Analytical procedures were according to standard methods (Eaton et al., 2005). Specific conductance (SC), dissolved oxygen (DO) and temperature were determined *in situ* with a sonde 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 twice-monthly during July – September in 2017, May-September in 2018, once/month in June, August, and September in 2021 and twice each of these three months in 2022 and 2023. Algal abundance was determined as biovolume in mm^3/L based on measured cell volumes of individual species observed and shown here as % blue-greens and % *Microcystis*. Samples were analyzed by Western Washington University algologists in 2017 and 2018 and Algae Analytical Services in 2021 - 2023. Samples for microcystin were collected at Blue Heron Park by Grant County personnel and at Connelly Park by MLIRD. Samples were analyzed by King County Environmental Laboratory using the ELISA method.

Water and TP budgets were determined for May-September in 2020 and 2021. Flow from Crab Creek was gauged at highway 17 (TS2). An average May-September flow of 58 cfs during 2008-2017 was used for currently ungauged Rocky Ford Creek. A base flow for Rocky Coulee wasteway of 2.2 cfs was determined from historical data. A groundwater flow of 6.9 cfs was determined in 2001 (Carroll, 2006). An average evaporation rate was taken from the Western Regional Climate Center and precipitation from the Grant County airport at Moses Lake. Lake levels were gauged. Outflow from the lake was assumed as total inflow minus evaporation, because data from the two outflow structures were unavailable. Total P concentrations were regularly determined in Crab Creek (TS2), Rocky Ford Creek (TS14) and CRW (TS1). Rocky Coulee wasteway TP was taken as 87 µg/L and ground water as 59 µg/L determined in 2001 by Carroll (2006). Total P in precipitation of 107 µg/L was assumed from budgets determined in the 1980s (Welch et al., 1989; Jones and Welch, 1990).

Water column stability was indicated by relative thermal resistance to mixing (RTRM), where

$$RTRM = (D_{bottom} – D_{surface})/(D_4 – D_5)$$

and 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). Symbols in the equation are SC, in µS/cm, which is much lower in CRW at 142 than in Crab Creek at 491 and Rocky Ford Creek at 371. SC in Crab

Creek was used for lower Parker/South Lake and an average of Crab Creek and Rocky Ford Creek was used for Rocky Ford Arm. The equation allows tracing of the low-SC CRW according to:

$$100\ [(LW - ELCW) / (CCW - ELCW)] = \%\ LW;\ \text{or}\ 100 - \%LW = \%CRW$$

Wind transport of water into Rocky Ford Arm

Specific conductance has consistently shown that low-P Columbia River water (CRW) reaches well up into Rocky Ford Arm (RFA). Prevailing SE to SW wind was shown in a spring 1981 study to be sufficient to transport water from Lower Parker Horn (LPH) several miles up RFA using a diffusion model (Welch et al., 1982). Water from LPH (site 5) with 77% CRW was calculated to reach middle RFA (TS11), a distance of 5.5 miles, over a period of 100 days and produce 30%CRW at that site. That prediction agreed with observations of %CRW. Wind velocity during the study averaged 2.6 miles/hour over the 17-hour study. CRW at 8.5 miles up RFA was predicted at less than half that at middle RFA. The work was performed by Ron Nece, a hydraulics Professor at UW at the time.

The study also showed that flow from Rocky Ford Creek would have had a minimal reverse effect on CRW movement up RFA. The cross-sectional lake area of 23,000-50,000 sq. ft. and an inflow from RFC of 78 cfs would have produced a down-arm flow of only 0.001-0.002 cfs (Welch et al., 1982).

Recent data show even greater effectiveness of water transport up RFA. Wind direction was from the SE to SW 82% of the time during May-August in 2020-2023, averaging 7.6 miles/hour. Wind was apparently adequate to account for CRW to average 70% at middle RFA (TS11) during July-August the last four years.

Pattern of CRW distribution in the lake

Entering low-TP CRW distributes throughout the lake due to wind, as described above. Wind, mostly from the SW, is sufficient to transport the CRW-lake water mix from lower Parker Horn well up into RFA (Welch et al., 1982). However, percent CRW at the surface in the lake was always higher in Lower Parker Horn and South Lake (TS5 and TS6) and occurred earlier than in middle RFA (TS11), which eventually reached around 60% CRW at 0.5 m by mid to late summer. That was the case in 2020 when CRW at South Lake (TS6), lower RFA (TS15) and middle RFA (TS11) averaged 66% at the surface (0.5 m) and 59% at 0.5 m off-bottom during July-September (Table 1). The CRW fraction was much higher (79 and 75%) at those sites and depths in 2021 and 2022 (75 and 71%) and nearly as high in 2023. Those three deep areas represent 58% of the lake area.

The higher fraction of CRW throughout the lake in mid to late summer 2021 that in 2020 was probably not due to more total CRW, which was 230,000 AF in 2021 versus 187,000 AF in 2020. Inputs of CRW were similar during April to June (153,000 versus 151,500 AF), while CRW at 0.5 m in June at the three deep sites (TS6,11, 15) was 58% in 2020 and 71% in 2021. Also, total CRW input through June in 2022 was 156,300 AF, similar to 2021, while surface % CRW in June was even higher at the three sites in 2022 (82%) than in 2021 (71%). The CRW fraction was similar in June the previous three years, 2017-2019, at 53% with less CRW through June.

There is another process that probably enhances dilution as the summer progresses and CRW input continues. Colder and denser CRW probably tends to sink below the warmer surface water. Temperature of CRW entering the lake is around 50F in early April. The water column during July-September was more stratified in 2021 and 2022 than in 2020 or 2023, as indicated by RTRM and the greater difference in temperature between surface and bottom (Table 1). The greater stratification may have allowed colder CRW to plunge below the warmer, less dense surface water. Also, bottom water at five sites (sites 5,6,7,11 and 15) in May 2021 and 2023 had on average 14% less SC and was 5.6F colder, indicating that colder CRW with less SC may have plunged as it entered the lake. That may indicate more effective dilution and account for the relatively high %CRW in deeper areas. There are no data for May 2023.

Lower lake level the end of March when CRW inflows began may also determine the effectiveness of %CRW distribution throughout the lake. The lake is normally drawn down as much as 6.5 feet during winter. Lake levels in 2021, 2022 and 2023 at the end of March, just before CRW began entering the lake, were on average at about 1042 feet (Table 2). That was 1.2 feet lower than in 2017-2019 (Figure 2). That area difference between 1046 and 1042 represents about 36% of the lake's full pool volume. That lower pre-CRW volume would have favored more effective mixing of CRW with lake water and a higher eventual %CRW. However, pre-CRW inflow lake level was also low in 2020 while %CRW was relatively low (Table 1). Nevertheless, lower lake level at the start of CRW input should increase the ratio of CRW input to lake volume and result in higher %CRW.

Table 1. July-September averages in 2020, 2021, 2022 and 2023 for thermal (density) resistance to water column mixing (RTRM), surface (0.5 m)-to-bottom (0.5 m) temperature difference (C), off bottom DO (0.5 m) and surface/bottom % Columbia River Water. Averages are from South Lake (TS6), lower Rocky Ford Arm (TS15) and middle Rocky Ford Arm (TS11).

Characteristic	**2020**	**2021**	**2022**	**2023**
RTRM	56	73	61	52
temperature difference	1.6	2.1	2.1	1.4
DO	4.5	3.8	4.6	5.3
% CRW	66/59	79/75	75/71	74/67

Lake-level effect on dilution

At elevation 1042 feet, the lake contains 64% of the full pool volume at 1046 feet. Filling the remaining capacity (36% of full pool) with low-TP Columbia River water (CRW) should provide more effective dilution than adding that CRW quantity to the lake with full pool. When the lake is full, following the start of CRW input, the lake volume should be 36% CRW and 64% remaining from over-winter. That assumes CRW is equally mixed with existing lake water. If the lake were at 1046 feet at the start of CRW input, which is around the end of March, dilution would be more gradual, taking longer to reach the 36% CRW. The rate of exchange of CRW at 1500 cfs with lake water at full pool would be 2.4%/day, versus 3.7%/day with the lesser-volume, over-winter pool.

There is apparently little CRW left in the lake at start of CRW input, as indicated by the tracer specific conductance (SC in µSiemens/cm). SC is conservative, composed of major ions that are unaffected by biological processes. SC has been verified as a valid tracer of CRW in the lake, because CRW is low in SC (142 µS/cm), while undiluted lake water is high in SC. USBR data from the outlet in 2017 and 2018 during February, October, and April, before CRW input, and May, averaged 373 µS/cm. Also, 373 is close to the volume-weighted average of 383 µS/cm from the major inflows of Crab Creek (491), Rocky Ford Creek (371) and groundwater (285). Lake water in 1969-1970, before the Clean Lakes Project, was 445 µS/cm, much higher than now possibly due to entering treated wastewater, which is high in sodium. Thus, lake water at the start of CRW input is probably around 373 µS/cm and probably still contains some CRW from the previous year, because normal inflow volume without CRW represents 0.6 lake volumes so requires more than a year to replace the existing volume. Thus, the SC in Crab Creek (491) is used to determine %CRW in the lower lake, because that area would eventually be mostly Crab Creek water without CRW input.

Starting with 36% CRW and 64% remaining over-winter volume, ultimate full-pool should be 58% CRW. However, continued input of CRW increased the fraction in the lake after reaching full pool. Lake elevation at the start of CRW input the past four years averaged 1042.1 feet and surface/bottom calculated CRW averaged 74%/68% during July-September at TS6 (South Lake), TS15 (lower RFA) and TS11 (middle RFA), which represents 58% of the lake area (Table 1). Spring-summer TP the past four years averaged 27 µg/L at TS5/6 and 30 µg/L at TS5/6, 7, 11 and 15, which is 74% of lake area (Table 2). Although CRW input was similar the past four years, averaging 192,000 AF, and lake level at the start of CRW input averaged 1042.1 feet, %CRW was much higher the past three years over 74% of the lake, consistent with lower TP at the surface and through the water column (Table 2). High %CRW results in lower TP (Figure 3).

Why there was higher %CRW in 2021-2023 versus 2020 is unclear. Total P loading, especially internal, was similar in 2020 and 2021, although May-September whole lake TP was much less in 2021. Total CRW inflow was considerably higher in 2021, which may have had a continuing effect in the subsequent years. Total P was slightly higher in 2023 with less CRW input (Table 2).

Table 2. May-September average Total P at 5 sites that represent 74% of lake area (TS5, 6, 7, 11 and 15), average July-September surface %CRW, total CRW inflow, lake elevation at start of CRW input and duration of CRW input.

	2020	2021	2022	2023
Total P surface 0.5 m	47	24	21	29
TP all depths	74	34	30	35
%CRW	65	77	73	73
CRW 1000s AF	187	230	190	160
Pre CRW elevation in feet	1042.3	1042.2	1041.3	1042.6
CRW input duration days	120	94	90	84

Lake Quality

Lake water quality was much improved in 2021 to 2023 compared to 2020 and the previous three years (Table 3). Average May-September surface TP at lower Parker Horn and South Lake (TS5 and 6) in 2021, 2022 and 2023 was 22 µg/L, about half that in 2020, and less than half in RFA as well (Table 3). Also, whole-lake, volume-weighted TP in 2021 and 2022 was less than half that in 2020 at RFA those three years; 34 and 29 vs 77 µg/L. Chlorophyll was even more reduced in 2021, 2022 and 2023 and transparency was double that in the previous four years (Table 3).

The improved lake quality in 2021 was partly due to more CRW, but there was 18% less CRW in 2022 and 30% less in 2023, yet TP was much lower all three past years (Tables 2 and 3). The CRW input was distributed earlier and more effectively the past three years as indicated by higher %CRW (Table 2). As noted above, the amount of CRW from April through June was about equal during 2020 and 2021, yet TP in 2020 was much higher during June averaging 63 µg/L at lower Parker/South Lake (TS5 and 6) and 120 µg/L at middle/upper RFA (TS11 and 12) versus 15 and 46 µg/L in 2021 at those sites, respectively. Total P during June was low at those sites in 2022 at 15 and 18 µg/L. While the reason(s) for the more effective distribution of CRW earlier the past three years is uncertain, the effectiveness of CRW diluting lake TP is clearly dependent on the resulting %CRW that persists in the lake (Figure 3).

Inputs of CRW increased 85% between 2017-2019 and 2020-2023, averaging 103,430 and 191,420 AF, respectively, and ranging from 49,400 to 230,000 AF for the seven years. The input was slightly less in 2023 at 159,300 AF, although TP was relatively low resulting in a May-September average of 27 µg/L during the past four years at lower Parker/South Lake (TS5 and 6, Table 3). Average TP was 30 µg/L in 2023 including data from middle RFA (TS11), lower RFA (TS15) and lower Pelican Horn (TS7; Table 4). Those five sites together represent about 74% of the lake area or 4900 acres. Thus, dilution with low-TP CRW has been very effective at maintaining relatively low average TP in the lower lake area the past four years when CRW input averaged 191,680 AF and lake CRW averaged 72%. However, TP was higher in middle/upper RFA, averaging 54 µg/L the past four years, although TP was much lower there as well in

2021-2023 when %CRW was higher (Table 3, Figure 3). Also, the blue-green algal fraction of total algal volume averaged only 23% the past three years (Table 4).

Table 3. May-September average TP, chlorophyll (chl), both in µg/L, and Secchi disc transparency in meters during 2017-2023 at Lower Parker Horn/South Lake (LPH/SL, TS5/6) and middle and upper Rocky Ford Arm (M/URFA, TS11/12). NS = not sampled. Chl* estimated from average past chl:TP ratios of 0.32 at 5/6 and 0.26 at 11/12, for 2 of 5 months wo/ data.

Site	year	TP	chl	SD
LPH/SL	2017-2019	32	13	1.4
	2020	41	22	1.6
	2021	20	7*	3.0
	2022	20	8	3.0
	2023	25	10	2.1
7-year Average		29	12	1.8
M/U RFA	2017-2019	81	38	NS
	2020	99	63	0.9
	2021	42	11*	1.9
	2022	30	11	1.9
	2023	45	20	1.6
7-year Average		58	31	1.5

Table 4. May-September average TP (µg/L) at surface (0.5 m) at middle RFA (TS11), lower RFA (TS15), lower Parker Horn (TS5), South Lake (TS6) and lower Pelican (TS7). These five sites = 74% of total lake area. Blue-green algae at TS6 and TS11 were not sampled in 2019 or 2020. Whole-lake volume weighted TP includes all depths and sites. DOE's TP action level to improve lake quality.

2017-2019	2020	2021	2022	2023	DOE action level
39	47	24	21	29	35
Blue-green algae fraction of total algal biomass at South Lake (TS6) and middle RFA (TS11)					
73% (2017-2018)		23%	22%	36%	
Whole-lake (all sites), volume weighted TP					
	74	34	29		

Internal loading

Lake TP concentrations increased throughout the lake as summers progressed. That increase, which was consistent from year-to-year, was due to internal loading from anoxic and oxic sediments. The increase was not due to the two major inflows, in which TP concentrations usually decreased or changed little during summer. In 2020, lake surface TP increased an average of 57% from May to June/July at five sites. Even in the high lake quality year of 2021, surface TP more than doubled (16 to 36 µg/L) from May to June-September at South Lake (TS6) and middle RFA (TS11) combined. Total P increased at those two sites by an average of 88% between May and June-September during 2017-2021. The increase in TP was more delayed in 2022 and 2023, but TP doubled from June-August to September and May/June-August to September, respectively (Table 5).

Total P in the two inflow streams, Crab Creek and RFC, decreased on average by 16 and 23%, respectively, between May and June-September in 2019-2021 and, thus, could not have been the source for the summer TP increase in the lake. Inflow TP either changed slightly or decreased during the summers of 2022 and 2023 (Table 5). Also, average TP during May-September was rather constant since the 1980s in RFC at 165 µg/L during 2015-2017 and 2021-2023 and 48 µg/L in Crab Creek during 1995-2018.

Mass balances showed that the summer increase in TP was due to internal loading, which has remained the major source to the lake. Internal loading averaged 39% of total loading during 1984-1988 after waste water diversion (Jones and Welch, 1990). The internal fraction was even higher at about half the total load in 2020 and 2021 (Table 5). The amount of internal loading in 2020 and 2021, at 8,318 and 10,281 kg, was on the order of the average during 1984-1988 of 9,346 kg. Total P mass balances were not determined in 2022 or 2023.

There is some uncertainty in some sources within the water budgets due to a lack of current data. Although RFC at 10% of the total was not gauged recently, its largely spring-fed and flow is rather constant; the average spring-summer flow during 2008-1017 varied by only 25%. The other uncertain sources, Rocky Coulee wasteway base flow (4%) and groundwater (9%) were relatively small fractions in the 2001 water budget (Carroll, 2006), and would not substantially change the dominance of the internal source even if their fractions were much higher or lower.

The average net sediment releases of P from the loading rates in 2020 and 2021 were 2.0 and 2.5 mg/m2 per day during the 150-day, spring-summer periods. Those rates were a combination of the release from areas that became anoxic (43% of the lake > 5 m) and the remaining shallower oxic areas. Gross release rates (before sedimentation loss) from the whole area would have been closer to 5 mg/m2 per day, as evidenced from rates in cores incubated under oxic and anoxic conditions, which averaged about 1 and 10 mg/m2 per day, respectively (Okereke, 1984). Thus, internal loading was by far the major source of TP that accounted for the summer increases in lake TP.

Table 5. Total P in µg/L in the surface inflows (Crab Cr. TS2, Rocky Ford Cr. TS14) and lake sites at 0.5 m during June-September 2022 and May-September in 2023. Change is from the June-August and May/June-August average to September. LPH/SL = Lower Parker Horn/South Lake (TS5/6), LRFA = Lower Rocky Ford Arm (TS15), MRFA = Middle Rocky Ford Arm (TS11), and URFA = Upper Rocky Ford Arm (TS12).

2022

Site	June	July	August	June-August	September	change
Crab Cr	52	63	41	52	57	+3
Rocky Ford Cr	226	153	192	190	144	-46
LPH/SL	15	16	19	17	36	+19
LRFA	16	29	22	22	46	+24
MRFA	18	28	21	22	52	+30
URFA	30	25	21	25	49	+24

2023

Site	May/Jun	July	August	June-August	September	change
Crab Cr	59	48	38	48	33	-15
Rocky Ford Cr	166	157	161	161	138	-23
LPH/SL	22	32	20	25	33	+8
LRFA	42	40	30	48	32	-16
MRFA	34	46	39	40	41	+1
URFA	43	62	46	50	58	+8

Cyanobacteria, microcystin and water quality

Microcystin concentrations near shore at Connelly Park in middle RFA (near TS11) were relatively low in 2018 and 2019 (20 and 13 µg/L), yet TP and chl concentrations in open water (TS11) were very high averaging 92 and 50 µg/L, respectively (Table 6). On the other hand, microcystins were relatively high at Blue Heron Park in 2018 (606 µg/L; Table 6) with open-water TP and chl concentrations at nearby lower Parker/South Lake (sites 5 and 6) less than half the levels at middle RFA. The alga *Microcystis* (MA) was the dominant cyanobacteria at both open water sites in 2018, despite the large difference in near-shore microcystin (Table 6). Total cyanobacteria (blue-green algae) also dominated algal biovolume in RFA (82%) and lower Parker/South Lake (43%) during July-September 2017, but microcystin was not sampled.

There was more microcystin at Blue Heron in 2019, with much less open water TP, than at Connelly Park (Table 6). Microcystin was similarly high at both sites in 2020, but TP and chl in open water at middle RFA (TS11) were more than double levels at lower Parker/South Lake in both 2019 and 2020. Also, the high microcystin concentrations at Connelly Park in 2021 (1098 µg/L) were inconsistent with the low *Microcystis* fraction (6%) of total algal biovolume and relatively lower TP (42 µg/L) in open water at middle RFA.

Total P was unusually low throughout the lake in spring and early summer 2021, especially at lower Parker/South Lake (average 14 µg/L). There was no *Microcystis* at middle RFA (TS11) or at lower Parker/South Lake (TS5 and 6) in June, and only 0.4 and 3.4 % of total biovolume at those sites, respectively, in August. Microcystin was not sampled at Blue Heron Park in 2021 due to no obvious scum formations that prompted sampling. That was consistent with the low % *Microcystis* and TP and chl concentrations in open water at lower Parker/South Lake (TS5 and 6; Table 6).

Cyanobacteria and *Microcystis* were low at both open-water sites in 2022, consistent with low TP and chl (Table 6). There were two small scums at Blue Heron in September 2022 that produced high microcystin concentrations, which was inconsistent with low TP, chl, cyanobacteria and *Microcystis* in open water at lower Parker/South Lake. Microcystins were usually determined at low, less than standard concentrations in the nearshore at Connelly Park, but not at Blue Heron except for the small scums in September. Total P and chl, as well as the *Microcystis* fraction of total algal biovolume, were higher at the open water sites in 2023 than the previous two years. Yet microcystins were relatively low (Table 6).

For most of the observations, there is no obvious relationship between concentrations of microcystin in algal accumulations from near- shore samples and algal composition or TP and chl in open water at these two sites. The inconsistent association between microcystin in near-shore water and open water TP, chl, % cyanobacteria and % *Microcystis* (MA) indicates that other factors besides open water conditions determine the accumulation of blue-greens, *Microcystis* and associated microcystin in near-shore areas. Wind is important in distributing buoyant cyanobacteria throughout the lake. They tend to accumulate at the surface in open water due to their buoyancy as the day progresses and are distributed to nearby shores as wind typically increases in the afternoon. Thus, relatively low concentrations of cyanobacteria can accumulate in large clumps on the surface in open water and those clumps can be transported downwind to shore. Microcystins have occurred in near-shore areas of other lakes with very low chl concentrations in open water (Jacoby et al. 2000; 2015). Also, *Microcystis* is usually in bottom sediment at high concentrations and can migrate vertically into and through the water column, as do other buoyant cyanobacteria (Barbiero and Welch, 1992). Those processes can account for the high variability observed in these data - nearly 100% of means in the near-shore microcystin concentrations.

These observations indicate that clumps of Microcystis, and its associated microcystin, could still accumulate in near-shore areas even if the spring-summer average open water TP were 20 -30 µg/L. Those accumulations would be expected to diminish eventually if an average TP of 20 µg/L were regularly attained, because the risk of cyanobacteria fractions of algal biomass over 50% is known to decrease as TP declines below around 30 µg/L (Downing et al., 2001). Nevertheless, open water TP averaged 22 µg/L at lower Parker/South Lake in 2021-2023, and while the nearby Blue Heron Park shoreline was not sampled in 2021 because a bloom was not obvious, there were relatively small scums with high microcystins there in late 2022, and three samples with low microcystins in 2023 (Table 6).

Cyanobacteria averaged 71% of total algal biovolume at four sites during 2017-2018 (TS11, 12, 5 and 6). *Microcystis* dominated at 78% of maximum cyanobacteria biovolume, while

Aphanizomenon averaged only 3%. In 2021, cyanobacteria did not dominate averaging 22 and 23% at the two sites and Microcystis averaged only 8% and *Apanizomenon* averaged 5%. In 2022, cyanobacteria were again low averaging 21%, as were *Microcystis* at 1% and *Aphanizomenon* at 15%. Cyanobacteria were more prevalent in 2023 at 27 and 45% of total biomass, but *Microcysits* was again low at only 1% and *Aphanizomenon* was 7 and 24%. These low concentrations of cyanobacteria are consistent with the low TP concentrations, especially in 2022.

Table 6. Average microcystin concentrations in µg/L from near-shore samples at Connelly Park and Blue Heron Park, near TS11 and 5, respectively, usually during mid to late summer with sample no. in (); NS = no samples taken. Open-water average percent cyanobacteria (CY%) and *Microcystis* (MA %) fractions of total biomass, TP and chl at 0.5 m depth in µg/L at middle RFA (TS11) and lower Parker Horn/South Lake (TS5/6) during May-September. NS = microcystin not sampled. No scums = no accumulations observed to sample.

	Connelly Park	Rocky Ford Arm				Blue Heron Park	Lower Parker/South Lake			
	microcystin	CY%	MA%	TP	Chl	microcystin	CY%	MA%	TP	Chl
2017	NS	82	57	37	10	NS	43	35	25	7
2018	20 (4)	79	67	83	49	606 (8)	87	64	41	18
2019	13 (11)	NS	NS	101	51	78 (15)	NS	NS	30	14
2020	220 (33)	NS	NS	99	63	197 (11)	NS	NS	41	22
2021	1098 (8)	23	6	42	11	No Scums	22	10	20	7
2022	2 (9)	30	1	27	11	575 (2)	12	1	20	8
2023	2 (1)	45	1	45	15	7 (3)	27	1	25	10

TN:TP Ratios

The ratios of TN:TP in the lake has more than doubled in recent years from the 1970s-1980s (Table 7). That increase was not due to changes in inflow nitrogen and phosphorus (Table 8). Total P in Crab Creek has been consistent at 48 µg/L during spring-summer since the 1980s and in RFC as well at 165 µg/L. Also, inflow nitrate-N has not changed significantly since the 1970s-1980s. Thus, the higher lake TN:TP ratios were likely due to lowered TP in the lake from dilution (Table 7).

The higher TN:TP ratios may have favored *Microcystis*, a non-fixer of atmospheric N, over *Aphanizomenon*, which dominated algal biovolume in the 1970s-1980s, and able to fix N (Welch, 2009). Reducing N to the lake would likely restore the dominance of *Aphanizomenon*, which produces toxins as well, and not reduce chl and % cyanobacteria. Thus, reducing P is the appropriate nutrient to reduce to improve lake quality as evidenced by the results of dilution.

Table 7. Average ratios of soluble and total N to P during spring-summer before and after dilution began in 1977 (from Welch, 2009) compared with recent years (data from USBR), compared with the Redfield ratio of 7.2.

Ratios	1969-1970	1977-1988	2003-2023
NO_3-N:SRP	1.2	5.2	10.6
TN:TP	7.5	7.3	19

Table 8. Average nitrate-N concentrations in µg/L during spring-summer in Rocky Ford and Crab Creeks (data during 1977-1988 from Welch et al., 1989; during 2003-2021 from USBR).

Surface inflow	1977-1988	2003-2023
Rocky Ford Creek	1125	1267
Crab Creek	929	891

Phosphorus, lead and microcystin in sediment

Lead and sedimentation rate

The sediment core analysis was originally in the 2021 report to MLIRD. It is repeated here to emphasize the point that the cyanobacterium Microcystis and associated algal toxin microcystin were not new to the lake when microcystin was detected in 2018.

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 (Table 9). 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. Microcystis may have become the dominant blue-green because the TN:TP ratio decreased due to dilution of lake TP. 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.

Table 9. 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. The three cores were 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.

	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

Water Temperature

Surface water temperature has increased on average about 2F at lower Parker/South Lake since the 1970s-1980s. The increase was about the same for mid-summer or the whole summer (Table 10). That is half the temperature increase recorded in 219 of 245 world lakes from 1985 extrapolated by decadal increase to 2025.

Blue-green algae tend to be favored by increase temperature. However, the dominance of blue-greens has been rather closely related to TP concentration, with low fractions of total algal biovolume occurring the past three years associated with TPs of 20-30 µg/L resulting from large inputs of low-P CRW. That is consistent with the risk that cyanobacteria fractions of algal biomass over 50% was shown to decrease as TP declined below around 30 µg/L (Downing et al., 2001). Also, the start of blue-greens in Moses Lake was shown in the 1980s to occur when lake temperature reached about 68F (20C). The average for May-June has not increased much above that in the past seven years.

Table 10. 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) and 2017-2023 (75,456 to 230,000AF). Sampling frequency during 1977-1988 was twice-monthly as well as during the past six 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
2022	190,304	68.2	74.3	76.8	73.1
2023	159,300	68.9	77.3	66.3	71.7
Column average		67.9	76.2	68.6	70.9
1977/79	186,950	64.9	75.9	65.8	69.5
1986-88	114,500	64.5	72.6	66.5	68.1

Summary

1. The fractions of CRW in the deep areas of the lake were higher the last three years with an average of 76% at the surface and 71% at the bottom during July-September over 58% of the lake's area (TS6, 11 and 15). The high %CRW was due to large inputs of CRW averaging 193,200 AF for the three years. CRW inflow was also high in 2020 at 187,120 AF, yet CRW averaged less at 66% and 59% at surface and bottom. The reason(s) for less %CRW in 2020, even with high CRW input, is unclear. The water column was more stratified in 2021 and 2022, which indicated that more cold-water inflow (50F) may have plunged accounting for higher %CRW at depth. However, the water column was less stratified in

2023 and %CRW was relatively high. While there is year-to-year variation in %CRW with similar CRW inflows, %CRW in the lake is strongly related with CRW inflow.

2. Lake level at the start of CRW input also affects %CRW in the lake. Less lake volume should increase the effectiveness of diluting the lake with low-TP CRW and produce lower lake TP. Lake level at the start of CRW input the last four years averaged 1042.1 feet, with represents 64% of full-pool volume. Filling rate at that level (64% of full pool) and 1500cfs CRW inflow amounts to an exchange rate in the lake of 3.7%/day, versus 2.4%/day at full pool (1046 feet). However, lake level in 2020 was also relatively low at 1042.3 feet, yet %CRW was less (66/50%) than the last three years (76/71%). Nevertheless, CRW averaged 74% at the surface and 68% at the bottom over 58% of the lake the past four years when lake level averaged 1042.1 feet.
3. The mixture of CRFW input and existing lake water is transported well up into Rocky Ford Arm (RFA) by prevailing SE and SW wind. That was demonstrated in 1981 by comparing predicted %CRW at various distances up RFA by a diffusion model with observed %CRW. Also, the reverse effect of Rocky Ford Creek inflow was minimal due to the large area of RFA. Thus, wind determines water movement in RFA.
4. Lake quality in terms of spring-summer average TP, chl and transparency, were much improved the past three years, compared to conditions in 2020 and 2017-2019. Total P averaged 22 µg/L the past three years at lower Parker/South Lake and 39 µg/L at middle/upper RFA. Less chl, a measure of total algal biomass, was due to less TP and greater transparency was due to less algae indicated by chl. Reduced TP was due to more CRW, which averaged 191,680 AF, an 85% increase over the CRW input in 2017-2019. As a result, the CRW fraction averaged 72% the past four years. Total P is strongly related to %CRW.
5. Internal loading is the release of phosphorus from bottom sediments. That source represented half the total loading to the lake in 2020 and 2021. Total P increased during summer by 57% from May to June/July in 2020 and doubled in 2021, 2022 and 2023 from May to June/September at South Lake and Middle RFA. Those increases were not due to inflows because TP in Crab Creek and Rocky Ford Creek decreased during

summer in 2019-2021 and either decreased or changed slightly in 2022 and 2023. Internal loading has added between 8,000 and 10,000 kg of TP to the lake in the 1980s and 202 and 2021.

6. Surface scums of algae were sampled for the toxin microcysitin the past six years at Connelly Park and Blue Heron Park. Concentrations have ranged widely from 2 to 1,098 µg/L. Average May-September cyanobacteria fraction of total algal biovolume ranged from 12 to 87% and *Microcystis*, the main source of microcystin, ranged from 12 to 67% of total algal biovolume at TS6 and TS11, in open water near the Parks. The inconsistent association between microcystin concentrations and/or near-shore scums, and open water TP, chl, and cyanobacteria and *Microcystis* fractions, is due to other factors such as wind direction and velocity. Relatively low concentrations of buoyant cyanobacteria in open water can accumulate at the surface and near shore during windy periods. Thus, above standard microcystin concentrations may occur in accumulated near-shore scums even with low open-water TP and chl. Nevertheless, relatively lower microcystin concentrations, or no scum formations to sample, occurred in four of the past six years at the two sites, consistent with lower TP, chl and % *Microcystis*.
7. The ratio of total N:total P has more than doubled in recent years due mostly to reduction of lake TP by dilution with low-TP CRW. The increase was not due to inflow nitrate concentrations, which have not changed. The increase in TN:TP may have favored *Microcystis*, which does not fix N. Reducing N would likely favor the N-fixing cyanobacteria *Aphanizomenon*, which is also a toxin producer, and would not improve lake quality, which is more dependent of P.
8. The sediment core analysis was in the 2021 report and is repeated here to emphasize that the algal toxin microcystin has been in the lake for many decades. At a sedimentation rate of 0.73 cm/year, a depth of 50-64 cm represents 1933-1952, before the Columbia Basin project. Sediment TP declined after the dilution project began, likely due to lower lake TP concentrations. Microcystins increased in the mid-1990s, although they were in the lake in the 1930s-1950s.
9. Lake temperature has increased about 2F since the 1970s-1980s, from 74 to 76F during July-August and about 69 to 71F during

May-September. That increase may have implications for lake quality. Blue-green algae tend to be favored with increased temperature, although the blue-green fraction of total algal biovolume in the lake has been determined mostly by TP concentration in recent years.

Literature Cited

Carroll J. 2006. Moses Lake phosphorus-response model and recommendations to reduce phosphorus loading. Washington Dept. of Ecology, Olympia, WA. Pub. No. 06-03-011.

Cooke GD, Welch EB, Peterson SA, & Nichols SA. (2005). Restoration of lakes and reservoirs, 3rd ed. Boca Raton, FL: CRC Press.

Downing JA, Watson SB, & McCauley E. (2001). Predicting cyanobacteria dominance in lakes. Canadian Journal of Fisheries and Aquatic Science, 58, 1905–1908. https ://doi.org/10.1139/f01-143

Eaton AD, Clesceri LS, Rice EW, Greenberg AE, Franson MAH. 2005. Standard methods for the examination of water and wastewater. 21st ed. American Public Health Association, Water Environment Federation and American Water Works Association.

Jacoby J, M Burghdoff, G Williams, L Read and FJ Hardy. Dominant factors associated with microcystins in nine midlatitude, maritime lakes. Inland Waters 5:187-202.

Kann J. and EB Welch. 2005. Wind control on water quality in shallow, hypereutrophic Upper Klamath Lake, Oregon. Lake and Reserv. Manage. 21(2):149-158.

Okereke VO. 1987. Internal phosphorus loading and water quality projections in Moses Lake. MSE Thesis, Civil and Environmental Engineering, University of Washington, Seattle, WA.
Perkins WW, Welch EB, Frodge J, Hubbard T. 1997. A zero degree of freedom total phosphorus model 2. Application to Lake Sammamish, Washington. Lake Reserv. Manage. 13:131–141.
US Department of Interior - Bureau of Reclamation. 2007. Potholes Reservoir Supplemental Feed Route Finding of No Significant Impact Environmental Assessment, Columbia Basin Project, Grant County, Washington. Pacific Northwest Region. August 2007.

Welch EB, CR Patmont. 1980. Lake restoration by dilution: Moses Lake, Washington. Water Res. 14:1317-1325.

Welch EB. 2009. Should nitrogen be reduced to manage eutrophication if it is growth limiting? Evidence from Moses Lake. Lake and Reservoir Management 25:401-409.

Welch EB, KL Carlson, RE Nece and MV Brenner. 1982. Evaluation of Moses Lake Dilution. Water Resources. Series Tech. Rep. No. 77, Dept. of Civil Engr., University of Washington.

Welch, E.B., C.A. Jones and R.P. Barbiero. 1989. Moses Lake quality: results of dilution, sewage diversion and BMPs – 1977 through 1988. Water Res. Ser. Tech. Rep. 118, Dept Civil & Environ. Eng., Univ. of Washington, Seattle, WA, 65 pp. http://mlird.org/cleanlakeproject.html
Welch E.B, SK Brattebo and C Overland. 2019. Four decades of diluting phosphorus to maintain lake quality. Water Environment Research 92:26-34.

Welch EB. 1992. Lake trophic state change and constant algal composition following dilution and diversion. Ecological Engineering 1:173-197.

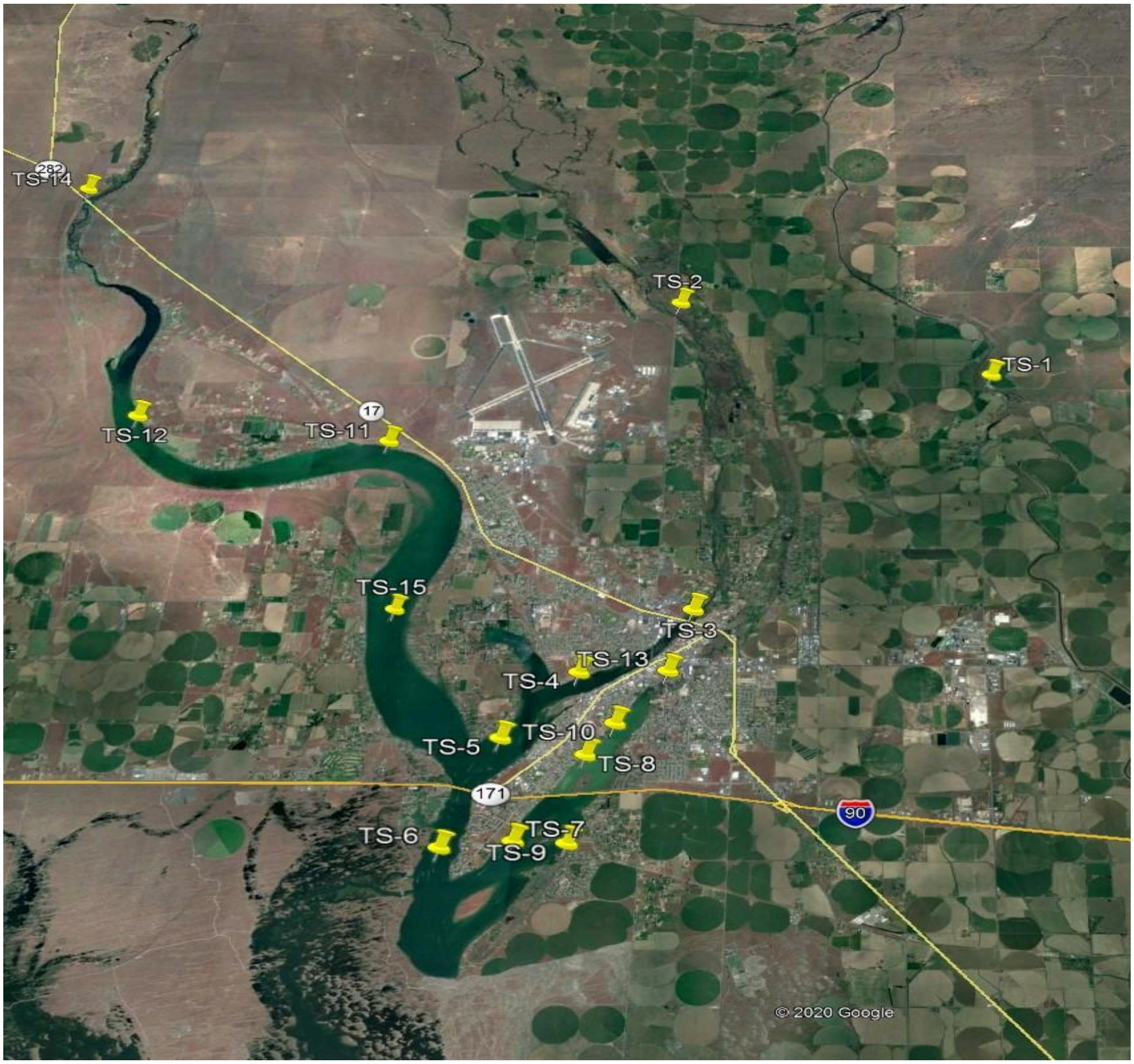

Figure 1. Sampling sites by MLIRD during 2017-2023. Most sites are similar to those sampled by UW, Civil and Environmental Engineering, during 1969-1970 and 1977-1988 (Welch et al., 1989).

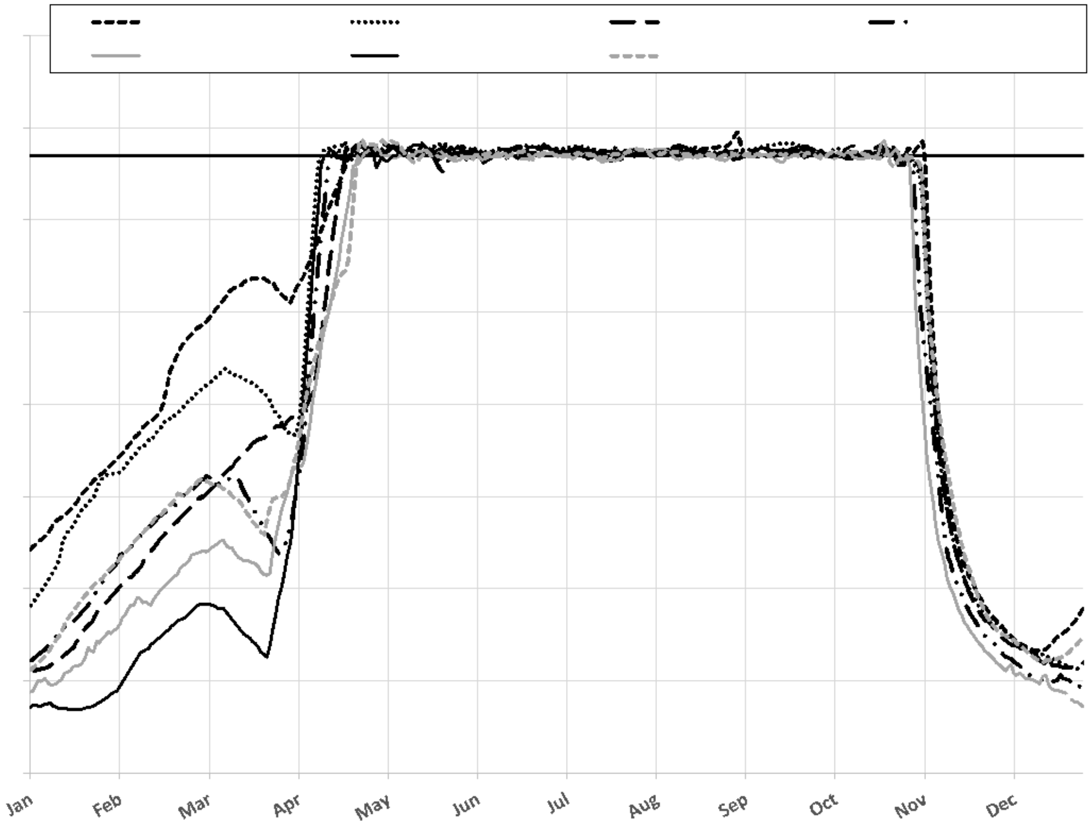

Figure 2. Elevation levels of Moses Lake during 2017-2023.

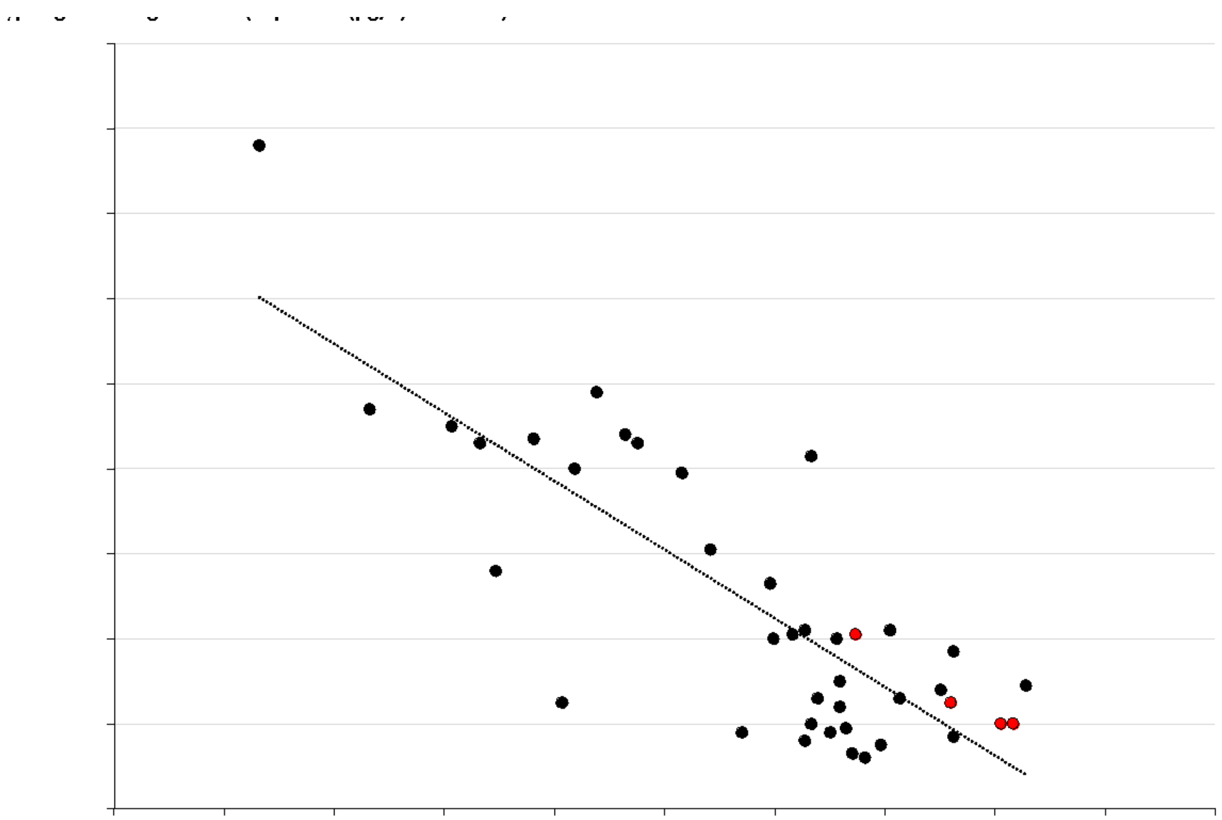

Figure 3. Relation between May-September average TP at South Lake (TS6) and lower Parker Horn (TS5) and % Columbia River water at 0.5 m from 1977 to 2023. The point at 10%CRW and 152 µg/L TP was pre-dilution in 1969-1970. Phosphorus and SC data for %CRW during 1977-1988 from Welch et al. (1989) and USBR at South Lake during 1995-2016.

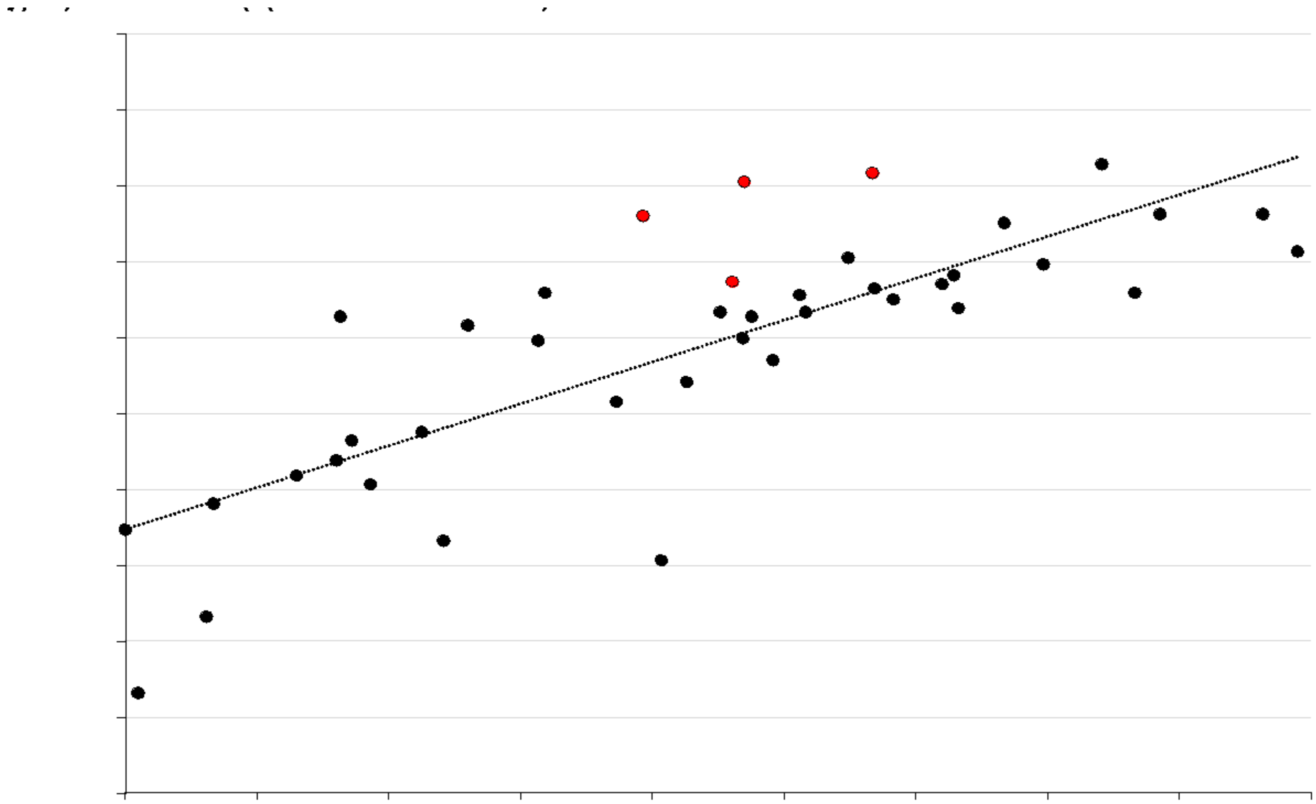

Figure 4. Relation between May–September % Columbia River water at 0.5 m at lower Parker Horn and South Lake (sites TS5 and TS6) from 1977 to 2023 and inflow of Columbia River water into Moses Lake. The point at 10%CRW was pre-dilution in 1969-1970. SC data for %CRW during 1977-1988 from Welch et al. (1989) and USBR at South Lake during 1995-2016.