Moses Lake Water Quality:
Causes and Benefits of Columbia River Water

Prepared for Moses Lake Irrigation and Rehabilitation District

By

Eugene B. Welch

Consulting Limnologist and

Prof. Emeritus, University of Washington

May, 2020

Introduction

This report summarizes the status of lake water quality in terms of total phosphorus (TP) and chlorophyll (chl) content over the past three years. The report is also a compilation of short reports on analyses during 2019. These short reports include analyses of the distribution of Columbia River water (CRW) added to Parker Horn determined by the conservative indicator specific conductance (SC), changes in internal loading of phosphorus since dilution with CRW began in 1977, changes in the inflow TP concentration since dilution began, and the relative importance of sources of TP to the lake including ground water from observations in the 1980s and 2001.

Perceptions of the lake's quality versus reality

Moses Lake's water quality is far better now than either before (1963, 1968-1970) or in the 1970s-1980s following the start of dilution with low-phosphorus CRW. The lake's quality is best indicated by spring-summer average TP concentrations, because phosphorus is the critical nutrient that determines the concentration of algae, which is usually at highest concentration during that period. As spring-summer TP increases, the prospect of harmful algal blooms (HABs) increases. That is the case for lakes and reservoirs in general and Moses Lake is no exception.

The water quality in Moses lake has greatly improved over the past four decades in response to varying inputs of low-phosphorus CRW (Welch et al., 2019). As a result of dilution by CRW, TP in lower Parker Horn and South Lake decreased from a spring-summer average of 152 ppb (ppb = parts per billion) two years before to 74 ppb during eight years after CRW input began, to 41 µg/L the following three-year period after wastewater was diverted from middle Pelican Horn and CRW input increased from an average of 96,000 to 114,000 AF (Welch et al., 1989; Welch et al., 1992; Table 1). Total P was 144 ppb in lower Parker Horn in 1963 (Sylvester and Oglesby, 1964). Input of CRW continued at similar amounts through most of the 1990s, but increased further after 2000 to an average of 260,000 AF during 2001-2016 (Figure 1). That increase in CRW reduced average TP in lower Parker Horn and South Lake to 23 µg/L (Table 1). Total P has averaged 32 µg/L the past three years and with less CRW input averaging 98,000 AF. That long-term effect of dilution represents an 80% lowering of TP in lower Parker Horn and South Lake as a result of continued and even increased CRW inputs, as well as wastewater diversion. That contradicts the perception that the lake's quality has worsened in recent years. Rather, its quality has continued at a relatively high level despite less CRW the past three years than during 2001-2016.

Table 1. Average period dilution volumes (CRW) in AF entering Parker Horn and TP in ppb in lower Parker Horn and South Lake (TS5/6) over the past 50 years.

Before 1969-1970	400 AF 152 TP
After 1977-1984	96,000 AF 74 TP
1986-1988	114,000 AF 41 TP
2001-2016	260,000 AF 23 TP
2017-2019	98,000 AF 32 TP

The perception that the lake's quality has worsened is due largely to recent detection of microcystin, a toxic product of the alga *Microcystis*, reported in 2018 and 2019 in nearshore samples of algal scums at concentrations exceeding the state standard. Microcystin and other algal produced toxins (e.g., saxitoxin) were very likely present in earlier years, but no tests for toxins were performed. The technique for measuring algal toxins was not available until the late 1980s – early 1990s, so comparable data are lacking. However, the producers of those toxins, the cyanobacteria (blue-green algae), represented 78% and 96% of algal biomass in lower Parker Horn in 1963 and 1970, respectively, before dilution, to 76% in the 1970s-1980s after dilution began. *Microcystis* was present during those years, but the dominant cyanobacteria was *Aphanizomenon*, a neurotoxin (saxitoxin) producer (Sylvester and Oglesby, 1964; Bush and Welch, 1972; Welch et al., 1992; and Bouchard, 1989). Cyanobacteria still averaged 65% of total algal biomass in 2018-2019, although *Microcystis* dominated rather than *Aphanizomenon*.

Total biomass indicated by chl has markedly decreased in recent years, averaging 58 ppb before dilution, to 21 ppb during 1977-1984, to 17 µg/L during 1986-1988 after dilution and wastewater diversion, to 13 ppb in 2017-2019. With less algal biomass, and proportionately less cyanobacteria in that biomass, the concentration of cyanotoxins may have decreased as well. Therefore, the recent alarm and concern about the lake's condition were not so much about water quality per se, but because samples were taken and analyzed for algal toxins.

That does not mean the lake's quality cannot be improved, but 32 ppb TP and 13 ppb chl in Parker Horn and South Lake the past three years should be recognized as a vastly higher lake water quality than existed 50 years ago. However, improvement to even lower TP in that area of the lake to say 20 µg/L may be difficult, and even at that level, blooms of *Microcystis* may still occur. This alga persists in bottom sediments and rises into the water column as waters warm. Sediment originating blooms of *Microcystis* occurred in Lake Sammamish where summer TP has consistently averaged 12 ppb (Johnston and Jacoby, 2003). Nevertheless, cyanobacteria were <5% of total biomass in lower Parker Horn and South Lake in 2001 when CRW was 220,000 AF, double that in 2017-2019, and average TP was 17 ppb (Carroll, 2006). Yet, cyanobacteria with mostly *Microcystis* and *Aphanizomenon* prevailed in Parker Horn in 2005 with 200,000 AF of CRW and average TP 30 ppb (Bergoon, 2006).

While water quality in lower Parker Horn and South Lake have markedly improved over the years, as CRW inputs increased, Rocky Ford Arm is still hypereutrophic. Total P in mid to upper Rocky Ford Arm (TS11/12) averaged 81 ppb and chl 26 ppb during 2017-2019. Although CRW reaches well up into RFA, it transports water from Parker Horn, which has higher TP concentrations than CRW's 7 ppb that initially entered Parker Horn.

Report purpose

In addition to the compilation of analyses and short reports during 2019, this report summarizes data from water samples collected by MLIRD at sites TS 5/6 and TS11/12 in the lake and two surface inflows during 2017-2019 (Figure 1). Conditions in 2017-2019 are compared with previous published data.

Methods

Water Sample Collection and Analysis

Water samples were collected in 2017-2019 with a Van Dorn bottle by MLIRD personnel at a depth of about 0.5 m at nine lake sites during April-September to early October (Figure 2). Sampling at TS12 was not begun in 2017 until July. Sampling was twice monthly in 2017-2018 and monthly in 2019. Inflows at two sites on Crab Creek (TS2, TS3) and the east low canal (TS1). Samples were collected at other sites shown in Figure 2, but the data are not presented.

Samples were shipped on ice to IEH Analytical Laboratories, Seattle, WA, for analysis. 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), temperature and dissolved oxygen were determined *in situ*.

Water samples for algae identification and enumeration were also collected in 2017 and 2018 from the Van Dorn bottle water, coincident with the sample for other constituents. Samples for algae were collected during regular monitoring events. 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. Methods are described in detail by Matthews et al. (2019).

Results and Discussion

Tracing CRW

Specific conductance (SC) is a measurement of conservative substances that represent a tracer for CRW, which has low SC (142 µS/cm). Lake SC in 1969-1970 before diltuion began was 445 µS/cm. Without CRW, lower Parker Horn and South Lake (TS5/6) would equal Crab Creek, which contains 491 µS/cm, and upper Rocky Ford Arm (TS12) would equal Rocky Ford Creek, which contains 371 µS/cm, while middle Rocky Ford Arm (TS11) would equal about half of each inflow stream or 431 µS/cm. Ground water in 2001 averaged less than those surface inflows; 322 µS/cm in the TS12 area , 256 µS/cm in the TS11 area and 276 µS/cm in the upper Parker Horn area (Pitz, 2003). Thus, ground water inflow SC tends to dilute inflow stream SC and ground water inflow volume was likely much less than stream inflow, as was the case in 2001 (Carroll, 2006).

Figure 1 shows that CRW entering through Crab Creek during April-May, as well as August-September, 2018, had lowered SC in lower Parker Horn and South Lake (TS5/6). As a result, CRW was already above 60% and increased in July-August to near 70%, probably due to late summer resumption of CRW input (Figure 3).

Dilution of Rocky Ford Arm was slower, especially in the upper portion (TS12), starting out at about the SC level in Rocky Ford Creek. Subsequently, SC decreased first in the middle Rocky

Ford Arm (TS11) and then in upper portion (Figure 1). Percent CRW rose to over 60% by mid July at TS11, and even reached the upper portion (TS12) to near 60% by July, falling back to 40% by September (Figure 3).

The calculated % CRW by summer's end was about 60% in lower Parker Horn and South LakeL, as well as in middle Rocky Ford Arm, while upper RFA was about 40% (Figure 3). Those CRW fractions of their respective lake volumes represent about half the total inflow of CRW during 2018. Some residual CRW probably remains through the winter, because the natural low flow of Crab Creek is slow to replace the volumes of lake water.

Effect of CRW on phosphorus

While CRW had moved well up into Rocky Ford Arm by mid-summer 2018, it had less effect at diluting incoming TP from Rocky Ford Creek, because entering CRW had mixed with higher TP water in lower Parker Horn and Sough Lake, so CRW was not directly diluting the high TP entering from Rocky Ford Creek with low TP CRW, as it had in lower Parker Horn and South Lake. Despite the lake being 60% or more CRW during July-September, TP neverless rose from less than 20 to over 50 ppb at lower Parker Horn and South Lake (TS5/6), and from about 40 to 70 ppb in middle Rocky Ford Arm (TS11). Also, TP rose from about 80 to over 100 ppb in upper Rocky Ford Arm (TS12) despite CRW representing about 40%. These increases in TP were probably due mostly to internal loading in the deeper areas of lower Parker Horn and South Lake and lower Rocky Ford Arm, as well as the rather constant high TP input from RFC containing around 150 ppb.

Input of CRW in 2018 was 106,000 AF, which was less than half the average input during 2000-2016 when TP at South Lake (TS6) averaged 23 ppb (Table 1). With more than double the average CRW input during that 17-year period, % CRW was doubtless much higher and TP lower in middle and upper Rocky Ford Arm than observed in 2018.

Current Water Quality

Water quality indicated by TP, chl and transparency (SD - Secchi DisK depth) varied during 2017-2019, although there were consistencies among lake areas. The most striking aspect was the consistently rather low seasonal average concentration of TP (32 ppb) in lower Parker Horn and South Lake (TS5/6), despite 62% less CRW than during 2001-2016, when TP averaged 23 ppb (Table 1 and 2). Also, TP in lower Parker Horn and South Lake was less than half that in Rocky Ford Arm. Although CRW reached well up into Rocky Ford Arm, as shown by the SC tracer (Figure 3), its effect at diluting the high TP from Rocky Ford Creek and internal loading was much reduced. Transparency averaged 1.4 m for 2017-2018 (no measurements in 2019), similar to 1986-1988 (1.5 m).

Consistent with TP, chl in Rocky Ford Arm was double that in lower Parker Horn and South Lake and transparency was much less (Table 2). Algae were strongly dominated by cyanobacteria (blue-green algae) in both areas of the lake, despite an algal biomass (as chl) difference of two-fold. Cyanobacteria still represented most of the algal biomass even though dilution had effectively reduced TP by nearly 80% over the years. Total algal biomass, indicated by chl, as well as the cyanobacteria fraction, decreased proportionately. Cyanobacteria are likely to dominate the algal biomass even if TP and chl were decreased further, although cyanobacteria would nevertheless be less concentrated in a water sample.

Cyanobacteria were not dominant in lower Parker Horn and South Lake in 2001 when CRW input was 220,000 AF and average TP was 17 ppb, but were dominant in Parker Horn in 2005 with CRW input at 220,000 AF and average TP 30 ppb (Carroll, 2006 and Bergoon, 2006). These data suggest that lowering average spring-summer TP well below 30 ppb may markedly reduce cyanobacteria biomass.

Table 2. Average May-September TP, chl, transparency (SD) and % cyanobacteria (2017 nd 2018 only) at TS5/6 and TS11/12 during 2017-2019.

		TP	chl	SD	% cyanobacteria
TS5/6	2017	25	7	1.4	43
	2018	41	18	1.4	87
	2019	30	14		
3-year	Average	32	13		
TS11/12	2017	58	15	1.0	75
	2018	83	49		79
	2019	101	51		
3-year	Average	81	26		

Inflow Phosphorus

Inflow phosphorus data are available over 50 years from UW, USBR and MLIRD (Table 3). The significance of these data is described below.

Table 3. Average total phosphorus (TP in ppb) in inflows and lower Parker Horn and South Lake (TS5/6) since 1968.

	1968-70 (UW)	1977- 79 (UW)	1986-88 (UW)	Recent years
Spring-summer				
Rocky Ford Cr.				
Below hatchery	172	167	165	144 (1995 -2018 USBR)
Above hatchery				115 (2010 -2018 USBR)
Crab Cr. above				
Rocky Coulee	111	92	47	32 (3003 -2018 USBR)
				54 (2017 -1018 MLIRD)
TS 5/6 lake	141*	87**	41***	23 (2001 -2018 USBR)***
				31 (2017 -1019 MLIRD)***

*before dilution
** after dilution
*** after dilution and wastewater diversion

1. Trout Lodge hatchery increased TP in Rocky Ford Creek, but its contribution apparently has not changed over the years.
2. The decrease in Crab Cr. TP in the 1980s was likely due to a gradual shift from rill to spray irrigation during the early 1970s (Welch et al., 1992).
3. An inflow TP concentration in Crab Creek of 40-50 ppb, if there were no Columbia River dilution water (CRW) and no internal loading, would normally reduce TP to 20-35 ppb in the Parker Horn and South Lake due to settling as function of normal water retention time.
4. Rocky Ford Creek is the principal surface inflow source of TP (Table 1).
    a. TP has remained very high and consistent year-to-year for 50 years and most is soluble, and, thus, readily available for algal assimilation.
    b. TP has varied little seasonally at around ± 20% indicating minimal effect of surface runoff.
    c. TP in Rocky Ford Arm averaged 81 ppb in 2017-2019 due mostly to high TP in Rocky Ford Creek, as well as internal loading.
    d. TP in lower Parker Horn and South Lake (TS5/6) averaged 32 ppb in 2017-2019 partly due to CRW diluting internal loading in mid to late summer.

External Loading

Rocky Ford Creek is the largest external source of P, both by concentration and load at over half the total external input (Table 4). Internal loading is probably around 40% on average of total loading (external + internal), based on TP budgets from the 1980s. However, internal loading may have declined possibly due to dilution and wastewater diversion (see Internal Loading).

Table 4. Annual inflow and external TP load. TP load = flow X TP concentration. Inflows from Carroll (2006) and current stream concentrations See Table 4 for stream concentrations.

	TP ppb	flow AF	TP load kg	%
Rocky Ford Cr	144	45,000	8000	55
Crab Cr	43	20,500	1088	8
Ground Water	59	73,620	5362*	37
*70% enters in winter (Pitz, 2003)				

Phosphorus from Ground Water

Ground water entering the lake at seven sites along Rocky Ford Arm and two in upper Parker Horn was sampled in May, July and October, 2001 (Pitz, 2003). Average soluble reactive phosphorus (SRP) concentration was 100 ppb (± 52%), which was double the background concentration (50 ppb). Howevr, Pitz assumed geometric mean concentrations of 35 ppb along Rocky Ford Arm and 54 ppb in upper Parker Horn as representative estimates for calculating annual flux of ground water phosphorus to the lake.

Loading of SRP to three areas of the lake (Rocky Ford Arm, upper Parker Horn and Pelican Horn) were estimated using three scenarios for inflow volume, of which 18% came from ground water. The average estimated loading to Rocky Ford Arm and upper Parker Horn represented 45% of the total loading to the lake from ground water. The other 55% entered Pelican Horn. Phosphorus loading from ground water was estimated at 24% of the total from all sources during May-September in 2001 (Carroll, 2006). Thus, only about 11% of the total load to Rocky Ford Creek and upper Parker Horn would have come from ground water (0.45 X 0.24). This indicates that the increase in TP in lower Parker Horn, South Lake and Rocky ford Arm during summer 2018 probably came largely from Rocky Ford Creek and internal loading, rather than from ground water.

~~G~~round water was estimated in water budgets for the lake during 1977-1988 and represented 29% on average of the total water inflow during May-September for that 12-year period. Total P loading (flow x concentration) from ground water averaged 31% of total loading using a ground water concentration of 50 ppb, which was the background concentration in ground water determined by Pitz (2003). The various water and TP budgets indicate that about one third of loading has entered via ground water.

The concentration of phosphorus in ground water entering the lake is actually more important than loading. That is, if entering ground water contained 50 ppb, the lake concentration would not exceed 50 ppb regardless of the magnitude of loading, and actually be less than 50 ppb if fed only by naturally occurring ground water, due to the fractional loss to sedimentation in the lake.

Internal Loading

Figure 4 shows that TP concentrations in lower Parker Horn and South Lake (TS5/6) during the past three years were much lower than would be expected given less Columbia River water (CRW) added. For example, TP concentrations during 1986-1988 averaged 41 ppb with 114,000 AF of CRW, while TP the past three years averaged 32 ppb with even less CRW - 98,000 AF. This suggests that internal loading has decreased over the past 40 years as low-phosphorus CRW depleted P in bottom sediments by increasing the sediment-to-water concentration gradient. Also, diversion of wastewater in 1984 would have had a similar effect on sediment-P release. Analysis of TP concentrations through the summers of 1986-1988 and 2017-2019 appear to support that contention.

Surface TP has usually increased during summer as water near the bottom became anoxic causing P to freely diffuse from the sediment as internal loading, with that released P reaching surface water through diffusion and entrainment of bottom water during wind mixing events. Less internal loading the past three years may explain why July-September average surface TP was much less in 2017-2019 than during 1986-1988; 41 versus 65 ppb, even though CRW input was similar; 98,000veersus 114,000 AF. Those TP levels in lower Parker Horn/South Lake were more than could be expected from normal Crab Creek inflow TP concentration, which averaged only 40 ppb during July-September 2017-2019 and 45 ppb for the same months in 1986-1988. Although there was essentially no difference between average inflow and lake TP concentrations the last three years, there was some internal loading, because lake TP would normally be less than the inflow concentration due to loss through sedimentation. Much higher in-lake TP than inflow in 1986-1988 (+20 ppb) indicates greater internal loading in the past.

While internal loading appears to be less now than in the 1980s, substantial internal loading was still evident in 2018 when July-September TP in lower Parker Horn and South Lake averaged 51 ppb and inflow TP in Crab Creek was only 37 ppb. Also, lake TP increased on average from April-June to July-September by 86% the last three years. That spring to summer increase during 1986-1988 was 240%. Thus, the two ways of assessing data both show that internal loading was much greater during 1986-1988, but that it still existed the past three years, especially in 2018, but at a slower rate.

Decreased rate of release of P from sediment into overlying water, or internal loading, has been the usual outcome in lakes following diversion of wastewater, or reduction of wastewater TP concentration (Cooke et al., 20015). Release rate decreased because inflowing water had a much lower P concentration, which then increased the rate of diffusional loss of P from bottom sediments. That may have occurred in Moses Lake. Sediment core data from 1983-1985 showed that average TP concentrations (mg/g dry weight) in the top 4 cm were: 0.92 in middle Pelican Horn, 0.92 in South Lake, 0.86 in Parker Horn and 1.17 in Rocky Ford Arm (Okereke, 1987). Two cores taken in middle and lower Pelican Horn in each of 2017 and 2018 had lower TP concentrations in the top 4 cm than in cores from the 1980s; 0.67and 0.83 mg/g for each of the two cores in 2017, and 0.66 and 0.79 mg/g in the 2018 cores.

The reduction of average sediment P in Pelican Horn of 20% may suggest the effect of wastewater diversion in 1984. Sedimentation rate in Moses Lake was recently estimated by the USGS at 0.6 cm/year. At that rate about 15 cm of sediment were deposited since the earlier cores, so the TP content in the top 4 cm of the recent cores would reflect reduced TP loading due to wastewater diversion. Increased diffusional loss of P from sediment may also have resulted from dilution with CRW. Although the sediment core analyses were from different laboratories (UW and IEH), the analytical procedures were similar.

While there is evidence that internal loading in lower Parker Horn and South Lake has decreased, average surface TP in upper Rocky Ford Arm (TS11) has not changed appreciably: 73 ppb in 1986-1988 versus 63 ppb in 2017-2019. Nevertheless, internal loading is evident in Rocky Ford Arm, because average TP at TS11 increased from April-June (50 ppb) to July-September (80 ppb) during 2017-2019. That difference indicates internal loading, because TP in the main external input, Rocky Ford Creek, is rather constant. Moreover, average May-September bottom TP in the TS11 area in 1986-1988 was 108 ppb, 35 ppb higher than average surface TP, probably due to release of phosphorus from sediment due occasional anoxic conditions (DO < 2 mg/L). Bottom TP was not determined in 2017-2019, but DO < 2 mg/L was evident below 30 feet (6 m) at TS11.

Effects of wind and oxygen on internal phosphorus loading

Moses Lake is relatively shallow and polymictic (more than one mixing per year) and, therefore, is more susceptible to internal P loading during summer than deeper lake, which are permanently stratified during summer. That is because the water column is less resistant to wind mixing, i.e., less difference in density (temp) between surface and bottom. A useful measure of wind effect is the Osgood Index (OI): mean depth (m)/square root of area in square km ($OI = m/\sqrt{km^2}$). For the whole Moses Lake area, the OI is 1.06, and 1.12, excluding middle and upper Pelican Horn ($5.78\ m/\sqrt{26.59\ km^2}$). Osgood found in a study of 96 Minnesota lakes that internal loading tended to be high if that index were less than 6-7, and even much less if greater than 8 (i.e., strongly thermally stratified). More strongly stratified means that wind has less chance of disturbing stratification, which tends to keep high phosphorus water contained near the bottom during summer. Thus, the low OI indicates that Moses Lake is highly susceptible to destratification by wind.

The other index that relates to internal loading, and other effects of water column stability, is relative thermal resistance to mixing (RTRM): $(D_b – D_s)/D_4 – D_5)$, where D is density determined from temperature, b is density of bottom water, s is surface water density, 4 is density of water at 4^0C and 5 is density at 5^0C.

The average RTRM at TS6 during June-September 2018 was 51, which was less than half the average of 110 (range 73-172) during that period in 1980-1988. Temperature, and therefore density, were constant through the water column on August 13, 2018 at TS6, giving an RTRM of zero, meaning there was no resistance to wind mixing and, hence, there was entrainment of phosphorus rich bottom water.

Internal phosphorus loading was highly inversely correlated with RTRM during 1980-1988; as RTRM decreased, internal loading increased. Internal loading was especially high in 1983, 1985 and 1988 when RTRM was low. (see pp. 43-46 in Welch et al., 1989).

Internal load is an important source of phosphorus during summer when external loads tend to be low due to low summer stream flows, although Rocky Ford Creek flow is rather constant. Internal loading will continue to add phosphorus to the water column even if external sources are reduced, and will probably be greater during windy summers than calm summers.

Internal loading is probably larger in lower Parker Horn, South Lake and lower Rocky Ford Arm, because depth is greater allowing more area of the bottom to go anoxic (anaerobic), which promotes high release rates of phosphorus from bottom sediments. Internal loading may also occur in shallower water where bottom sediments may go anoxic during periods of calm weather when surface temperature increases during the day and temporary stratification occurs briefly. Phosphorus is also released from oxic (aerobic) sediments, but at a slower rate. Laboratory experiments with Moses Lake sediments in 1984 showed phosphorus release rates ten times higher from anoxic than oxic sediments (Okereke, 1987). The calculated internal loading from those lab release rates, and respective areas of the lake that were oxic and anoxic, was 7,013 kg during May-September. The average internal loading calculated directly from mass balance during 1984-1988 was 9,345 kg, or 43% (Welch et al., 1989).

Summary

1. Water quality in the lake has been perceived as worsened, because above standard concentrations of microcystin were recently detected. In fact, water quality, as judged by the usual criteria (TP and chl), has markedly improved since dilution with CRW began in 1977, and by nearly 80%. The cyanobacteria *Microcystis*, a microcystin producer and *Aphanizomenon*, a neurotoxin producer, have been major components of algal biomass for most of the past 40 years. Blooms of these cyanobacteria, which recruit from bottom sediment, may still occur even if TP were further reduced.

2. Low specific conductance (SC) of CRW is used to trace the water's distribution throughout the lake. By mid to late summer 2018 CRW represented 60% of the water in middle Rocky Ford Arm (TS11), and even 40% in the upper arm (TS12). Thus, CRW entering via Rocky Coulee Wasteway through Crab Creek effectively moves through the lake, even well up into Rocky Ford Arm. Nevertheless, TP rose from 20 to 50 ppb in lower Parker Horn and South Lake and from 40 to about 70 and 100 ppb in middle and upper Rocky Ford Arm, respectively, by late summer 2018, despite the high fraction of CRW. Those increases in TP were due mostly to internal loading. While CRW effectively moves through the lake, its effect on lowering TP is much greater in lower Parker Horn and South Lake than in Rocky Ford Arm.
3. Spring-summer TP increased to an average of 32 ppb in lower Parker Horn and South Lake during 2017-2019, compared to 23 ppb during 2001-2016. While that increase reflects 62% less CRW, maintaining a spring-summer average around 30 ppb may be possible if CRW input is at least 100,000 AF. Average TP in Rocky Ford Arm was 81 ppb, more than double that in the lower Parker Horn and South Lake, as was chl concentration. Cyanobacteria dominated algal biomass throughout those lake areas in 2017-2018. Transparency averaged 1.4 m in lower Parker Horn and South Lake, similar to that in 1986-1988, but much less in Rocky Ford Arm, but measurements were incomplete. Cyanobacteria were not dominant in lower Parker Horn and South Lake in 2001, but were in lower Parker Horn in 2005 and CRW was high in both years.
4. Total P concentration in Rocky Ford Creek has shown relatively little year-to-year or seasonal variation over the past 50 years. Its soluble fraction (SRP) is large and readily available to algae. In contrast, TP in Crab Creek is much lower, especially since the shift from rill to spray irrigation in the early 1970s. Input TP from Crab Creek represents less effect on lake water quality than input from Rocky Ford Creek, which is a major cause for perpetual poor water quality in Rocky Ford Arm. Total P in lower Parker Horn and South Lake has decreased in proportion to that in Crab Creek over the past 50 years.
5. The magnitude of TP input from Rocky Ford Creek, in terms of flow and concentration (loading), is seven times greater than from Crab Creek, and much greater than from ground water, especially during summer.
6. Analysis of soluble P inputs form ground water in 2001 indicated that 45% entered Rocky Ford Arm and upper Parker Horn, while the remainder entered Pelican Horn. Only about 11% of TP input to the lake entered Rocky Ford Arm and upper Parker Horn, given that ground water contributed 24% of all sources of TP. Ground water contributed 31% of total loading to the lake on average in TP budgets during 1977-1988.
7. Internal phosphorus loading, via recycling from bottom sediments, has probably declined with continuous inputs of low-P CRW and diversion of wastewater. Much less CRW during 2017-2019 should have produced at least double the TP concentration in lower Parker Horn and South Lake than observed, based on the relation of TP with CRW inputs over the past 50 years. According to that relation, 250,000 AF of CRW should have been required to produce the observed 32 ppb TP in 2017-2019, but CRW input

was actually less than half that volume. Also, similar CRW inputs during 1986-1988 (after wastewater diversion) and 2017-2019 resulted in 65 and 32 ppb TP, respectively. Some internal loading still exists, although less than in the past, as evidenced by July-September TP concentrations in lower Parker Horn and South Lake exceeding inflow TP concentration in Crab Creek. Internal loading in Rocky Ford Arm probably has not changed as indicated by surface TP.

8. Internal loading is enhanced in relatively large and shallow lakes like Moses Lake, due to a large surface area and wind fetch and high oxygen demand of bottom sediments that lead to low DO in bottom water during thermal (density) stratification. Calm periods allow DO overlying sediment to deplete increasing sediment-P release rate by tenfold, as shown in sediment core results in the laboratory in 1984. Subsequent windy periods mix the water column entraining the high-TP bottom water. Internal loading, determined by mass balance, during 1980-1988 was highly indirectly related to thermal (density) resistance to mixing in Moses Lake. That is, periods of substantial wind disturbed or broke up thermal (density) stratification entraining high-TP bottom water increasing water column TP concentration. This process probably accounts for average surface (0.5 m) water TP in Rocky Ford Arm (TS11) increasing from 50 ppb in April-June to 80 ppb in July-August during 2017-2019. That increase could not have come from ground water (50 ppb), nor from Rocky Ford Creek, which has high TP, but relatively constant flow.

Recommendations

While these data indicate less internal loading in recent years, a mass balance analysis of inputs and outputs is needed to determine if internal loading has actually decreased and by how much. To do that analysis, TP data are needed from several depths in the water column. Data from the past three years are available from the 0.5-meter depth only. Future work should include sampling from at least four depths in the water column; 0.5, 2, and 5 m and 0.5 m off the bottom.

References

Bouchard, D. 19. Carbon dioxide: its role in the succession and buoyancy of blue-green algae at the onset of a bloom in Moses Lake, MS Thesis. Department of Civil and Environmental Engr., University of Washington, Seattle, WA.

Bergoon, P. 2006. 2005 summary of water sampling for Moses Lake. Water Quality Engr., Wenatchee, WA.

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, G.D, E.B. Welch, S.A. Peterson and S.A Nichols. 2005. Restoration of Lakes and Reservoirs. CRC Press, Boca Raton, FL, 3rd ed.

Johnston, B.R. and J.M. Jacoby. 2003. Cyanobacterial toxicity and migration in a mesotrophic lake in western Washington (USA). Hydrobiologia 595:79-91.

Okereke, V.O. 1987. Internal phosphorus loading and water quality projections in Moses Lake. MSE Thesis, Civil and Environmental Engineering, University of Washington, Seattle, WA.

Pitz, C.F. 2003. Moses Lake total maximum daily load groundwater study. WA State Dept. Ecology,
Olympia, WA. Pub. No. 03-03-005.

Sylvester, R. O. and R. T. Oglesby. 1964. The Moses Lake water environment. Univ. of Washington, Dept. of Civil Engineering.

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.

Welch, E.B., R.P. Barbiero, D. Bouchard and C.A. Jones. 1992. Lake trophic state change and constant algal composition following dilution and diversion. Ecol. Eng. 1:173-197.

Welch, E.B., S.K. Brattebo and C. Overland. 2019. Four decades of diluting phosphorus to maintain lake quality. Water Environment Research 92:26-34.

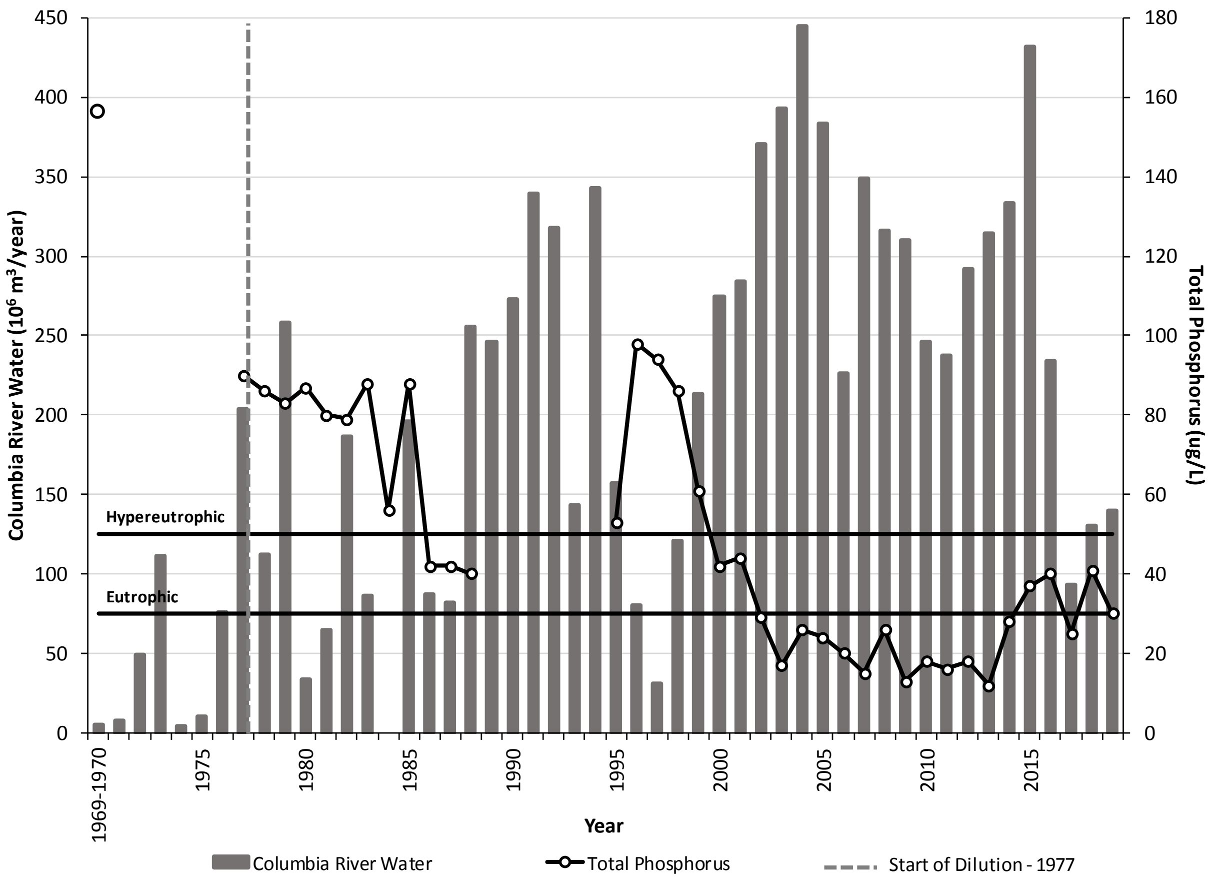

Figure 1. Inflow of Columbia River water into Moses Lake over 50 years and average spring-summer TP concentration in lower Parker Horn (TS5) and south lake (TS6) during 1969-1988 (May-September) from Welch et al. (1992), during 2017-2019 from MLIRD data and south lake near north outlet during 1995-2016 from USBR (mid-April to mid-October).

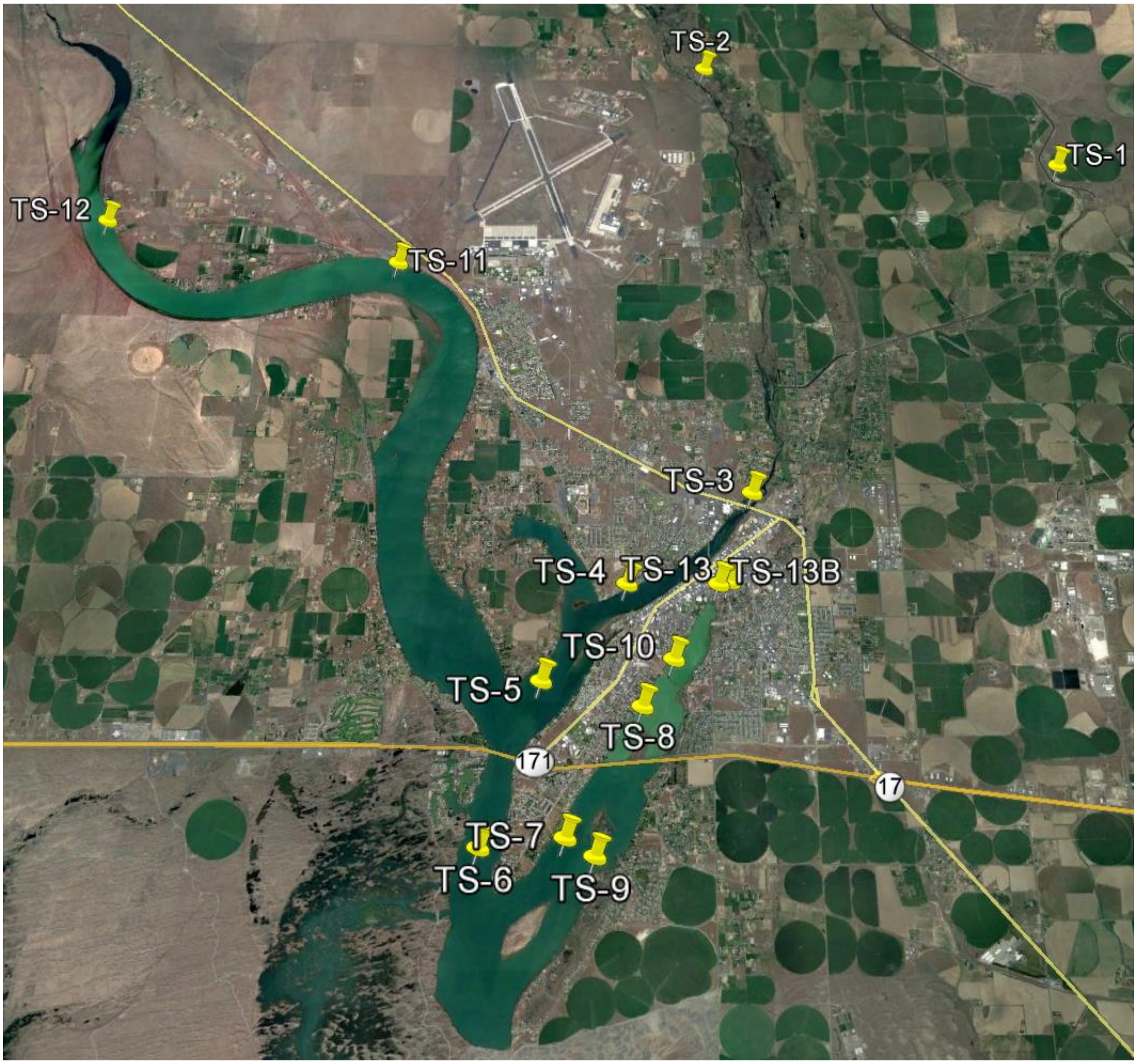

Figure 2. Sampling sites during 2017-2019d and similar to those sampled during 1969-1970 and 1977-1988 (Welch et al., 1989).

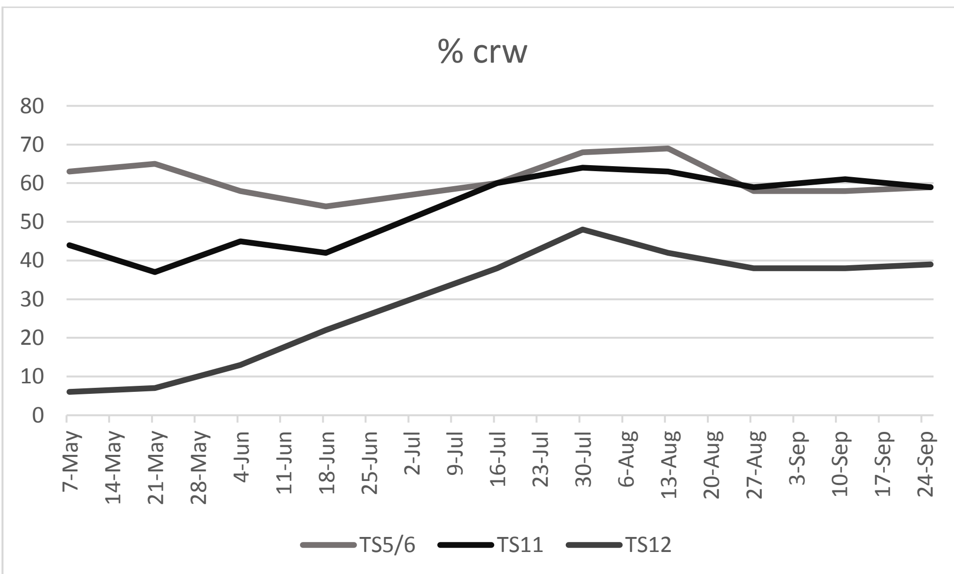

Figure 3. Percent CRW in lower Parker Horn and South Lake (TS5/6; upper light gray), middle Rocky Ford Arm (TS11) dark and upper Rocky Ford Arm (TS12) medium gray.

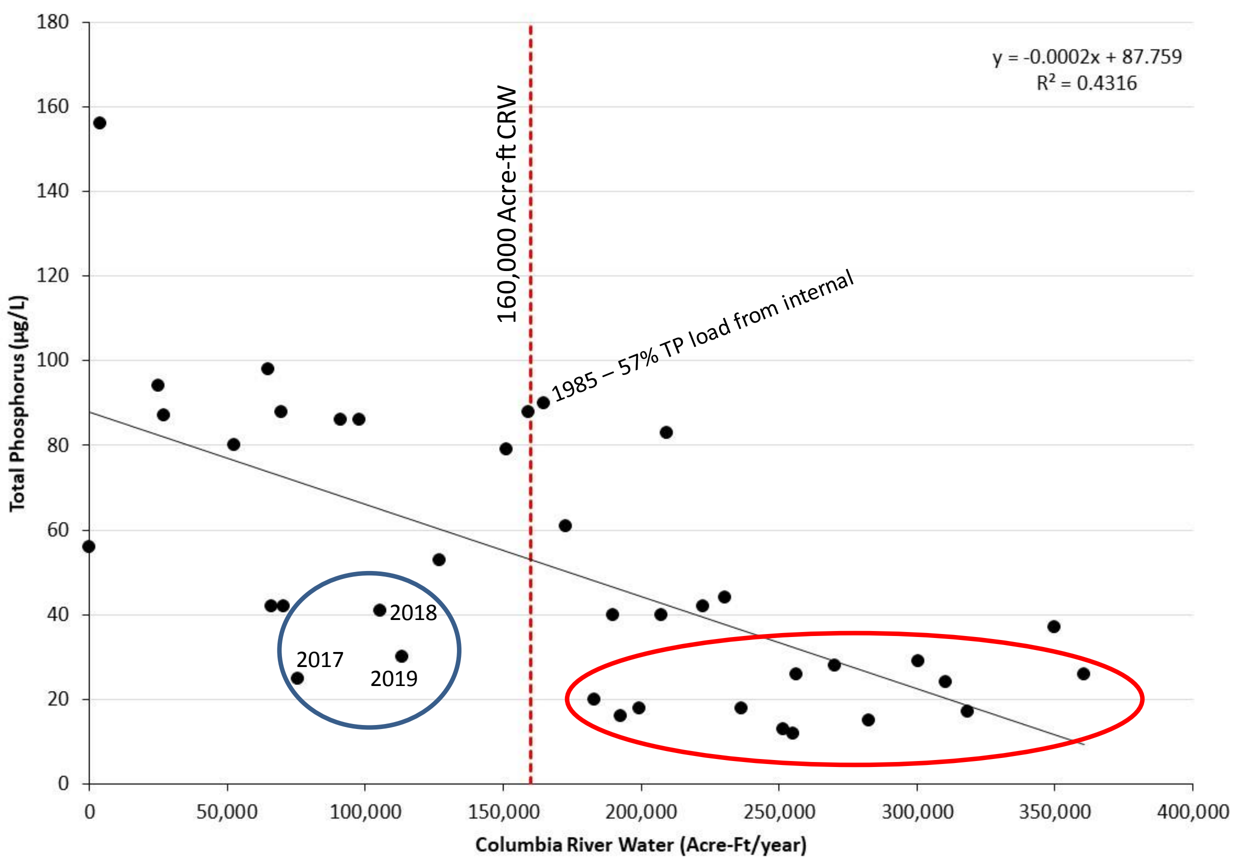

Figure 4. Relation between Columbia River water (CRW) and spring-summer TP at TS5/6 (or TS6 near outlet by USBR). Circled data show relatively low TP despite much lower CRW input during 2017-2019.