TETRA TECH

MEMO

To:	Bill Bailey, Moses Lake Irrigation and Rehabilitation District
Cc:	
From:	Shannon Brattebo (Environmental Engineer, Tetra Tech) and Dr. Gene Welch (Consulting Limnologist)
Date:	March 16, 2022
Subject:	Moses Lake – Whole Lake Mass Balance Model & Management Alternatives Evaluation

Moses Lake Bathymetry

Tetra Tech digitized the existing historical bathymetric map of Moses Lake from the 1964 Sylvester and Oglesby report using ArcGIS (Figure 1). Using the newly digitized electronic bathymetric information, both surface area and volume for various depth contours were determined throughout the lake. Table 1 summarizes the surface area and cumulative volume by depth for Moses Lake. Also, volumes were determined by depth contour for areas within the lake that corresponded to water quality monitoring stations. Thus, a volume-weighted total phosphorus (TP) concentration could be calculated for each monitoring station and sampling date in 2020. The detailed bathymetric information was also used to develop a volume-stage (depth) relationship for the lake.

Table 1. Moses Lake Surface Area and Cumulative Volume by Depth.

Depth		Elevation	Surface Area		Cumulative Volume	
m	ft		m^2	acres	m^3	ac-ft
0	0.0	1046.0	27,640,029	6,830	155,436,019	126,000
1	3.3	1042.7	24,043,688	5,942	113,365,020	91,896
2	6.6	1036.2	20,626,857	5,098	82,086,770	66,541
3	9.8	1026.3	17,452,406	4,313	57,966,406	46,989
4	13.1	1013.2	14,520,333	3,589	39,989,308	32,416
5	16.4	996.8	11,830,639	2,924	27,140,852	22,001
6	19.7	977.1	9,383,325	2,319	18,406,416	14,921
7	23.0	954.1	7,178,388	1,774	12,771,379	10,353
8	26.2	927.9	5,215,831	1,289	9,221,118	7,475
9	29.5	898.4	3,495,653	864	6,741,010	5,464
10	32.8	865.5	2,017,853	499	4,316,434	3,499
11	36.1	829.5	782,432	193	932,768	756

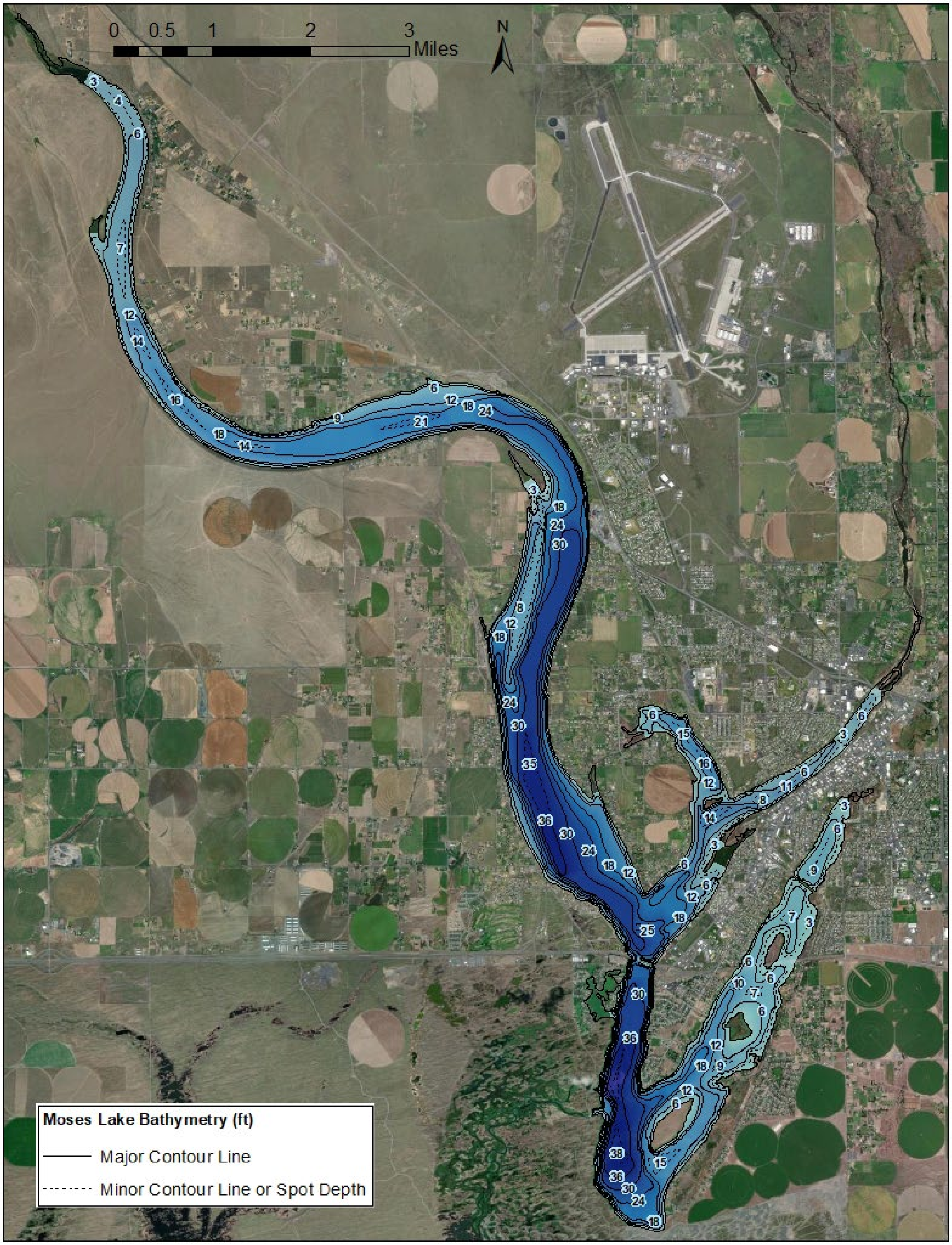


Figure 1. Bathymetric Map of Moses Lake, WA. Bathymetric data digitized from map produced by University of Washington Department of Civil Engineering in August 1963 at a lake water surface of 1046 ft (Sylvester and Oglesby, 1964)

Water Budget

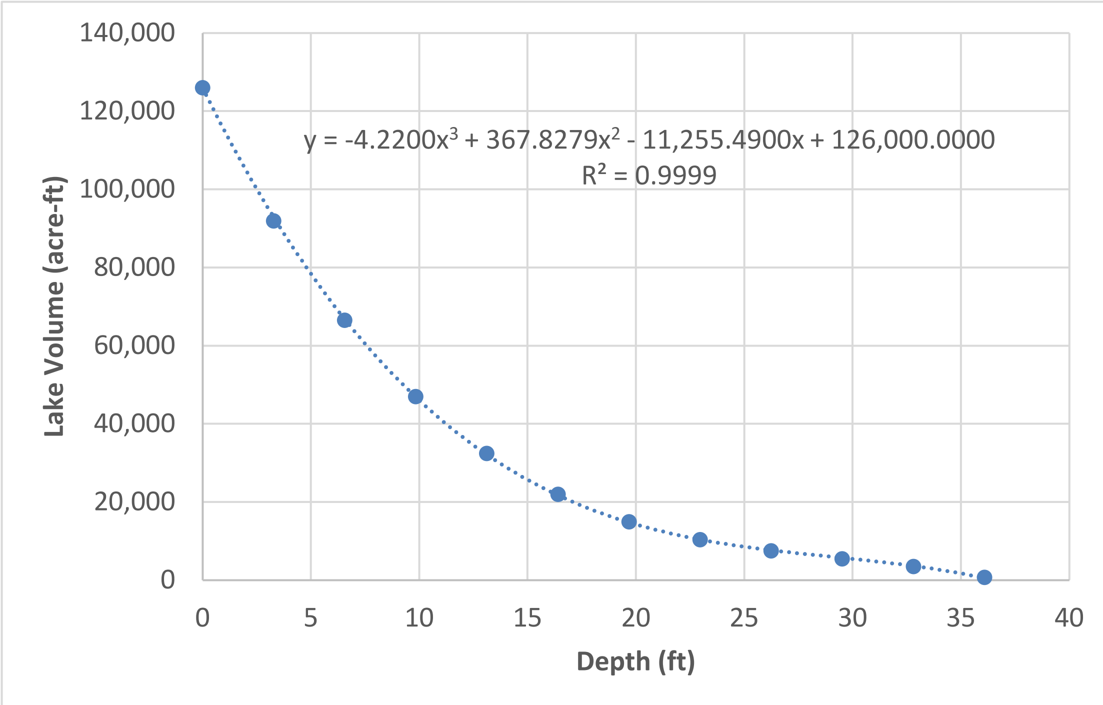
A water budget was developed for Moses Lake that used observed and estimated water inflows and outflows for May through September 2020. Moses Lake has a surface area of approximately 6,830 acres at full pool, (elevation 1046.7 ft) with a mean depth of 18.5 ft (5.6 m) and a maximum depth of 38 ft (11.6 m). At full pool (elevation 1046.7 ft) the estimated lake volume is 126,000 acre-ft or 155,419,740 m^3. The primary sources of water flowing into the lake include: 1) precipitation, 2) Crab Creek, 3) Rocky Coulee Wasteway (both baseflow and Columbia River Water [CRW]), 4) Rocky Ford Creek, and 5) groundwater. The outflows from the lake include: 1) evaporation, 2) the Moses Lake Irrigation and Rehabilitation District (MLIRD) dam, 3) the US Bureau of Reclamation (USBR) dam, and 4) groundwater.

The Moses Lake water budget used the following equation:

$$\begin{aligned}\Delta\, Lake\ Volume &\\ &= \left[Precip + Crab\ Creek + Rocky\ Coulee\ Wasteway\ Baseflow\right.\\ &\left.+ Rocky\ Coulee\ Wasteway\ CRW + Rocky\ Ford\ Creek + GW_{gain}\right]\\ &- [Evap + MLIRD\ Outlet + USBR\ Outlet + GW_{loss}]\end{aligned}$$

Stage-Storage Rating Curve

Based on the bathymetry data digitized from the historical map in Sylvester and Oglesby (1964) the surface area of each bathymetric contour (lake depth) was determined in GIS (Table 1). The cumulative lake volume was also determined for each bathymetric contour in GIS (Table 1) and a volume-stage (depth) relationship was developed (Figure 2). This relationship was used to calculate the lake volume at each time-step in the water budget based on the lake level (elevation) measured at the USGS Moses Lake gaging station (#12471000).



Observed or Estimated Water Budget Parameters

The following water budget quantities were either measured during May through September 2020 or estimated from existing climate data or historical datasets:

Change in Lake Volume (ΔV): Lake level measurements are recorded every 15 minutes at the USGS gaging station #12471000 Moses Lake at Moses Lake, WA. Lake volume for each time-step was calculated based on the lake level measurement (elevation) observed at the end of each time-step and the above depth to volume relationship (Figure 2). USGS lake level measurements in elevation were converted to depth with the assumption that a water surface elevation of 1046.7 ft was equivalent to a "0" depth.

Precipitation: Precipitation records from nearby Moses Lake Grant County Airport (Station: USW00024110) were used for May through September 2020. Precipitation data from the Moses Lake Airport was collected by the National Weather Service and was downloaded from the NOAA National Climatic Data Center (NCDC) and was assumed to be the best reliable dataset available. Daily precipitation for each two-week time-step was multiplied by a constant lake surface area of 27,640,029 m^2.

Crab Creek Inflow: Crab Creek flows into Upper Parker Horn on the eastern shoreline of the lake. USGS operates a real-time gaging station (#12467000) on Crab Creek upstream of the lake near Road 7 NE. This station is upstream of the confluence with Rocky Coulee Wasteway and records flow every 15 minutes. Mean daily flows from May through September 2020 were converted to a total volume of water (cubic ft) for each day. This volume for each day was summed for each two-week time-step and converted to cubic meters for input to the water budget.

Rocky Coulee Wasteway Inflow: Columbia River water was routed through Moses Lake from the East Low Canal through Rocky Coulee Wasteway and Crab Creek into Parker Horn. Rocky Coulee Wasteway mean daily flow, which is the amount of CRW entering the lake, was provided by MLIRD for May through September 2020. Mean daily flow was converted to a total volume of water (cubic ft/cubic m) for each day and then summed for each two-week time-step in the water budget. The baseflow of Rocky Coulee Wasteway (without CRW) was estimated from historical data and assumed to be a constant 24 cfs (0.68 cms), and computed to a total flow volume of 821,560 m^3 for each two-week time-step in the water budget.

Rocky Ford Creek inflow: Rocky Ford Creek is a large tributary that flows into the north end of Rocky Ford Arm. Rocky Ford Creek is largely spring-fed. There are no current, operational gaging stations on Rocky Ford Creek, nor were any discharge measurements collected in May through September 2020. Instead, the inflow from Rocky Ford Creek was assumed to be a constant average flow of 63 cfs (1.78 cms), which was the average recorded flow during May through September 2008 – 2017. This resulted in a total flow volume of 2,158,120 m^3 for each time-step.

Groundwater Inflow: Groundwater was assumed to be 73.6 cfs (2.1 cms) annually. This flow is based on the 2001 water budget (Carroll, 2006). The Washington Department of Ecology (Ecology) also determined that 70% of the total groundwater inflow to Moses Lake occurred in the winter, leaving only 30% in the summer. It was assumed that this 30% occurred during May through September and was split evenly among the water budget time-steps. The total volume of groundwater entering Moses Lake per time-step was estimated at 1,792,492 m^3.

Evaporation: Evaporation from Moses Lake was based on historical monthly average pan evaporation data from the Western Regional Climate Center. The period of record for the historical data at Moses Lake was 1943 – 1979. Monthly average evaporation in inches was converted to meters for a daily evaporation rate. This rate was then used to calculate the total evaporation loss for each two-week time-step in the water budget.

Modeled Water Budget Parameters

An initial water budget for May through September 2020 was developed using the above observed and estimated data. The remaining unmeasured components of the budget included groundwater loss, outflow from the MLIRD dam, and outflow from the USBR dam. These three outflow components were combined in the water budget equation as a single unknown. The water budget equation was solved for this single unknown outflow. The water budget was balanced by assuming the negative residual accounted for the combined outflow from groundwater, the MLIRD dam, and the USBR dam.

Water Budget Results

Table 2 summarizes the total inflows and outflows from May through September 2020. The total inflow during this time was 227,950,164 m^3, with 67% coming from Rocky Coulee Wasteway (CRW flow), 10% from Rocky Ford Creek, 9% from both Crab Creek and groundwater inflow, 4% from the Rocky Coulee Wasteway baseflow, and just 1% from precipitation. Over the course of May – September 2020 the lake level remained constant ranging from 1046.70 ft to 1046.76 ft. Total estimated outflows were slightly higher than total inflows at 229,343,969 m^3.

Table 2. Moses Lake Inflows and Outflows for May – September 2020.

	Volume (m^3)	Volume (acre-ft)	Percent
Inflows			
Precipitation	2,021,923	1,639	1%
Crab Creek	20,538,308	16,651	9%
Rocky Coulee Wasteway (CRW)	152,896,041	123,954	67%
Rocky Coulee Wasteway Baseflow	9,037,164	7,326	4%
Rocky Ford Creek	23,739,319	19,246	10%
Groundwater	19,717,409	15,985	9%
Total Inflow	**227,950,164**	**184,801**	**--**
Outflows			
Evaporation	28,649,675	23,227	12%
Combined Outflow (Groundwater, MLIRD Dam, USBR Dam)	200,694,294	162,704	88%
Total Outflow	**229,343,969**	**185,931**	--

Moses Lake Phosphorus Budget

A total phosphorus (TP) budget was developed for Moses Lake using observed data from May through September 2020, as well as historical data and information. The phosphorus budget was based on the water budget and therefore also used a two-week time-step extending from 5/1/2020 to 10/1/2020. The phosphorus budget was developed based on the conservation of mass; meaning that all inflows of phosphorus to the lake minus all outflows should equal the change in phosphorus mass in the lake over the time period.

The Moses Lake TP budget used the following equation:

$$\Delta TP_{Lake} = TP_{inputs} - TP_{outputs}$$

Or

$$\Delta TP_{Lake} = \underbrace{[TP_{precip} + TP_{Crab\ Creek} + TP_{Rocky\ Coulee\ Wasteway} + TP_{Rocky\ Coulee\ Wasteway\ Baseflow} + TP_{Rocky\ Ford\ Creek} + TP_{GW} + TP_{Internal}]}_{inflows} - \underbrace{[TP_{Combined\ Outflow} + TP_{Sedimentation}]}_{outflows}$$

Phosphorus Inflows

Precipitation: Total phosphorus concentration in precipitation to Moses Lake was assumed to be a constant 107 µg/L based on the TP export coefficient (0.185 kg/ha-yr) determined for Moses Lake in Welch et al. 1989. Multiplying the export coefficient by the lake surface area results in an estimate of the annual level of TP associated with precipitation to the lake, of approximately 511 kg TP/year. In 2020, a total of 6.78 inches (0.17 m) of precipitation was recorded at the Moses Lake airport which equals a total volume of precipitation of 4,760,114 m^3. The annual TP load, 511 kg TP/yr, was divided by the total volume of precipitation for 2020 to get the resulting concentration of 107 µg/L. This concentration was then applied to the precipitation volume that fell during May – September 2020 to determine the TP load from precipitation.

Crab Creek: Total phosphorus concentrations were determined in Crab Creek by the MLIRD at station TS-2 at least once per month during May through September 2020 and on occasion twice per month. The sampling station, TS-2, is located upstream of the confluence with Rocky Coulee Wasteway. Concentrations for time-steps between sampling events were interpolated between the preceding and following weeks. The TP concentration measured on 5/21/2020 was used for the first 2 time-steps in the budget.

Rocky Coulee Wasteway - CRW: Total phosphorus concentrations were determined in the East Low Canal by the MLIRD at station TS-1 at least once per month during May through September 2020 and on occasion twice per month. TS-1 is located within the East Low Canal which diverts CRW from Banks Lake to Rocky Coulee Wasteway. The sampling location is upstream of the confluence of the canal and Rocky Coulee Wasteway and represents the TP concentrations in CRW. Similar to Crab Creek, the TP concentration (7 µg/L) measured at TS-1 on 5/21/2020 was used for the first 2 time-steps and concentrations for time-steps between sampling events were interpolated using the preceding and following weeks.

Rocky Coulee Wasteway – Spring Baseflow: Total phosphorus concentration for Rocky Coulee Wasteway baseflow was taken as a constant 87 µg/L from 2001 data (Carroll, 2006).

Rocky Ford Creek: Total phosphorus concentrations in Rocky Ford Creek were determined by the MLIRD at station TS-14 at least once per month during May – September 2020 and on occasion twice per month. The TP concentration on 5/21/2020 was applied to the first 2 time-steps in the budget. Concentrations for time-steps between sampling events were interpolated using the preceding and following weeks.

Groundwater: A constant TP concentration of 59 µg/L was used to calculate the TP load from groundwater. This constant TP concentration was determined in groundwater during 2001 (Carroll, 2006). Groundwater TP at TS-9 during 1977 – 1988 averaged 50 µg/L (Welch et al., 1989).

Internal Loading: Internal loading occurs from the release of phosphorus from bottom sediments to the water column. It is also referred to as sediment phosphorus release. Net internal loading was determined during May through September 2020 as an unknown quantity in the phosphorus budget. Net internal loading is the difference between gross release of phosphorus from sediment and loss due to sedimentation.

Phosphorus Outflows

Combined Outflows: The TP concentrations used for the combined outflows (groundwater loss, outflow from the MLIRD dam, and outflow from the USBR dam) were from surface TP concentrations determined at TS-6, the South Lake station. This station is the closest monitoring station to the two outlet structures. Historically, surface TP concentrations at station TS-6 have agreed with surface TP concentrations near the USBR dam collected by USBR (Welch, 2018; Welch et al., 2020).

Sedimentation: Settling or sedimentation is the movement of TP through the water column to eventually settle on the lake bottom. It is also referred to as burial. Sedimentation was not directly measured during May through September 2020 but was determined as a residual.

Internal Load and Sedimentation

Internal TP loading and sedimentation were determined indirectly during May through September 2020. They were the unknown terms in the nutrient budget and were determined as residuals in the mass balance. If the residual was positive for a two-week time-step, net internal loading occurred. If the residual was negative, net sedimentation occurred. To solve for the residuals the TP budget equation was rearranged:

$$Net\ P_{internal\ loading}\ or\ P_{sedimentation}$$
$$= \frac{[TP_{Combined\ Outflows} + \Delta TP_{Lake}]}{outflows}$$
$$- \frac{[TP_{precip} + TP_{Crab\ Creek} + TP_{Rocky\ Coulee\ Wasteway} + TP_{Rocky\ Coulee\ Wasteway\ Baseflow} + TP_{Rocky\ Ford\ Creek} + TP_{GW}]}{inflows}$$

Net internal phosphorus loading was positive and occurred during the first 5 time-steps in the budget, 5/1 – 7/9/2020. Total net internal load was calculated as the sum of all positive values during May – September 2020 and equaled 8,318 kg, which was about 50% of the TP load to the lake (Table 3). The total external load in May through September 2020 was just slightly higher at 8,344 kg (Table 3). Rocky Ford Creek contributed the largest portion of external load with a total of 4,017 kg. Overall, there was a net sedimentation of phosphorus during May through September 2020 of only 375 kg.

Table 3. Moses Lake Total Phosphorus Budget Summary, May – September 2020.

Source	Total Phosphorus Load (kg)	% Phosphorus Load
Inflows		
Direct Precipitation	216	1.3%
Crab Creek	975	5.9%
Rocky Ford Creek	4,017	24.1%
Rocky Coulee Wasteway (Baseflow)	786	4.7%
Rocky Coulee Wasteway (CRW Dilution)	1,186	7.1%
Groundwater	1,163	7.0%
Internal Loading	8,318	49.9%
Total Phosphorus Load	16,662	--
Outflows		
Combined USBR, MLIRD, and Groundwater	6,643	43.3%
Sedimentation	8,693	56.7%
Total Phosphorus Loss	15,336	--

Net internal loading averaged 9,346 kg during May – September 1984 – 1988 and was 43% of total loading (Welch et al., 1989), similar to the phosphorus budget results for 2020. There was no net internal loading for the same period in 2001 (Carroll, 2006). Net internal loading was strongly dependent on wind mixing – inversely correlated with RTRM (relative thermal resistance to mixing) during the 1970s – 1980s (Jones and Welch, 1990).

Calculated gross internal loading using laboratory-determined rates from anoxic and oxic sediments in the 1980s was 7,013 kg during May – September (Okereke, 1987). Mass balance determined net internal loading averaged 6,587 kg during 1984-1988 (Welch et al., 1989).

Reduction of internal loading in August and September in the budget is consistent with no observed anoxia below 5 m at TS6 and TS11. Anoxia (< 2 mg/L DO) existed on all three sampling dates in July at TS6 and on July 22 at TS11, but not in August and September. The presence of anoxia was consistent with high TP concentrations ≥ 100 µg/L at 5 m and below.

Anoxic sediment phosphorus release may also have occurred during pre-dawn hours in shallow, thermally unstratified areas due to high rates of algal photosynthesis/respiration in this highly productive lake. For example, sampling occurred during 6:20 – 6:55 AM on July 8 and DO at 0.5 m was much less saturated at TS6, 11, and 15 (average 97%) than on July 14 and July 22 when sampled later in the day, during 8:30 – 9:40 AM and 8:00 – 10:20 AM, with more light for photosynthesis (average 172%). Very high photosynthetic rates during the day, producing super-saturated DO, result in low DO at night with high respiration and no photosynthesis, and possible anoxic conditions (< 2 mg/L DO) at the sediment water interface. That would produce high rates of internal phosphorus loading well above the 1 mg/m^2 per day rate set for “aerobic” release in the model (see discussion below).

Another process that may have reduced the effect of internal loading in August and September is the distribution of CRW with depth. Specific conductance (SC), which is a tracer of lower SC CRW, was usually well distributed with depth in August and September 2020, but not in July. That distribution of CRW with depth probably diluted phosphorus released from sediment despite anoxic conditions in August. There was strong thermal stratification of the water column at all sites (TS5, 6, 11, 15) during July that would have allowed high rates of sediment phosphorus release.

Moses Lake Phosphorus Mass Balance Model

A one-layer, seasonal mass balance TP model was developed for Moses Lake for summer (May through September) 2020 and calibrated against the observed values found in the phosphorus budget. The model is the same type used for Lake Onondaga, NY, and Lakes Sammamish, Pine, Green, Jameson, Ketchum, and Liberty in WA (Perkins et al. 1997; Auer et al. 1997; Tetra Tech 2008, 2009; Brattebo et al. 2017; LLSWD & Tetra Tech, 2018). Moses Lake was assumed to be completely mixed during the modeling period. This assumption is supported by specific conductance (SC) measurements at TS11 and TS12 indicating that CRW moved from Parker Horn (TS5) well up into Rocky Ford Arm (Figure 3). The mass balance TP model was calibrated to closely mimic observed whole-lake volume-weighted average TP concentrations in 2020, but not verified for lake conditions in other years. The model was used to estimate the potential and relative effect of lake treatment alternatives on average summer (May – September) whole-lake TP concentrations. Summer surface lake TP, which determines the concentration of algae and chlorophyll was interpolated from model-predicted whole-lake TP. Algal biomass and chlorophyll does not predict the occurrence of cyanobacteria scums, which tend to accumulate during periodic calm conditions.

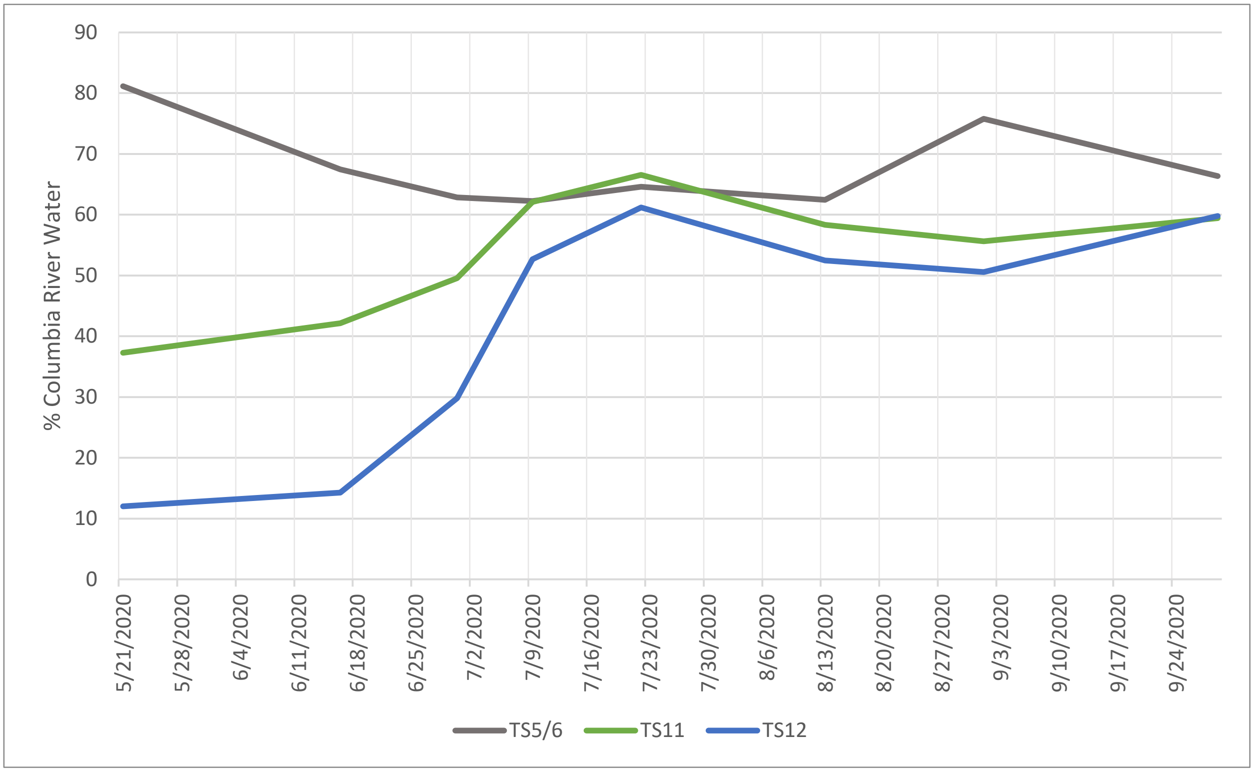


Figure 3. Percent CRW in South Lake compared to Rocky Ford Arm, Moses Lake, 2020.

Model Components

The TP mass balance model used the same external inputs and outflows as the phosphorus budget (Table 3). However, the internal loading and sedimentation required additional calculations and assumptions that are described below.

Phosphorus Internal Loading

Internal loading, also known as sediment release, is the loading of phosphorus from bottom sediment to the overlying water column. Sediment release typically occurs when oxygen profiles indicate that lower waters are anoxic (< 2 mg/L DO). Sediment release can also occur under aerobic (with oxygen) conditions and with mineralization of sediment phosphorus by bacteria. Internal phosphorus can also occur due to carp excretion and bioturbation of the sediments. The sediment release rate (SRR) is based on units of mg/m^2 per day. The SRR for the anoxic area of Moses Lake (depths of 5 m and below) was set at either 3.0, 8.0 or 10.0 mg/m^2 per day to mimic the observed concentrations. An SRR of 8.0 mg/m^2 per day was used for the first two model time-steps (May 1 – May 28), then the rate was increased to 10.0 mg/m^2 per day during May 29 – July 9, followed by a decrease to 3.0 mg/m^2 per day for the period of July 10 - July 23. The SRR for the oxic area was set at 3 mg/m^2 per day for each time-step; 2.0 mg/m^2 per day for internal load from carp and 1.0 mg/m^2 per day from mineralization of sediment phosphorus by bacteria and biota, as well as temporary diurnal anoxia at the sediment surface.

Reduction of internal loading in the phosphorus budget as well as the gross sediment phosphorus release rate in August and September in the mass balance model is consistent with observations of less anoxia and TP concentrations below 5 m. Strong thermal stratification existed in July 2020 with bottom anoxia at TS5, 6, 11, and 15 and usually high TP concentrations (>100µg/L) below 5 m. Stratification was still present in mid-August at TS6 and 15 with anoxia and high bottom TP at TS6 only. By September and with surface cooling, the water column was not stratified, and no anoxia and high TPs were observed.

The calibrated gross rates (before sedimentation) of sediment phosphorus release agree with those determined with Moses Lake sediments and in other lakes. The model rates of 8 – 10 mg/m^2 per day during June and July from anoxic sediments (43% of the lake) are consistent with those from results with sediment cores in the laboratory in the 1980s. Those laboratory release rates were 10 mg/m^2 per day from anoxic (anaerobic) sediment and 1 mg/m^2 per day from oxic (aerobic) sediment (Okereke, 1987).

The rate of 3 mg/m^2 per day from the oxic shallow areas (56%) of the lake includes the 1 mg/m^2 per day from direct sediment phosphorus release and 2 mg/m^2 per day from carp excretion and bioturbation of surface sediment. Carp were observed to mix sediment to a depth of 13 cm (5.1 inches) on average with maximum of 25 and 28 cm in a shallow lake (Huser et al., 2015). Carp (at 200 kg/ha) were observed (in enclosures) to excrete 2.2 mg P/m^2 per day in a Minnesota lake (EPA, 1993). Carp density is unknown in Moses Lake, but 200 kg/ha (178 lbs/acre) is a modest estimate. Carp density in Green Lake, much less productive than Moses Lake, was determined at 120 kg/ha (107 lbs/acres; Herrera Consultants; WDFW).

Settling/Sedimentation

Settling or sedimentation is the movement of phosphorus through the water column to eventually settle on the lake bottom. It is defined by the settling rate or velocity (m/day). The settling rate is then multiplied by the lake TP concentration and the area of settling to determine the TP loss to sedimentation. For a polymictic lake which is periodically mixing like Moses Lake, the settling rate (or burial rate) is constant throughout the water column.

Several iterations and adjustments were required to calibrate the mass balance model to approximate observed whole-lake, volume-weighted TP. A range of reasonable settling rates were tested to calibrate the model. The goal was to determine a single calibrated settling rate. However, in order to match the observed data, 3 different settling rates were used. During the first 5 time-steps of the model (May 1 – July 9) a settling rate of 0.15 m/week was used. The rate was increased to 0.25 m/week for the next two time-steps (July 10 – August 6) and then doubled, 0.5 m/week for the remaining time-steps. This resulted in model predicted TP closely aligned with observed whole-lake, volume-weighted TP. The settling rates were multiped by the whole lake surface area to estimate the kg of TP lost to sedimentation each time-step.

Period Rate of Change or Change in Whole Lake TP Mass

The rate of change in the mass of phosphorus for each time-step was calculated by subtracting the outflow mass from the sum of the inflow masses.

Predicted Whole Lake TP Mass (kg)

The predicted whole-lake TP mass for each time-step was calculated by adding the change in TP mass (period rate of change) to the whole-lake TP mass from the previous time-step. For the first time-step in the model the starting volume-weighted, whole-lake concentration of 45 µg/L, the normal inflow concentration in Crab Creek, was used to calculate the starting mass of phosphorus in the lake.

Moses Lake TP Model Calibration

Several iterations and adjustments were required to calibrate the model to closely approximate whole-lake, volume-weighted TP concentrations. A range of reasonable settling rates were tested while keeping the SRR constant based on the observed increases in water column TP through the summer. Additional adjustments were made to account for SRR while keeping the settling rate consistent. The final calibrated model closely aligns with 2020 observed volume-weighted, whole-lake TP concentrations during May – September (Figure 4). Predicted summer (May – September) mean TP was close to observed volume-weighted, whole-lake TP; (73.5 µg/L vs. 70.9 µg/L).

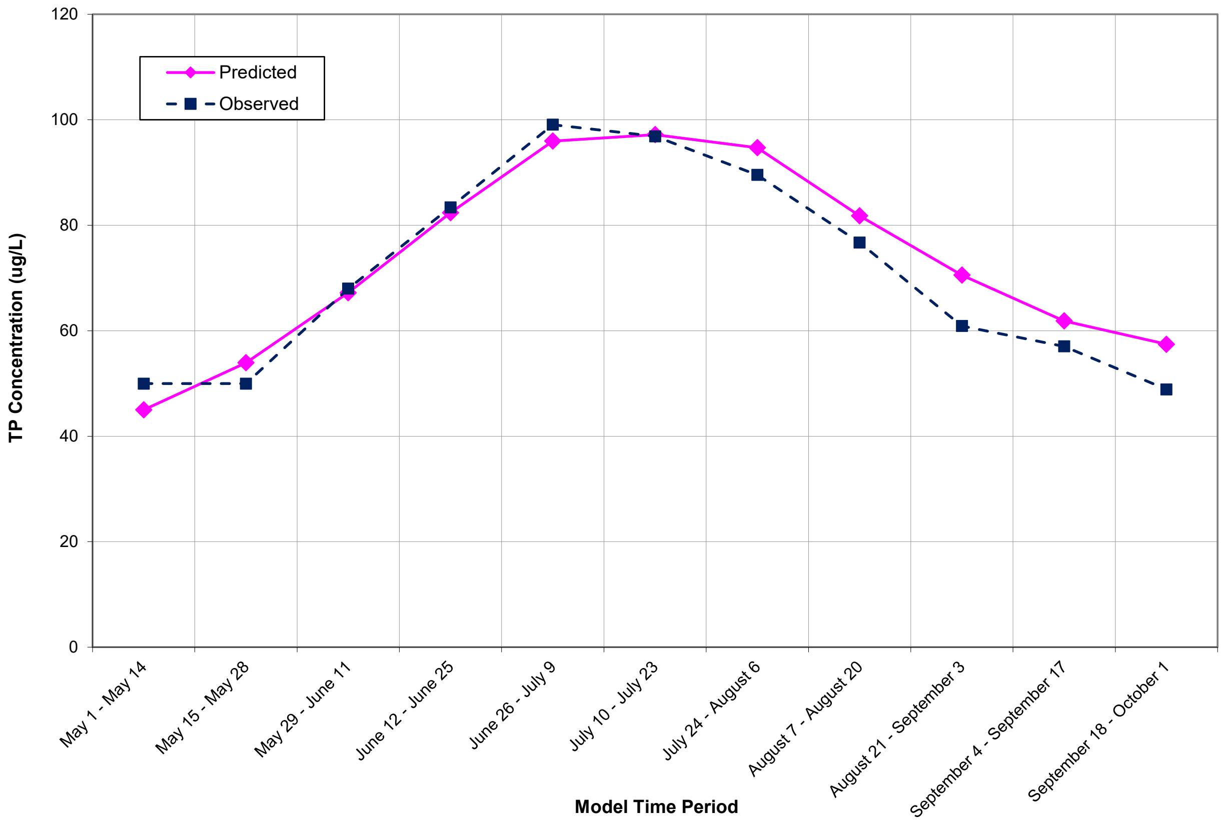


Figure 4. Predicted model volume-weighted, whole-lake TP versus observed volume-weighted, whole-lake TP in Moses Lake during May – September, 2020.

Moses Lake TP Budget and Mass Balance Model Results

The TP budget shows that internal loading made up a sizable portion of the total May – September TP load in Moses Lake. The dominance by internal loading is incorporated into the TP mass balance model. Internal TP loading is usually the primary cause for algal production and biomass during the growing season. Internal loading contributes 50% of the TP load to Moses Lake during May – September (Table 3). In 2020, internal loading was greatest in June and early July when Rocky Coulee Wasteway (CRW) flows were low (Figure 5). Internal loading continued to occur through July as evidence in the calibrated mass balance model. Internal loading from the anoxic area diminished towards the end of July but internal loading from aerobic sediment release and carp excretion probably continued throughout the summer. External TP loading from Crab Creek, Rocky Ford Creek, and Rocky Coulee Wasteway remained fairly consistent throughout the summer (Figure 5). Rocky Coulee Wasteway baseflow and groundwater were set as a constant inflow.

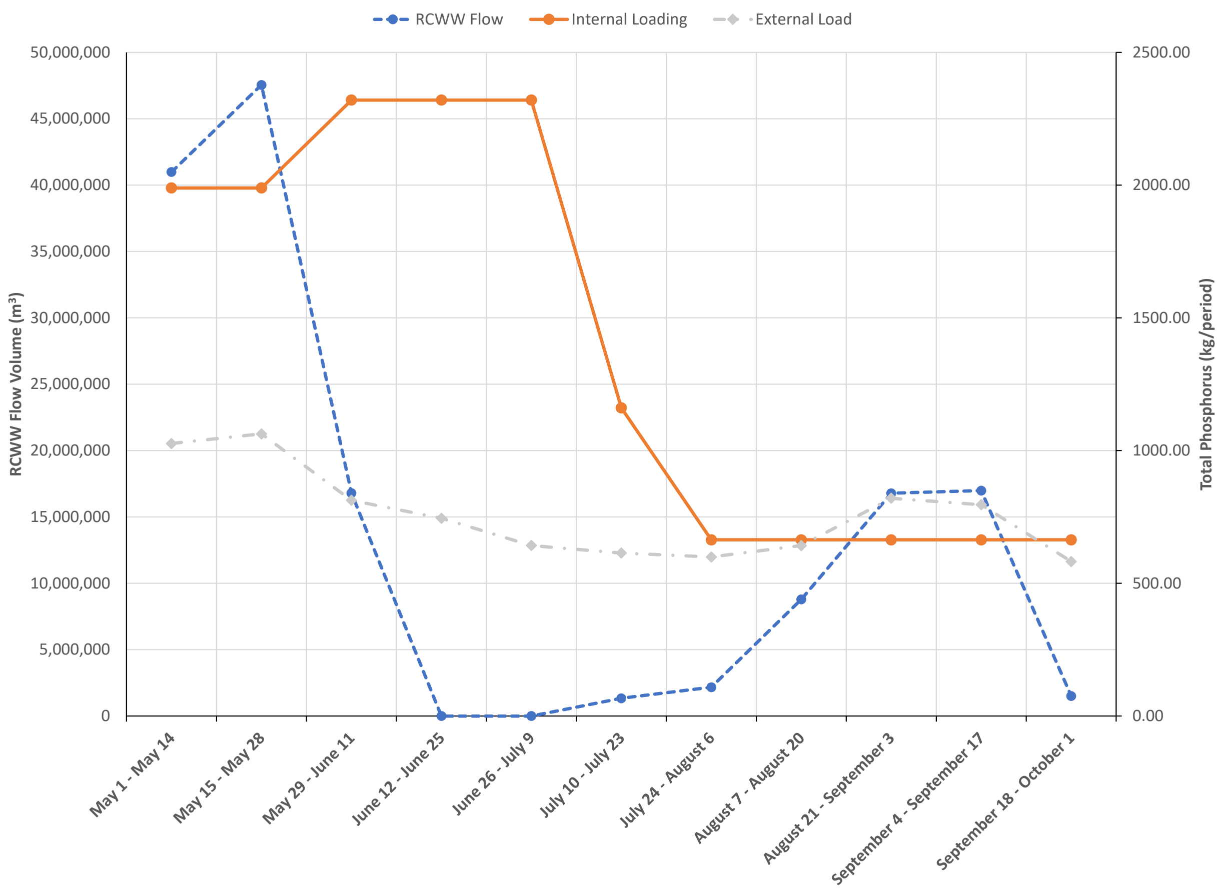


Figure 4. Predicted model Internal and External Loading to Moses Lake during May – September 2020.

Evaluation of Moses Lake Treatment Alternatives

The calibrated mass balance model was used to predict volume-weighted, whole-lake TP for several treatment alternatives. A description of each alternative evaluated, and the assumptions in the model to mimic treatment conditions, are described below.

- ***Reduce external load from Crab Creek by 50% -*** Assumed that the TP load entering the lake from Crab Creek during each time-step was reduced by 50%. The total TP load during May – September from Crab Creek was reduced from 975 kg to 488 kg.
- ***Reduce external load from Rocky Ford Creek by 50% -*** Assumed that the TP load entering the lake from Rocky Ford Creek during each time-step was reduced by 50%. The total TP load during May – September from Rocky Ford Creek was reduced from 4,017 kg to 2,008 kg.
- ***Reduce external load from Rocky Ford Creek by 80% -*** Assumed that the TP load entering the lake from Rocky Ford Creek during each time-step was reduced by 80%. The total TP load during May – September from Rocky Ford Creek was reduced from 4,017 kg to 803 kg.
- ***Reduce external load from Crab Creek and Rocky Ford Creek by 50% -*** Assumed that the TP load entering the lake from both Crab Creek and Rocky Ford Creek during each time-step was reduced by 50%. The total TP load during May – September from both Crab Creek and Rocky Ford Creek was reduced from 4,992 kg to 2,496 kg.

- ***Water column stripping alum treatment applied to the entire lake*** – A water column stripping alum treatment applied to the whole lake area was assumed to remove 80% of water column TP. The treatment would be applied prior to May, the start of the model time period. The water column stripping treatment reduced the starting volume-weighted, whole-lake TP concentration from 45 µg/L to 9 µg/L. A water column stripping treatment dose of 3.6 mg Al/L was determined based on lake conditions and jar tests conducted by HAB Aquatics in 2020.
- ***Sediment inactivation alum treatment applied to entire lake*** – A sediment inactivation alum treatment applied to the entire lake was assumed to reduce internal loading of phosphorus from the anoxic sediments by 80%, the oxic sediments by 33% and water column TP by 80%. The internal load contributed by carp excretion was assumed to continue unaffected. The treatment would be applied prior to May, the start of the model time period. A sediment inactivation dose of 9.1 mg Al/L was determined from sediment phosphorus data analyzed in 2020. The total dose, sediment inactivation plus water column stripping would equal 12.7 mg Al/L.
- ***Sediment inactivation alum treatment applied to areas of the lake with a depth of 5 m or greater*** – A sediment inactivation alum treatment applied to the areas of the lake with a depth of 5 m or greater, equal to the anoxic area, which covers about 43% of the lake. The treatment was assumed to reduce internal loading of phosphorus from the anoxic sediments by 80% and water column TP by 80%. The internal load contributed by oxic sediments and carp excretion was assumed to continue unaffected. The treatment would be applied prior to May, the start of the model time period. The treatment dose would be the same as the whole lake sediment inactivation treatment, 12.7 mg Al/L.
- ***Increased dilution with CRW (using 2021 RCWW Flows) with a starting whole-lake, volume-weighted TP concentration of 45 µg/L*** – Assumed the same dilution with CRW as in 2021. RCWW flows in May – September 2021 equaled 183,180 acre-ft compared to only 123,954 acre-ft during 2020. The 2021 RCWW flows were inserted into the water budget to determine the outflow volume for this scenario. The starting whole-lake, volume-weighted TP concentration remained unchanged at 45 µg/L.
- ***Increased dilution with CRW (using 2021 RCWW Flows) with a sediment inactivation alum treatment applied to entire lake –*** Assumed increased dilution with CRW equal to the 2021 RCWW measured flows and a sediment inactivation alum treatment applied to the entire area of the lake. The treatment was assumed to reduce internal loading of phosphorus from the anoxic sediments by 80%, the oxic sediments by 33% and strip water column TP by 80%. The internal load contributed by carp excretion was assumed to continue unaffected. The treatment would be applied prior to May, the start of the model time period.
- ***Increased dilution with CRW (using 2021 RCWW Flows) with a sediment inactivation alum treatment applied to areas of the lake with a depth of 5 m or greater –*** Assumed increased dilution with CRW equal to the 2021 RCWW measured flows and a sediment inactivation alum treatment applied to areas of the lake with a depth of 5 m or greater. The treatment was assumed to reduce internal loading of phosphorus from the anoxic sediments by 80% and strip water column TP by 80%. The internal load contributed by oxic sediments and carp excretion was assumed to continue unaffected. The treatment would be applied prior to May, the start of the model time period.
- ***Increased dilution with CRW (using 2021 RCWW Flows) with a starting whole-lake, volume-weighted TP concentration of 15.2 µg/L*** – Assumed increased dilution with CRW equal to the

2021 RCWW measured flows. RCWW flows in May – September 2021 equaled 183,180 acre-ft compared to only 123,954 acre-ft during 2020. The 2021 RCWW flows were inserted into the water budget to determine the outflow volume for this scenario. The starting whole-lake, volume-weighted TP concentration was changed to reflect lake TP in May 2021, 15.2 µg/L. This scenario was used to determine if the calibrated model could accurately predict the summer average volume-weighted, whole-lake TP concentration in 2021, assuming that external and internal loads were similar.

Predicted average May – September whole-lake, volume-weighted TP concentrations for each of the above treatment alternative and model scenarios are summarized in Table 4 compared to observed and model predicted existing TP concentrations. Table 4 also summarizes the estimated average summer surface TP concentration at TS5 and TS 6 (Lower Parker Horn and South Lake). This concentration was estimated based on the average ratio (0.55) between observed whole-lake, volume-weighted TP in 2020 and the surface TP concentrations.

There has been an assumption that continuous input of CRW to Parker Horn throughout the summer rather than most entering in the spring would improve summer water quality. Model predictions show little difference in May – September average TP concentration if CRW inflows in either 2020 or 2021 entered mostly early or were evenly spread out over the summer (Figure 5). While whole-lake TP actually decreased slightly in September as CRW inflows resumed in 2020, May – September average TP was about the same at 67 µg/L whether inflows were continuous or were concentrated in spring and early summer as is usual (Figure 5; Table 4). That is because the water exchange rate from normal inflows is very low, so entering low phosphorus CRW tends to remain throughout the lake whether added mostly in spring and early summer or continuously throughout the summer.

Estimated costs, aluminum dose, treatment area and treatment volume for various alum treatment scenarios are summarized in Table 5. The first three rows of Table 5 summarize costs for the three scenarios run through the mass balance model. The remaining rows of Table 5 provide cost estimates for various treatment areas within the lake for comparison purposes.

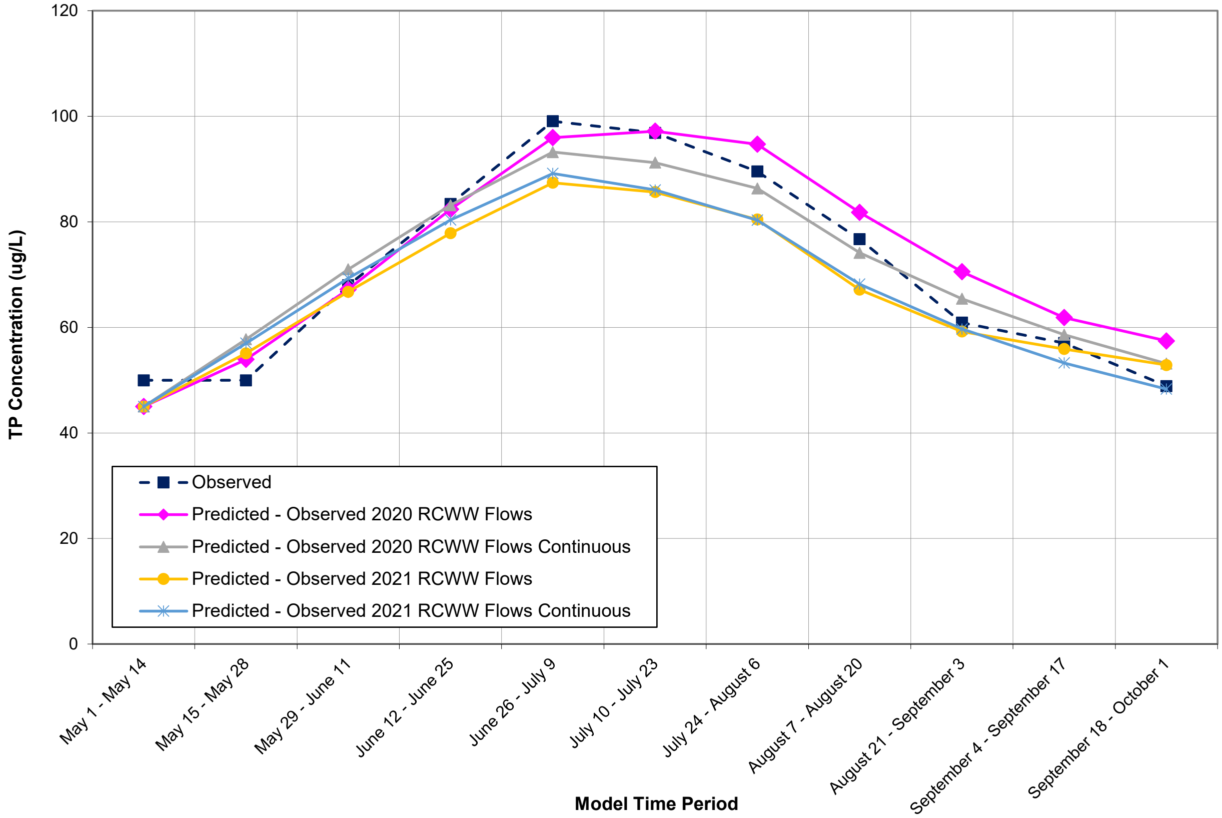


Figure 5. Predicted whole-lake, volume-weighted TP for two patterns of CRW: continuous and non-continuous (concentrated in spring) during May – September 2020.

Table 4. Predicted Average May-September Whole-Lake and TS-5/TS-6 Surface TP Concentrations in Moses Lake Following Various Treatment Alternatives.

Scenario	Mean May - September Whole Lake TP (ug/L)	Mean May - September Surface TS-5 & TS-6 TP (ug/L)
Observed	*70.9*	*39.1*
Modeled Existing Conditions (2020)	**73.5**	**40.4**
Reduce Crab Creek TP Load by 50%	72.6	39.9
Reduce Rocky Ford Creek TP Load by 50%	69.5	38.2
Reduce Rocky Ford Creek TP Load by 80%	67.1	36.9
Reduce Crab Creek & Rocky Ford Creek TP Load by 50%	68.6	37.7
Whole Lake Alum Treatment - Water Column (WC) Only *(Reduce WC TP by 80%)*	55.1	30.3
Whole Lake Alum Treatment WC & Sediment Inactivation *(Reduce WC TP by 80% & Anerobic SRR by 85% & Aerobic SRR by 33%)*	33.1	18.2
Half Lake Alum Treatment (>5 m) WC & Sediment Inactivation *(Reduce WC TP by 80% & Anerobic SRR by 85%)*	46.9	25.8
Increased Dilution: 2021 RCWW Flows with starting Whole Lake TP of 45 ug/L (2020)	66.7	36.7
Increased Dilution: 2021 RCWW Flows with Whole Lake Alum WC & Sediment Inactivation *(starting Whole Lake TP of 45 ug/L)* *(Reduce WC TP by 80% & Anerobic SRR by 85% & Aerobic SRR by 33%)*	31.1	17.1
Increased Dilution: 2021 RCWW Flows with Half Lake Alum (>5 m) WC & Sediment Inactivation *(starting Whole Lake TP of 45 ug/L)* *(Reduce WC TP by 80% & Anerobic SRR by 85%)*	43.5	24.0
Increased Dilution: 2021 RCWW Flows with starting Whole Lake TP of 15.2 ug/L (5/13/2021)	53.1	29.2

*assumed all alum treatments conducted prior to beginning of May

**2021 RCWW Flows = 183,180 acre-ft May through September

Table 5. Moses Lake Alum Treatment Alternatives Cost Estimates.

Treatment Alternative	Alum Dose (mg Al/L)	Treatment Area (acres)	Treatment Volume (ac-ft)	Estimated Cost[1]
Whole Lake Alum Treatment - Water Column (WC) Stripping	3.6	5,928[2]	118,091[2]	$ 5,611,948
Whole Lake Alum Treatment - Sediment Inactivation & WC Stripping	12.7	5,928	118,091	$ 19,797,655
Half Lake Alum Treatment (<5m) - Sediment Inactivation & WC Stripping	12.7	~3,000	74,543[3]	$ 12,496,943
Middle Rocky Ford Arm Alum Treatment - WC Stripping	3.6	1,774	38,544	$ 1,831,700
Middle Rocky Ford Arm Alum Treatment - Sediment Inactivation & WC Stripping	12.3	1,774	38,544	$ 6,258,301
Cascade Alum Treatment - WC Stripping	3.6	954	26,706	$ 1,269,139
Cascade Alum Treatment - Sediment Inactivation & WC Stripping	10.3	954	26,706	$ 3,631,120
South Lake, Lower Parker Horn & Cascade Alum Treatment - WC Stripping	2.4	2,600	62,697	$ 1,986,337
South Lake, Lower Parker Horn & Cascade Alum Treatment - Sediment Inactivation & WC Stripping	11.7	2,600	62,697	$ 9,683,365

[1]Estimated costs based on $1.80 per gallon of alum applied plus 20% mobilization and 9% tax. Cost estimates do not include any contingency.

[2]Whole Lake area and volume do not include Upper or Lower Pelican Horn.

[3]Volume for half lake assumed to include 2/3 of South Lake, ½ of Lower Parker Horn, all of Cascade, and 2/3 of Middle Rocky Ford Arm.

Summary

The treatment alternative that resulted in the lowest average May – September whole-lake, volume-weighted TP and lower lake surface TP concentration is a sediment inactivation alum treatment applied to the entire lake with or without the increased CRW input in 2021. Sediment release of phosphorus from anoxic and oxic sediments, as well as carp excretion, contributed the largest portion of the TP load to the lake. Therefore, treating internal load would have the most benefit. Also, routine monitoring shows an increase in TP concentrations in the lake that cannot be explained by external sources from Crab Creek, Rocky Ford Creek, or groundwater. Observations in 2001 showed that the majority of groundwater enters the lake during the winter months. The average spring-summer groundwater phosphorus concentration of 59 µg/L was used then and again here to calculate loading from that source (Carroll, 2006; Pitz 2003). Even doubling groundwater phosphorus concentration would not be sufficient to increase lake TP concentration. Thus, the major phosphorus source is internal recycling from bottom sediments.

A sediment inactivation treatment applied to areas of the lake with depths of 5 m or greater, with or without increased CRW input (as in 2021), decreased the average summer whole-lake TP concentration to around 44 to 47 µg/L, which is a substantial improvement from observed lake conditions. Moreover, probable near-surface TP (0.5 m), where algae grow, would be much lower, probably around 25 µg/L in the lower lake (TS5/6). At that average concentration algal biomass as chlorophyll would likely be less than 10 µg/L and cyanobacteria not dominant. A water column stripping treatment would reduce volume-weighted, whole-lake TP by only 25% to 55 µg/L and 30 µg/L in the lower lake – only a slight improvement over the average for the past four years (34 µg/L). The benefit of a stripping treatment is expected to last about a year with only slight carry over the following year, because the dose is insufficient to inactivate sediment phosphorus.

Reductions in external loading to the lake, either from Crab Creek or Rocky Ford Creek, would not have a substantial effect on average summer TP concentration. Predicted whole-lake, volume-weighted TP from external load reductions ranged from 67 to 73 µg/L, which is not expected to greatly improve lake quality.

Recommendations

1. Continue the lake monitoring program as conducted the past two years (2020, 2021). Continue using IEH Analytical Laboratories for sample analysis in order to have comparable data over time. Continue collection of samples for algae at 0.5 m at TS11 and TS6 with analysis by Jim Sweet.
2. Predicted TP concentrations resulting from treatment alternatives clearly show that reduction of internal recycling of phosphorus from bottom sediment is needed to substantially lower lake TP to a level that will effectively mitigate summer blooms of cyanobacteria (blue-green algae).
3. Reduction of phosphorus in external inflows would be much less effective than sediment inactivation treatments or even water column phosphorus stripping treatments. Even reducing TP from Rocky Ford Creek, which has high TP would lower lake TP only 9%. That is due to the slow water exchange of Rocky Ford Arm water from Rocky Ford Creek inflow (0.5% per day). Also, internal loading would continue to add phosphorus to the water column.
4. Sediment phosphorus inactivation throughout the whole lake would be the most effective treatment. Whole-lake TP would be lowered to around 33 µg/L – a 55% decrease – and surface

TP in the lower lake (TS 5/6) would drop below 20 µg/L, a concentration that would drastically limit blue-green algal blooms. However, TPs in middle and upper Rocky Ford Arm would still probably be double that, but nevertheless, greatly improve water quality. This treatment, however, may not be possible due to cost.

5. The next most effective treatment is a half-lake sediment phosphorus inactivation in areas greater than 5 m depth that tend to go anoxic and have the highest sediment phosphorus release rates – ten times those from shallower oxic sediments. That treatment would lower whole-lake TP by about 36% - to around 44 – 47 µg/L and the lower lake (TS 5/6) surface TP to around 25 µg/L. Such a treatment of less lake area (approximately 3,000 acres) could be staged in sections over time as funds became available. Sediment inactivation treatments last about 10 years, if dosed properly, before the alum floc layer sinks through the sediment and more external phosphorus enters the lake. The treatment may last longer because Moses Lake sediment has a relatively low water content (78%).
6. Water column stripping of TP would lower whole-lake concentrations by 25% and lower lake surface TP to about 30 µg/L, substantially lower than observed in 2020 (40 µg/L). That would cost about one-fourth of the treatment discussed in number 4 above. However, TP may remain higher in Rocky Ford Arm at over 70 µg/L. Average TP in Rocky Ford Arm (TS 11, 12, and 15) in 2020 was 95 µg/L. Treatment of the water column only (stripping) and/or sediment inactivation should be most cost-effective in Rocky Ford Arm due to its high TP concentration. Total phosphorus concentrations in the lower lake (TS 5/6) have averaged much lower during 2017-2020 (34 µg/L) due to the grater effectiveness of CRW proximal to RCWW.
7. Dilution of lake TP with low-phosphorus (7 µg/L) CRW was always highly effective at maintaining relatively good water quality, especially in the lower lake (TS 5/6), with an average TP of 34 µg/L. The model predicted that the higher volume of CRW in 2021 would have lowered whole-lake TP only slightly (10%) from that predicted for the lower input in 2020. Nevertheless, the high CRW input in 2021 lowered lake TP to well below 2020 levels through July. Whole-lake, volume-weighted TP in April 2021 was around 15 µg/L, much lower than in May 2020. The most cost-effective treatment expected to occur is with at least 200,000 acre-ft of low-phosphorus CRW whether mostly added in early spring and summer or added continuously. Total CRW input in April – September 2020 was 184,128 acre-ft compared to 226,620 acre-ft in 2021. May to September average whole-lake, volume-weighted TP in 2020 was 77 µg/L. May through August average whole-lake, volume-weighted TP in 2021 (September data unavailable) was much lower at 32 µg/L. Also, 230,000 acre-ft in 2001 resulted in average May – September TP of 19 µg/L in the lower lake (TS 5/6) and 36 µg/L in Rocky Ford Arm (TS 11).

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