Cherry Creek Reservoir Sediment Phosphorus Study Report

Dates: Samples were collected May and Sept 2021 by Solitude Lake Management
and data reported May 2022 by LRE Water.

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Introduction

This Reservoir Sediment Phosphorus Monitoring Study was conducted to analyze the sediments in Cherry Creek Reservoir for The Cherry Creek Basin Water Quality Authority (CCBWQA). The objectives of the monitoring program were to determine the spatial variability of the Reservoir's sediment phosphorus concentrations, the state of the phosphorus (mobile/bound), and to determine vertical depth variability of phosphorus concentrations and fractionation. Understanding the phosphorus state and cycling provides information on the role that the sediments may play in internal phosphorus loading, reservoir primary productivity (algal growth), and chlorophyll-a concentrations. Sampling was completed in May (Phase I) and September 2021 (Phase 2), with data and findings presented in this report.

The study provides the CCBWQA with detailed information on:

- areas in the Reservoir with higher sediment phosphorus concentrations,
- areas with mobile phosphorus fractions that may be involved in nutrient cycling and are readily available to drive algal growth, and
- the variability of these concentrations and fractions with sediment depth.

This analysis provides valuable information to better understand the role the sediments may play in internal loading and assist with planning future in-basin management actions.

Reservoir sediment sampling was completed in two phases. The detailed spatial analysis of phosphorus concentrations was completed in Phase 1, with samples collected in May 2021. Based on the analysis of the results obtained in Phase 1, Phase 2 samples were collected in September 2021 to provide a more detailed analysis of the types of phosphorus present.

Phase 1 Methods - Spatial Analysis of Surface Sediment Phosphorus Concentration and Composition

The Phase 1 sample collection locations were determined by using ArcGIS to divide the surface area of Cherry Creek Reservoir into a grid with 26 equal cell sizes of approximately 40 acres (Figure 1.) The CCBWQA's bathymetric map (2013) was used to ensure the water depth at the sampling locations would be at least 5 feet deep to ensure boat access. Waypoints were converted from latitude/longitude to a .usr file and uploaded into a Lowrance Sonar and handheld GPS unit to provide accurate and efficient navigation to sampling locations. This equipment also allowed for recording accurate depth measurements at each sampling location in the field log.

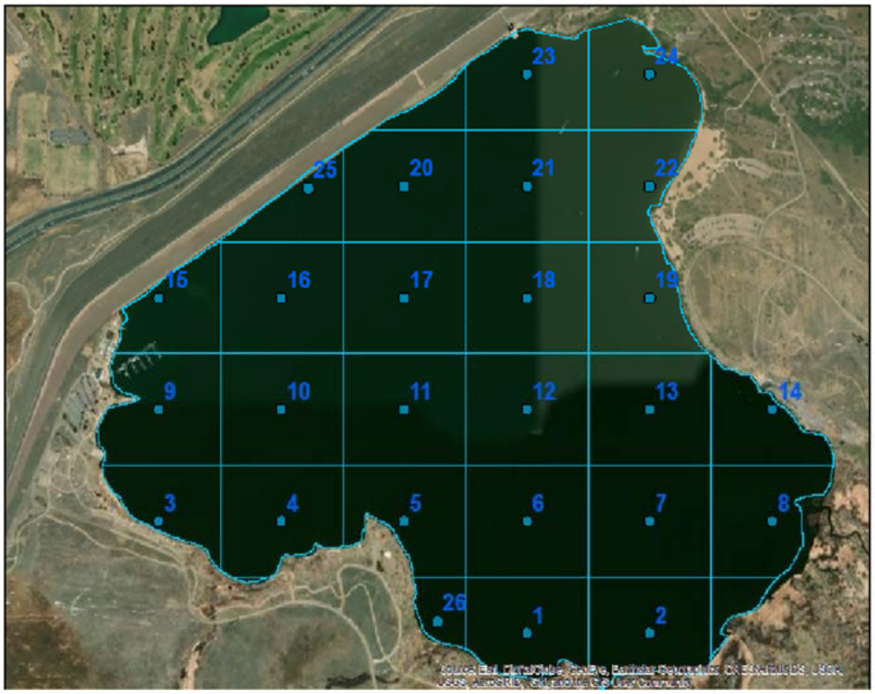

Figure 1. Sediment sampling locations at Cherry Creek Reservoir

Samples were collected using an Eckman Dredge which was lowered down through the water column to the bottom of the reservoir. Once at the bottom, a messenger weight was released which triggered the spring-loaded mechanism which scooped and contained the sediment sample. The collected sediment was then raised to the surface, where the excess water was poured off and the dredge contents were emptied into a 5-gallon bucket (Image 1.)

At each location, three dredge samples were collected and combined to provide a representative composite sample for analysis. The maximum sample depth collected was 6” (15 cm) but the majority of the sample volume was collected from 0-10 cm. Visual observations were made on sediment composition (clay, silt, sand, level of consolidation, color, odor, etc.) and logged in the field notes. Each sample was analyzed for total phosphorus (total P), total solids, and moisture content.

Image 1. Eckman dredge used for sampling

The results of the laboratory analyses were used to determine spatial variability by comparing sample concentrations between grid cells. Total P concentrations were entered into ArcGIS for geostatistical processing to visually demonstrate estimated total phosphorus variability in Cherry Creek Reservoir’s sediments. The Kriging method was used to generate an interpolated heat map that represents the total P in colors based on concentration. The Kriging method is based on autocorrelation, which is developed from the statistical and geographical relationship between the sampling sites. This method assumes the distance between sediment sampling sites reflects a spatial correlation that can explain total phosphorus variation along the reservoir's sediment surface, which is a fair assumption considering that variable depths, accumulation over time, proximity to the shoreline, and inflows of sand or fine inorganic sediment will cause variability at the bottom of the reservoir.

Phase 1 Results and Discussion

The composition of the sediments ranged from medium to large sand particles to very fine organic sludge. Image 2 shows the sediments from each sampling location. Table 1 Provides a summary of the laboratory results from Phase 1.

There was a distinct correlation between lighter-colored, drier, sandy soils containing less phosphorus and darker and wetter samples containing more phosphorus (Table 1.)

The phosphorus concentration of the sediments collected ranged from 67.2 to 1,282 mg/kg with an average value of 616 mg/kg and a median value of 702 mg/kg. The sediment moisture content (% water) was highly variable, ranging from 14 to 80.5% of the sample.

Image 2. Sediment samples as collected with respect to location in the Reservoir (Figure 1).

The composition of the sediments ranged from medium to large sand particles to very fine organic sludge. Image 2 depicts the appearance and composition of the sediments from each sampling location. The results of the laboratory analysis demonstrated that the lighter-colored, drier, sandy soils and the darker and wetter samples had distinct differences in regard to moisture and phosphorus content (Table 1).

Table 1. Results of laboratory analysis of sediments. Phase 1, collected May 2021.

SAMPLE ID	% Solids	% Water	Total Phosphorus (mg/kg)
CC 1	68.20%	31.80%	707.0
CC 2	70.10%	29.90%	539.0
CC 3	81.00%	19.00%	201.0
CC 4	71.30%	28.70%	642.0
CC 5	85.90%	14.10%	67.2
CC 6	65.10%	34.90%	551.0
CC 7	81.30%	18.70%	92.0
CC 8	75.40%	24.60%	250.0
CC 9	32.30%	67.70%	865.0
CC 10	45.60%	54.40%	791.0
CC 11	24.00%	76.00%	915.0
CC 12	35.50%	64.50%	681.0
CC 13	82.10%	17.90%	112.0
CC 14	84.50%	15.50%	82.3
CC 15	68.70%	31.30%	723.0
CC 16	23.20%	76.80%	886.0
CC 17	19.50%	80.50%	1282.0
CC 18	22.50%	77.50%	887.0
CC 19	29.80%	70.20%	764.0
CC 20	19.70%	80.30%	892.0
CC 21	20.80%	79.20%	895.0
CC 22	76.90%	23.10%	297.0
CC 23	22.10%	77.90%	998.0
CC 24	61.20%	38.80%	825.0
CC 25	59.20%	40.80%	377.0
CC 26	65.00%	35.00%	696.0
Average	**53.50%**	**46.50%**	**616.1**

The phosphorus content was directly correlated to the moisture content of the sediment samples (Figure 2). The percent solids/moisture content of the samples indicates that higher water content in sediment increases the potential for higher phosphorus content. Sediment with higher water content is indicative of increased organic material and fine-grained clay particles, both of which will contain higher concentrations of phosphorus.

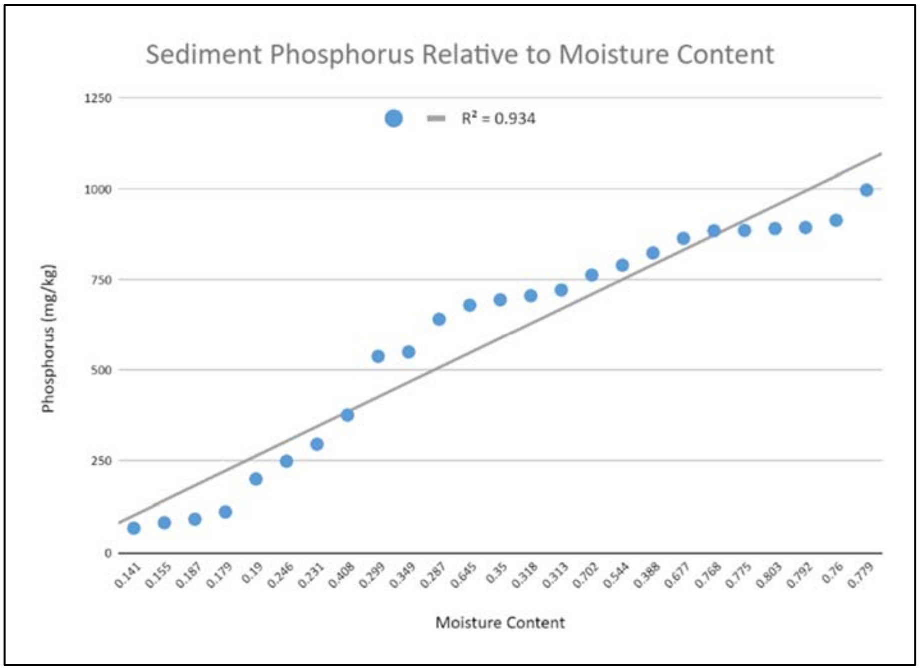

Figure 2. Relationship between moisture content and Total Phosphorus (Phase 1)

The sampling locations with similar phosphorus concentrations and physical locations within the reservoir were classified into four groups or “zones”. Seven sites with a representative phosphorus concentration and location in each zone were selected for Phase 2 of the study. Figure 3 shows the grouping of sampling sites into Zones 1-4 and the sampling locations for Phase 2.

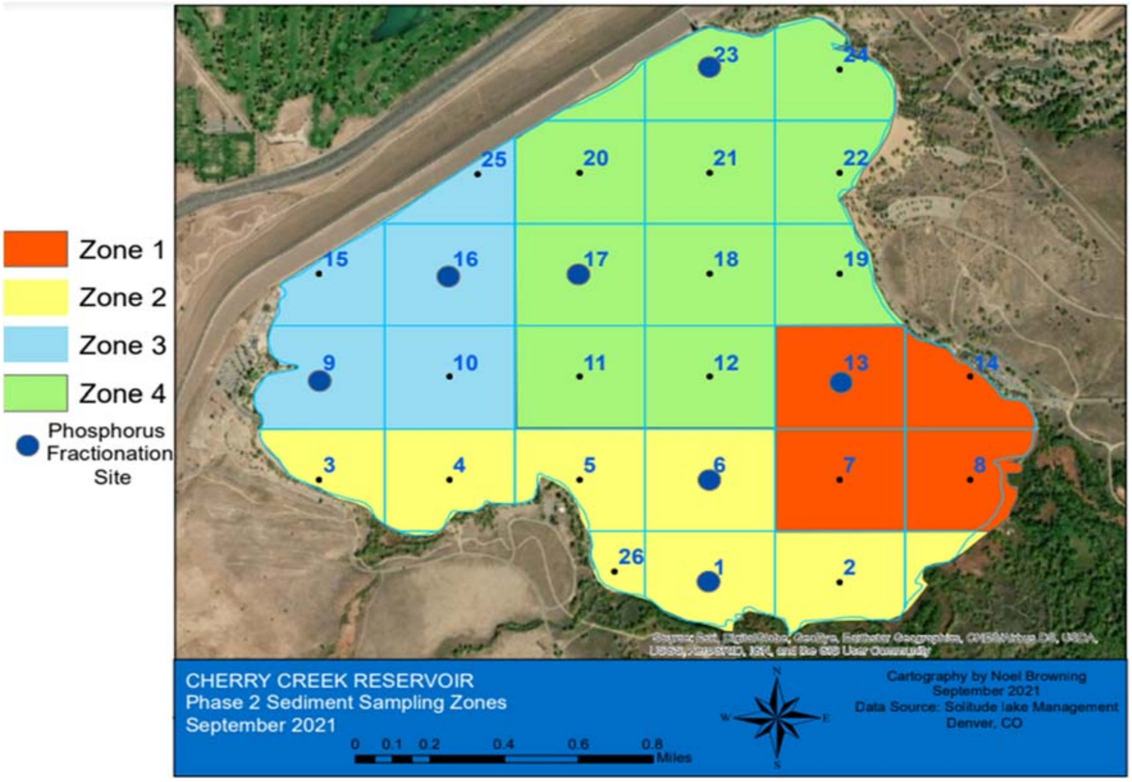

Figure 3. Reservoir Zones and Phase 2 Sampling Sites

Table 2. Zone Summary and Phase 2 Sampling Locations

Zone	**Phase 1 Sampling Sites**	**Average Phosphorus Concentration**	**Phase 2 Sampling Site(s) – TP**	**General Location**
Zone 1	7, 8, 13, and 14	134 mg/kg	13 - 112 mg/kg TP	South - Cherry Creek Inlet
Zone 2	1, 2, 3, 4, 5, 6, and 26	510 mg/kg	1 -707 mg/kg and 6 - 551 mg/kg TP	South - Cottonwood Inlet and Western Shoreline
Zone 3	9, 10, 15, 16, and 25	728 mg/kg	9 - 865 mg/kg and 16 - 886 mg/kg TP	Marina and Western side of Dam
Zone 4	11, 12, 17, 18, 19, 20, 21, 22, 23 and 24	862 mg/kg	17 - 1282 mg/kg and 23 - 988 mg/kg TP	Middle Reservoir, Eastern side of Dam and Swim Beach

Figure 4 illustrates the spatial variability of total phosphorous throughout the Reservoir. The heat map demonstrates:

- the highest TP sediment concentrations occur in the middle of the Reservoir in the areas with the greatest water depth,
- the lowest TP concentrations occurred in the inlet areas of Cherry Creek
- TP concentrations where Cottonwood Creek enters the Reservoir were slightly higher than near the Cherry Creek inlet.

The laboratory results corresponded with site observations. The areas closest to the inlets of Cherry Creek and Cottonwood Creek were composed of larger sandy particles which contained a lower phosphorus content. The areas closest to shore, such as Site 5, contained the largest particles observed, including sand and small gravel (Image 2), and also contained the lowest phosphorus concentrations of all the samples (67 mg/kg). Due to the method chosen for the GIS analysis, the low concentration at site 5 is not as visible in the heat map due to its proximity to shore and the higher concentrations of the nearby samples.

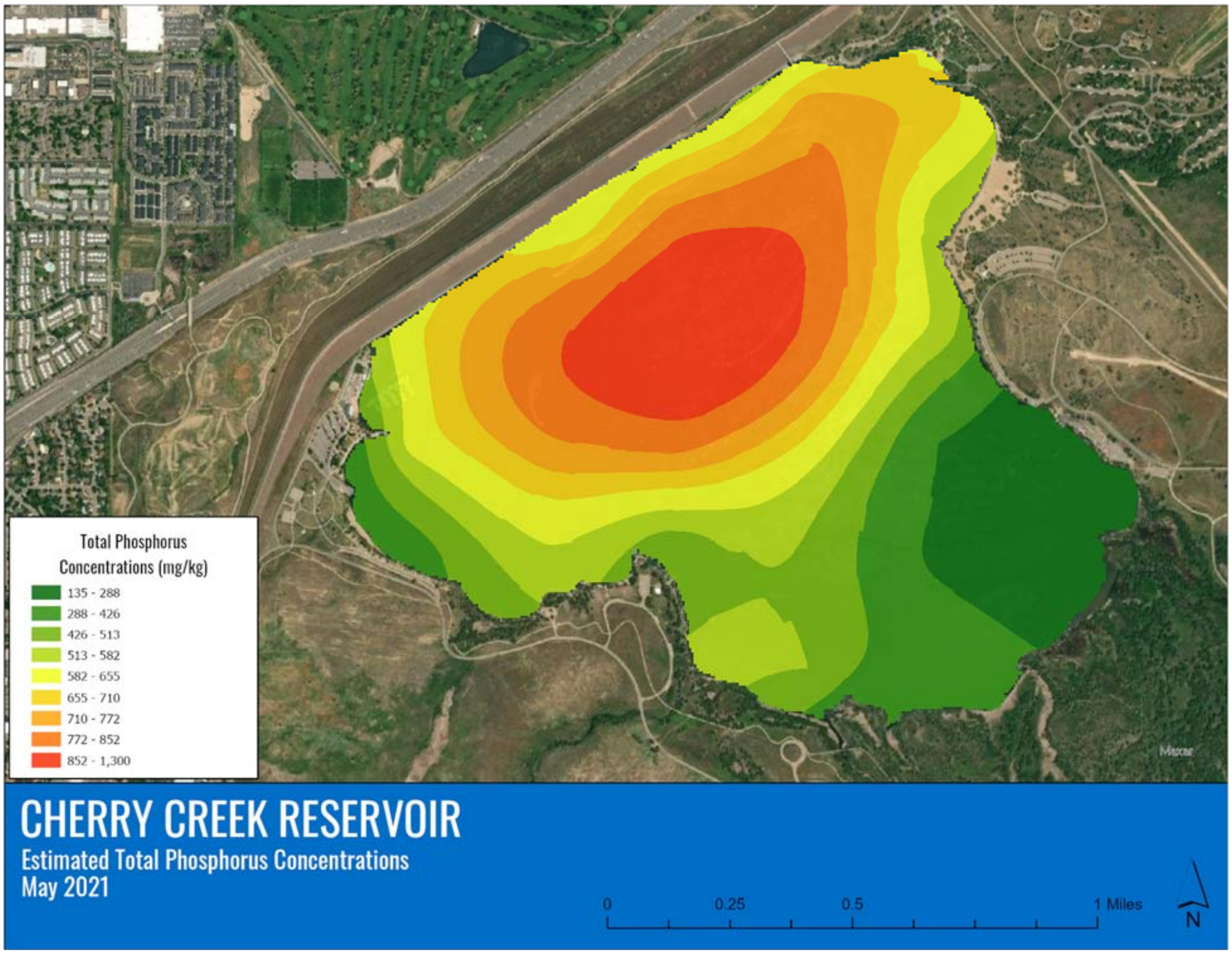

Figure 4. Estimated Total Phosphorus Concentrations in Cherry Creek Reservoir Sediments. Phase 1 (May 2021)

Phase 2 – Sediment Sample Collection Methods for Phosphorus Fractionation Analysis

Phase 2 sample collection was completed at the end of September 2021 at the seven representative zone samples described above. The objective of the Phase 2 sampling was to determine what percentage of the phosphorus represented a mobile fraction that could be involved in nutrient cycling in the Reservoir. Two sample depths were also collected to evaluate the difference in phosphorus fractionation with depth that would indicate the potential impact of internal loading over time.

Analysis of samples from two depths: 0-5 cm (A) and 5-10 cm (B) was completed to determine the variability of phosphorus fractionation with depth. This information can inform on the potential P transport upwards through sediment layers over time. Laboratory analyses included fractionation analysis for TP including: mobile P, aluminum (Al) bound P, iron (Fe) bound P, calcium (Ca) bound P, total organic P, and biogenic P, as well as total solids, Ca, Fe, and Al.

A gravity core sampler was used to collect sediment core samples of up to 0.5 m in depth, depending on sediment composition. Samples were extruded from the cores in the field and were divided into multiple sections based on the length of the cores. The sections analyzed for all cores were 0-5 cm and 5-10 cm. An additional 10-20 cm section was retained and frozen in case the results indicated analysis of deeper sediments should be completed.

Images 3 and 4. Sediment core sampling samples and section collection

Phase 2 - Phosphorus Fractionation Results

Table 3 presents Phase 2 results for the seven sediment collection sites. Phase 2 results were consistent with Phase I results: 1) the sites closer to the shoreline of the Reservoir had lower moisture content along with lower phosphorus and metals concentrations, and 2) the finer grain, silty, or clayey particles with a higher percentage of water content had correspondingly higher phosphorus concentrations.

The minimum phosphorus concentration was 188 mg/kg (Site 1) and the maximum was 1,645 mg/kg (Site 16). The moisture content of the sediment sampled ranged from 22% to 78%, which corresponded to the sites with the minimum and maximum phosphorus concentrations.

The two depth sections analyzed had minimal variability (approximately 10% between the A and B samples) of moisture content. The B sections, from 5-10 cm, had a lower moisture content than the samples from 0-5cm, with the exception of site 13, which was ~ 2% higher than the deeper section.

Table 3. Moisture and Total Phosphorus Results, Phase 2.

SAMPLE ID	Solids (%)	WATER (%)	TOTAL P (mg/kg)
Zone 1 Site 13A	78.40%	21.60%	188
Zone 1 Site 13B	76.70%	23.30%	383
Zone 2 Site 1A	59.10%	40.90%	943
Zone 2 Site 1B	69.50%	30.50%	816
Zone 2 Site 6A	69.70%	30.30%	768
Zone 2 Site 6B	72.90%	27.10%	697
Zone 3 Site 9A	31.40%	68.60%	1,604
Zone 3 Site 9B	35.00%	65.00%	889
Zone 3 Site 16A	24.00%	76.00%	1,645
Zone 3 Site 16B	32.80%	67.20%	1,038
Zone 4 Site 17A	21.30%	78.70%	1,279
Zone 4 Site 17B	25.80%	74.20%	1,497
Zone 4 Site 23A	28.90%	71.10%	1,229
Zone 4 Site 23B	32.60%	67.40%	1,138

The results demonstrated that the phosphorus concentrations were directly correlated with moisture content, similar to Phase 1. Figure 5 displays the relationship between moisture content and phosphorus concentrations from the two depth sections in Phase 2 along with the results from the same site locations from Phase 1. The size of the bubble corresponds to the percent moisture of each sample where larger bubbles represent a higher moisture content. Similar to Phase 1, the samples with the highest moisture content and near the deepest part of the Reservoir had the highest phosphorus concentrations (e.g., larger bubbles are typically seen at higher total P levels).

In Phase 2, the fine grained, more silty particles that have a much higher percentage of water had corresponding high phosphorus concentrations, and the larger particles and sand type material had lower phosphorus concentrations. The three sites in the area near the south of the Reservoir (1, 6, and 13) near the inlets of Cottonwood Creek and Cherry Creek had the lowest average moisture content (29%) and the lowest corresponding phosphorus concentrations (632.5 mg/kg) for the two depths sampled.

The rest of the sites, near the center or the Reservoir (sites 16 and 17), in the cove near the marina (site 9), and the cove near the swim beach (site 23) had much higher average moisture content (75%) and higher average phosphorus concentrations (1,290 mg/kg) for the two depths sampled.

Site 1 had similar phosphorus concentrations to some of the samples (site 9 and 16); however, the moisture content was lower. Figure 5 also shows that the phosphorus concentrations from Phase 2 were higher than in Phase 1 (orange) and the surface section from 0-5 cm (light blue) contained higher phosphorus concentrations than the deeper samples collected from 5-10 cm (dark blue). However, sites 13 and 17 had slightly higher phosphorus content from the 5-10 cm samples than the other samples. It is important to note that the samples collected in Phase 1 likely represent samples from 0-10 cm or even slightly deeper.

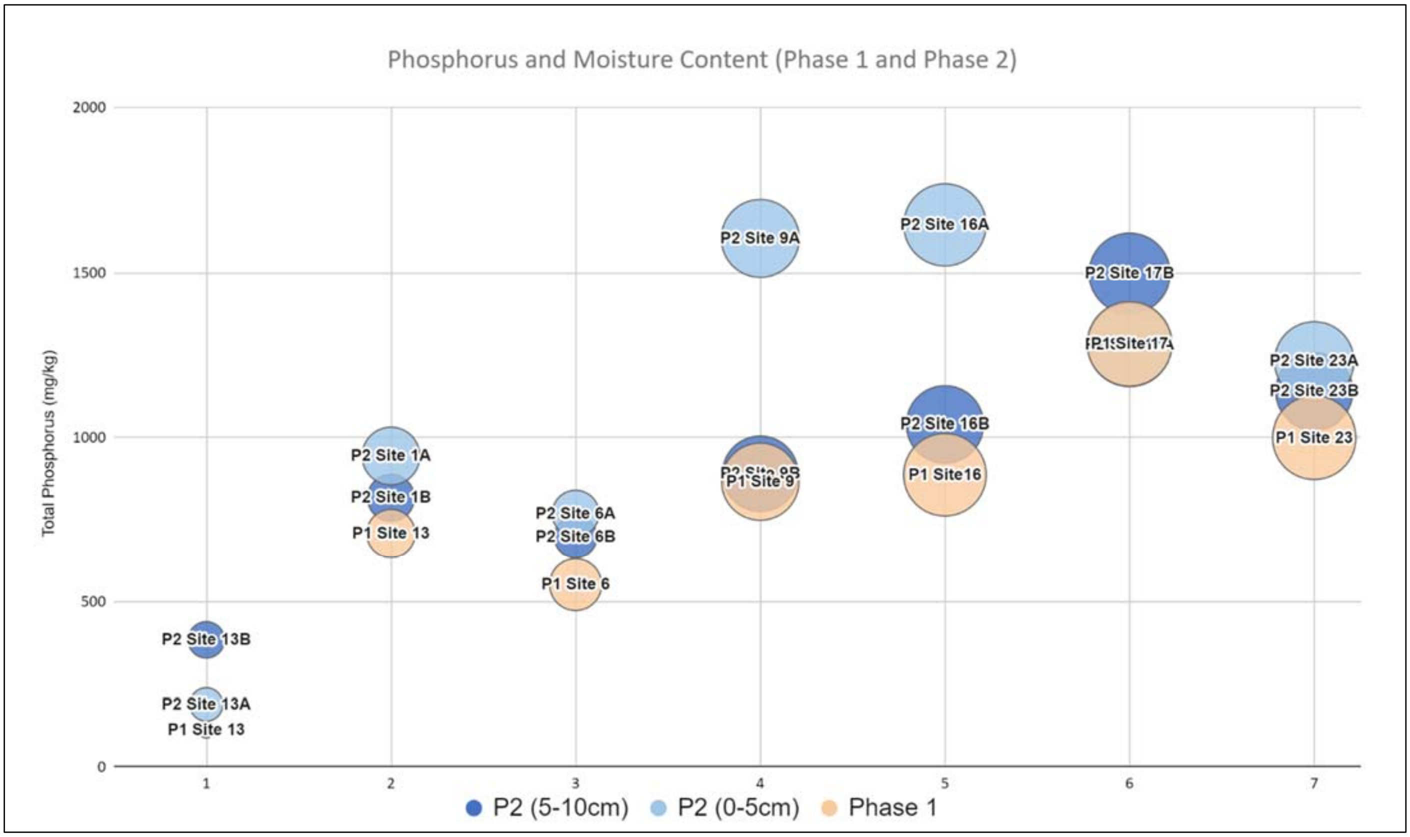

Figure 5. Relationship between Phosphorus Concentration and Moisture Content (Phase 1 and 2 A and B). Bubble size represents moisture content.

The laboratory used sequential phosphorus extraction methods to identify different bound forms of P and to determine mobile and permanent P fractions (Table 4). The mobile forms are considered to be potentially involved in internal loading that could drive productivity (algal growth and chl-a production) and the permanent forms would remain unavailable deposited in the sediment. The A sections, collected from 0-5 cm, would have the most immediate interactions in the nutrient cycle and the B sections, from 5-10 cm, would be more likely to have impact over time as biological organisms move the sediment upward towards the sediment-water interface but could also remain buried and inactive depending on reservoir conditions.

Table 4. Phosphorus Fractionation Results, Phase 2.

Phosphorus Form		**Mobile**	**Mobile**	**Mobile**	**Permanent**	**Permanent**	**Permanent**
		Phosphorus Fraction (mg/kg)					
SAMPLE ID	**Depth (cm)**	**Loosely Bound P**	**Fe-Bound P**	**Biogenic-P**	**Al-Bound P**	**Ca-Bound P**	**Refractory Organic P**
Zone 1 Site 13A	0-5	<2.00	9.86	<2.00	31.7	126	20.3
Zone 1 Site 13B	5-10	<2.00	17.6	<2.00	97.5	236	31.8
Zone 2 Site 1A	0-5	<2.00	23	52.5	62.2	643	162.5
Zone 2 Site 1B	5-10	<2.00	25.6	26.6	53.5	643	66.7
Zone 2 Site 6A	0-5	<2.00	22.7	24	74	570	77
Zone 2 Site 6B	5-10	<2.00	23.2	24.2	69.6	522	57.9
Zone 3 Site 9A	0-5	<2.00	66.8	121	97.5	877	441
Zone 3 Site 9B	5-10	<2.00	50.1	41.6	85.1	533	179.4
Zone 3 Site 16A	0-5	<2.00	68.4	168	167	781	461
Zone 3 Site 16B	5-10	<2.00	45.2	87.4	116	557	232.6
Zone 4 Site 17A	0-5	<2.00	67.2	265	71.7	575	300
Zone 4 Site 17B	5-10	<2.00	34.7	123	85.6	706	548
Zone 4 Site 23A	0-5	<2.00	94.6	100	179	596	260
Zone 4 Site 23B	5-10	<2.00	90.7	85.3	143	615	203.7

Soluble or loosely bound phosphorus is the fraction normally extracted first using ammonium chloride (NH_4Cl) and is considered highly mobile or able to be released during reducing conditions. This fraction mainly represents pore water and loosely absorbed phosphorus released to diffusion or desorption. This fraction, which normally represents a small percentage of the total sediment P, was below the detection limit in all of the samples. Loosely bound P would likely become bound to iron as the sample was oxidized during sample collection, handling, and shipping to the laboratory so it would most likely be represented as part of the Fe-bound fraction. The highly mobile and mobile fractions are considered to represent the "bioavailable" phosphate or phosphorus that can be made available under natural conditions or processes in the sediments. The semi-permanent and permanent fractions would not be readily be released under physical, chemical, or biological environmental conditions that would occur in lakes or reservoirs.

Iron-bound (Fe-bound) phosphorus is extracted using a bicarbonate buffered dithionite and represents a fraction that is considered mobile that would release in periods of anoxic conditions. Manganese-bound phosphorus can also potentially be released under anoxic conditions and would also be included in this fraction.

Sodium hydroxide (NaOH) is used to extract organic P and the aluminum-bound (Al-bound) P fraction. In this case, the organic P is further divided into biogenic and organic P representing the labile and refractory fractions (Lukkari, et al., 2007).

Biogenic P in the sediments is phosphorus incorporated in cell material, such as recent algal deposition, plants, leaves, or even dead organisms. The biogenic P can become mobilized as cellular material degrades through bacterial decomposition processes. The remaining organic P is more refractory and biologically unavailable and is calculated by subtracting the biogenic P from the organic P fraction. Refractory organic P forms include P bound to humic and fulvic acids, as well as P incorporated in compounds such as tannins and lignins.

Aluminum-bound (Al-bound) P is typically adsorbed on or included in the formation of clay minerals and is considered refractory or permanent.

Calcium-bound (Ca-bound) phosphorus is extracted using hydrochloric acid (HCl) and represents apatite P (calcium phosphate mineral) and a fraction that is considered permanent and would usually not be released in natural conditions.

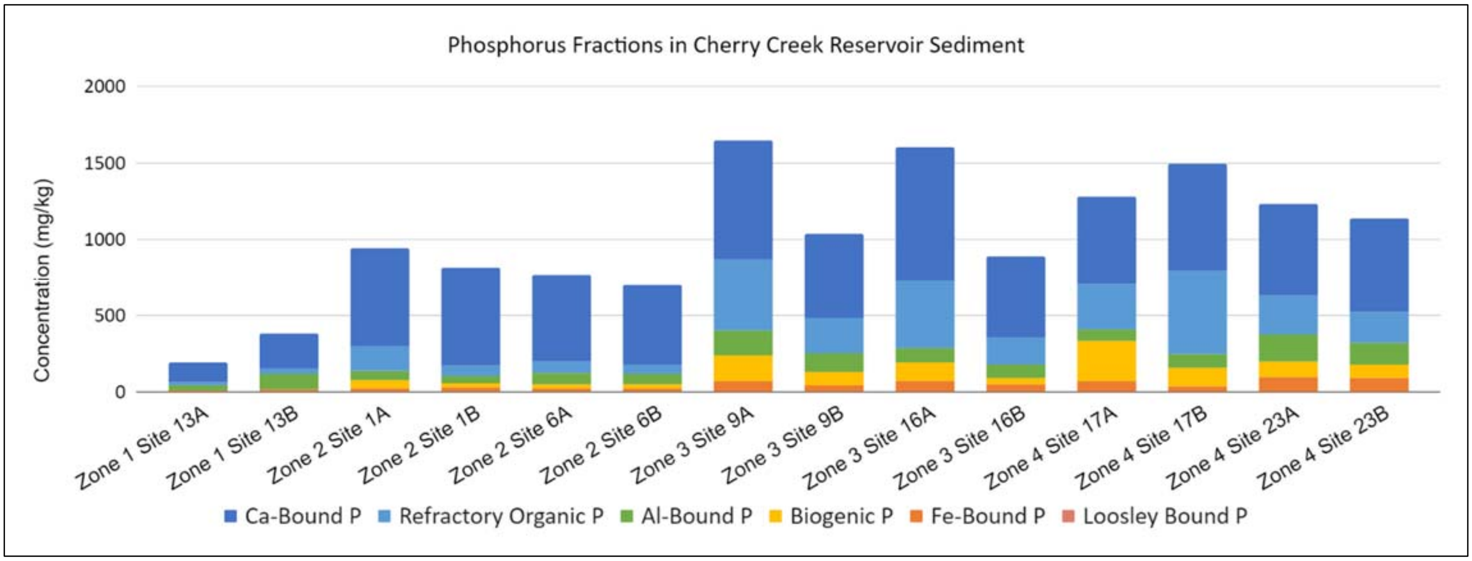

Figure 6. Total Concentrations of Phosphorus in Fractions

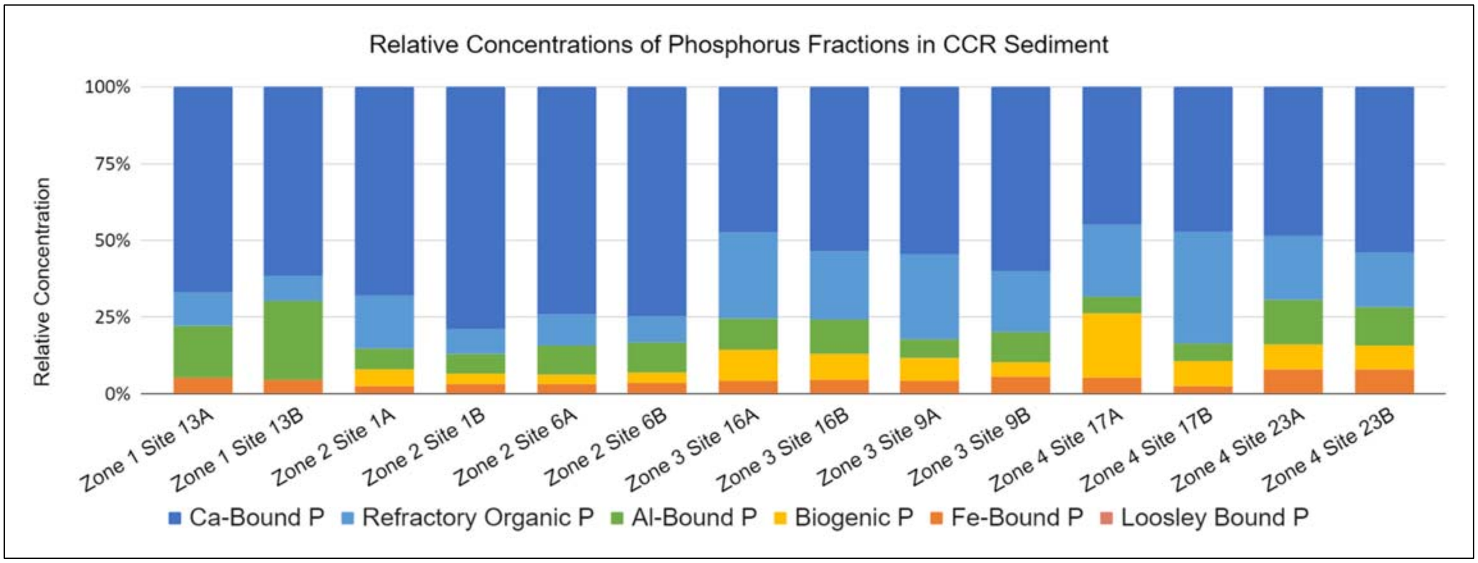

Figure 7. Relative Concentrations of Phosphorus Fractions

Figures 6 and 7 represent the total and relative phosphorus concentrations from each of the fractions found in each sample. Overall, the P fraction that is considered mobile is represented by the Fe-bound (light blue) and biogenic P (yellow) fractions. Fe-bound P could be released during anoxic conditions. Biogenic P can also potentially become mobilized as cellular organic material decomposes and is released over time.

Figure 8 shows the relative concentrations of the total P that is considered mobile or likely to be involved in nutrient cycling under natural conditions in the Reservoir. The mobile P averaged 127 mg/kg or approximately 11% of the total P in all samples.

Of the surface samples collected from 0-5 cm (shown in light blue), Site 13 had the lowest percent mobile at 5.3% (9.9 mg/kg) and Site 17 had the highest at 26% (332 mg/kg). From the samples collected from 5-10 cm (shown in dark blue), Site 17 had the lowest mobile P percent of the total at 4.6% (17.6 mg/kg) and site 23 had the highest at 15.5% (176 mg/kg). Zones 1 and 4 had a lower percentage of mobile P in the surface sample A from 0-5 cm but in all other sites it was higher at the lower depth B sample from 5-10 cm.

The areas to the south of the Reservoir and near the inlets (Sites 1, 6, and 13) averaged 41.5 mg/kg mobile P or 6.2% of the total P. At the sites near the center or deeper areas of the Reservoir (Sites 9, 16, 17, and 23) the mobile P averaged almost four times (181.6 mg/kg) the mobile P at the other sites. In addition, the relative percentage of the mobile fraction to total P was 14.2%, which is more than two times the other sites. The center of the Reservoir had the highest concentrations of mobile P at 332.3 mg/kg (Site 17) and 236.4 mg/kg (Site 16) and represented about 16% of the total P.

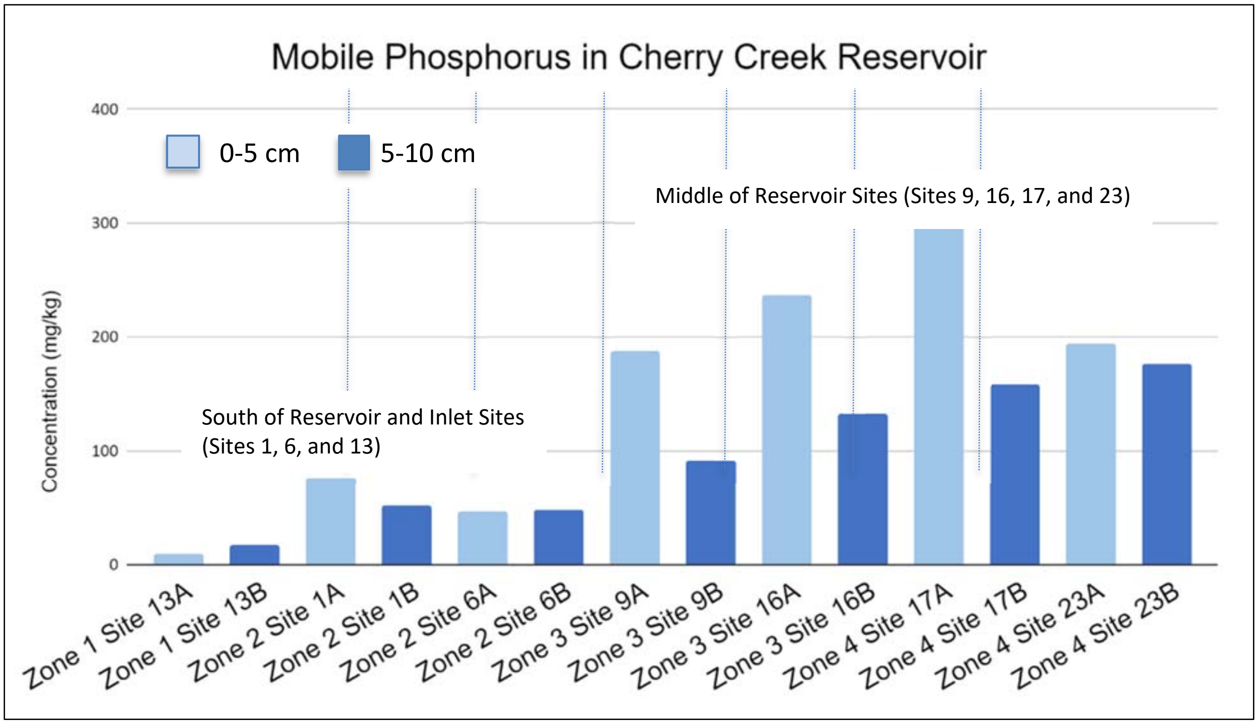

Figure 8. Concentrations of Mobile Fractions of Phosphorus in Cherry Creek Reservoir

Figure 9 illustrates the spatial variability of mobile P throughout the Reservoir estimated using the Kriging GIS analysis, using the average mobile P fraction of the two depth sections (0-5 cm and 5-10 cm) at each of the seven sample sites. The heat map in Figure 9 shows a similar trend as the heat map pf total P in Figure 4. Although the mobile P concentrations are lower than the total P, the deepest areas in the middle of the Reservoir contained the highest concentrations of mobile P in the sediments. Site 17 had an average mobile P fraction of 245 mg/kg, and sites 16 and 23 both averaged 185 mg/kg mobile P for the two depths. The average mobile P was 139 mg/kg at site 9 near the marina, slightly less than the mid- Reservoir sites but much higher than those to the south near the inlet. Sites 1, 6, and 13 averaged 64 mg/kg, 47 mg/kg, and 14 mg/kg mobile P, respectively.

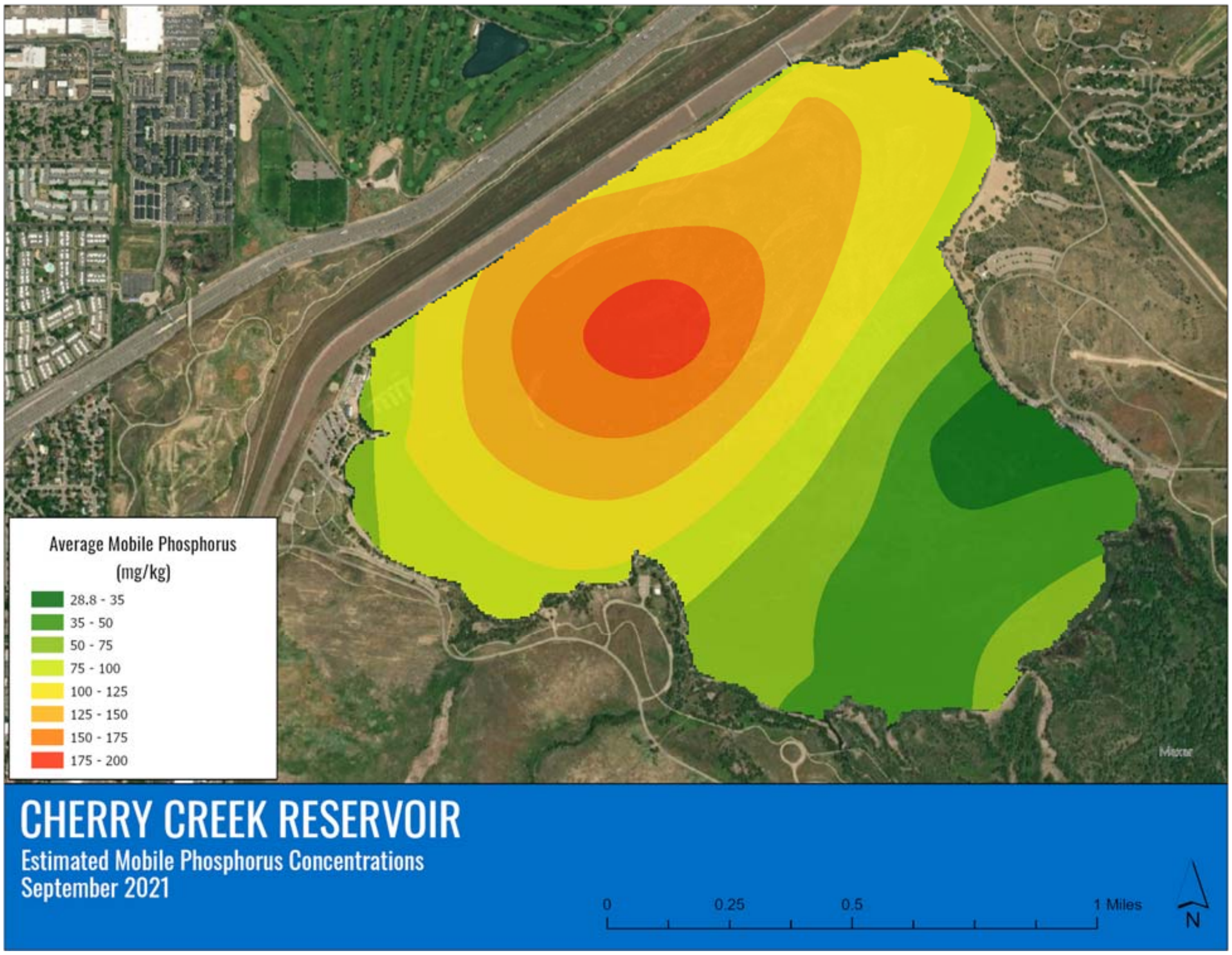

Figure 9. Estimated Mobile Phosphorus Concentrations in Cherry Creek Reservoir Sediments – Average Concentrations from A/B Sections from Phase 2. (Sept 2021)

Phase 2 - Phosphorus Fractionation Results

In addition to the phosphorus fractionation, the associated metal concentrations in the sediments were also analyzed. These values represent the minerals bound or available to bind P in the sediments. Table 5 and Figure 10 show the metal/mineral concentrations from each of the samples and depths sampled.

Table 5. Results of laboratory analysis of sediments, Metals Analysis. Phase 2, collected Sept 2021.

Site	ALUMINUM (mg/kg)	IRON (mg/kg)	CALCIUM (mg/kg)
Zone 1 Site 13A	1,550	2,750	2,040
Zone 1 Site 13B	4,170	5,480	1,850
Zone 2 Site 1A	6,310	10,300	29,200
Zone 2 Site 1B	6,330	10,400	19,000
Zone 2 Site 6A	4,850	10,900	9,020
Zone 2 Site 6B	5,490	10,700	8,840
Zone 3 Site 9A	11,500	15,300	69,600
Zone 3 Site 9B	11,200	15,700	66,000
Zone 3 Site 16A	13,300	17,900	67,200
Zone 3 Site 16B	11,600	15,300	54,200
Zone 4 Site 17A	15,100	20,100	71,100
Zone 4 Site 17B	15,300	19,500	57,200
Zone 4 Site 23A	9,050	12,300	44,900
Zone 4 Site 23B	10,900	14,400	47,300

Site 1 had the lowest concentrations of aluminum (Al), iron (Fe), and calcium (Ca). Site 17 had the highest concentrations of Al (15,100 and 15,300 mg/kg) and the highest concentration of Fe (20,100 and 19,500 mg/kg) from the two depth sections A and B (0-5 cm and 5-10 cm). Site 9 had the highest Ca content (69,600 and 66,00 mg/kg) in the A and B sections. The Ca concentrations are very high and average 55% of the total metals in the samples based on molecular weight. The high concentrations of Ca are reflected in the high percentage (~60%) of the total P that was determined to be Ca-bound. Al and Fe averaged 26% and 19% of the total mineral pool based on molecular weight. Although much lower than the Ca-bound P, the Al- and Fe-bound P represented 10 and 5% of the total P.

Fe represented a higher percentage of the total metals than the percent that was determined to be Fe-bound in the fractionation analysis. This implies that there is the potential for additional binding of P in the water or sediments to Fe if oxidizing conditions were present.

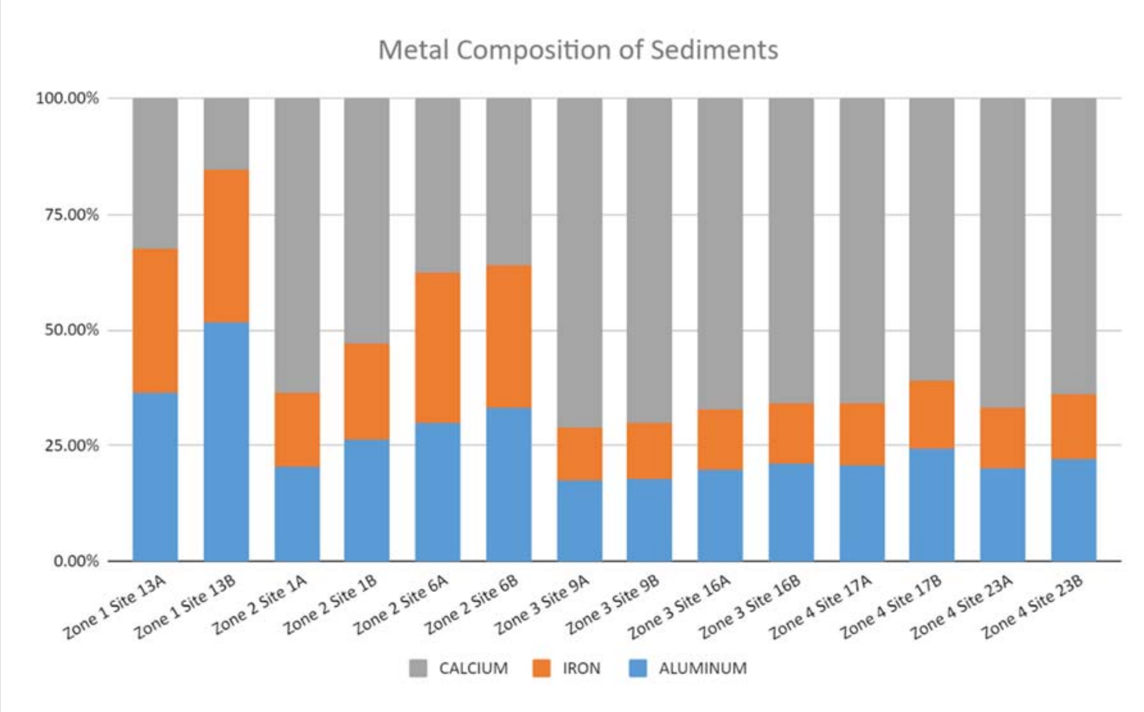

Figure 9. Metal-Mineral Concentrations in Cherry Creek Reservoir.

Discussion

This sediment study provides valuable information on the nutrient dynamics in Cherry Creek Reservoir sediments. Analysis of the results identified trends in sediment size and water content based on the sample locations' proximity to shore and water depth. Lower total P concentrations were associated with larger particles, such as sand and gravel, and lower moisture content was present in sediments in the shallow areas, locations closer to shore, and to the south of the Reservoir near the inlets of Cottonwood and Cherry Creek.

The highest concentrations of total P were found in sediment in the deepest areas in the middle of the Reservoir. These areas also appeared to have the largest accumulations of fine organic sediment (sludge) (Image 2). These samples closer to the middle of the reservoir also contained higher percentages of Fe-bound and biogenic P. These fractions are considered mobile forms of P that would be released into the water column under anoxic conditions. Although the mobile P only represented a small fraction of the total P, the concentrations of these fractions were not insignificant. In the middle of the Reservoir, the concentrations of mobile P ranged between 133 and 332 mg/kg in the samples collected from the surface sediment (0-5 cm). The concentrations from the samples collected at the deeper section (5-10 cm) were only slightly lower and provide insight as to how these sediments would potentially impact the water as biological activity moves the bottom sediment towards the surface. Internal loading can be impacted by sediment depths up to 20 cm (Sondergaard et al., 2003).

The positive relationship between total P and biogenic P suggests that P release from the sediments may play a role in eutrophication (Ahlgren et al., 2005) and the cycling of P in the water column. The high rates of productivity and deposition of algal biomass may seasonally affect the concentrations of biogenic P. The timing of deposition of dead algal material and decomposition rates will also affect the concentrations of biogenic P in the sediments. Sediment concentrations of mobile P can be used to predict future internal loading and the impact of lake sediments regardless of external loading (Ramm and Scheps, 1997).

Oxidation at the sediment-water interface reduces the potential for Fe-bound P to be released into the water column. Under normal conditions, Cherry Creek Reservoir typically sees periods of anoxia (low oxygen) during the months of June through September when the Reservoir is also more likely to experience cyanobacteria blooms. The metal and mineral pool concentrations in the sediment were correlated to the concentrations of Fe-, Al-, and Ca-bound P, although Fe concentrations indicate that additional Fe would be available to bind P in oxidizing conditions. The high Ca concentrations and Ca-bound P concentrations suggest that internal calcite precipitation may be sequestering P in the sediments making it permanently bound in the sediments.

Additional Considerations and Implications for Future Studies

This evaluation of the concentrations of P in the sediments and the mobile fractions that may be involved in internal loading provides information as to what additional factors may be involved in driving algal growth and associated chlorophyll-a concentrations in Cherry Creek Reservoir. Accurately quantifying internal loading is complicated, especially in polymictic reservoirs such as Cherry Creek. In 2008, Nurnberg and LaZerte calculated internal loading in Cherry Creek Reservoir using three different methods with median values that ranged from 183 to 255 mg/m^2/year. Results from the Nurnberg and LaZerte study could be combined with a more detailed study on the extent of summer anoxia in Cherry Creek Reservoir, possibly using the same sites used in this sediment study, to provide a reasonably good estimate of internal P loading. Hydros Consulting reviewed the LRE study results and noted that the spatial pattern for sediment phosphorus content and mobile phosphorus concentrations aligned closely with the model designations for spatially-varying sediment release rates.

Although more accurate estimates of in-situ internal loading potential requiring laboratory incubated P-flux analysis can be completed, they are not recommended for use in the Reservoir model at this time (Hydros, 2022). These studies are very labor intensive and require intact core samples collected from the Reservoir so redox conditions in an incubation chamber can be simulated. Although these studies measure P concentrations from the water in the core samples over time so that the release rates can be calculated to estimate internal loading (Ogdahl et al., 2014), this additional information is subject to significant uncertainty, thereby limiting its utility in the Reservoir model (Hydros, 2022). Other factors that may play a role in internal loading include wind action, macrophyte coverage, bioturbation from fish, and macroinvertebrate activity in the sediments.

The role of internal P concentrations and internal loading should also be a consideration if in-lake alternatives are considered as a management option. The 2020 WWE Evaluation of In-Reservoir Treatment at Cherry Creek Reservoir listed management options such as liquid alum injections incorporated into a destratification system or whole-lake single dose aluminum sulfate (alum) applications. In-lake addition of alum would bind phosphorus in the water column and also limit diffusion of the mobile forms (loosely-bound, Fe-bound, and biogenic P) from the sediment into the water column. The addition of aluminum sulfate to water forms an aluminum hydroxide floc, which has a high affinity to available forms of P that could be released from the mobile fractions. The application would convert the mobile forms of P to more tightly bound fractions, such as Al-bound.

An oxidative environment at the sediment-water interface would provide conditions that P would bind to iron or manganese in the sediments that would reduce the potential for internal loading into the water column. The 2019 Bubble Plume Model Report completed by Hydros found that it would be very difficult to provide significant benefit to the bottom dissolved oxygen concentrations with the existing destratification system.

Hydros (2022) reported that the calcium-bound P fraction in Cherry Creek was higher than that observed in Chatfield Reservoir when a similar study was completed. This difference could be an indication of geological sources contributing to the consistently high concentrations of phosphorus entering Cherry Creek Reservoir. Elevated concentrations of phosphorus are observed in the headwaters of the Cherry Creek watershed. Hydros (2022) suggested that understanding these potential sources could be useful to support bounding exercises on the ultimate potential to reduce inflow phosphorus concentrations.

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