

**CHERRY CREEK
BASIN WATER
QUALITY AUTHORITY**



2016 CHERRY CREEK MONITORING REPORT

January 2017



TETRA TECH

2016 Cherry Creek Monitoring Report

January 2017

PRESENTED TO

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EXECUTIVE SUMMARY

The 2016 *Cherry Creek Monitoring Report* provides a comprehensive update of monitoring efforts conducted in Cherry Creek Reservoir (Reservoir) and its watershed during the 2016 water year, October 1, 2015 to September 30, 2016. The reservoir and watershed monitoring program (“program”) is conducted in the Cherry Creek basin (Figure ES-1) in accordance with Cherry Creek Reservoir Control Regulation No. 72 (CR72) and the Cherry Creek Sampling and Analysis Program and Quality Assurance Procedures and Protocols (SAP/QAPP, 2016). The program is comprised of routine and continuous monitoring of physical, chemical and biological conditions, including evaluations of:

- Attainment of long term water quality goals and compliance with water quality standards, including the growing season chlorophyll-a (chl-a) water quality standard in Cherry Creek Reservoir, pursuant to CR72.
- Water quality characterization of inflows and the Reservoir.
- Effectiveness of the pollutant reduction facilities (PRFs) within the Cherry Creek basin, owned and operated by the Cherry Creek Basin Water Quality Authority (Authority).
- Streamflow measurements during base flow and stormflow conditions.
- Flow weighted total phosphorus (TP) and total nitrogen (TN) concentrations conveyed to Reservoir from Cherry Creek and Cottonwood Creek.
- Trends observed over the long-term since 1987 when the Authority began collecting data, including flow based concentration of phosphorus.

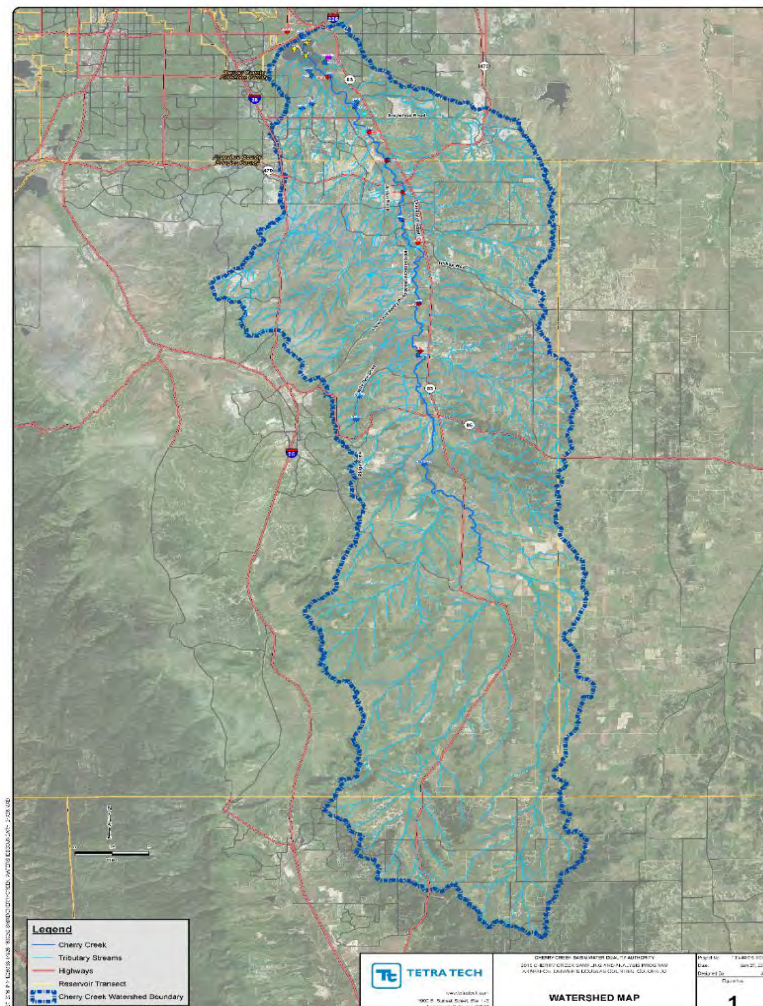


Figure ES-1. Cherry Creek Watershed Map. The Cherry Creek Basin is generally located in the Denver metropolitan area, south of Interstate 225 and east of Interstate 25.

Key watershed and Reservoir findings from the 2016 monitoring season are summarized below.

2016 Watershed Highlights

Higher than normal streamflow was observed in the watershed April through September. The streamflow from April – September was above the historical median measured in Cherry Creek (ES-2). Annual precipitation, 15.3 inches, was 93 percent (%) of average, however, the July through September total was only 44% of average (ES-3). The higher Cherry Creek inflows observed July through September may be a function of recharged shallow groundwater from the March through June precipitation events, resulting in delayed return flows through September.

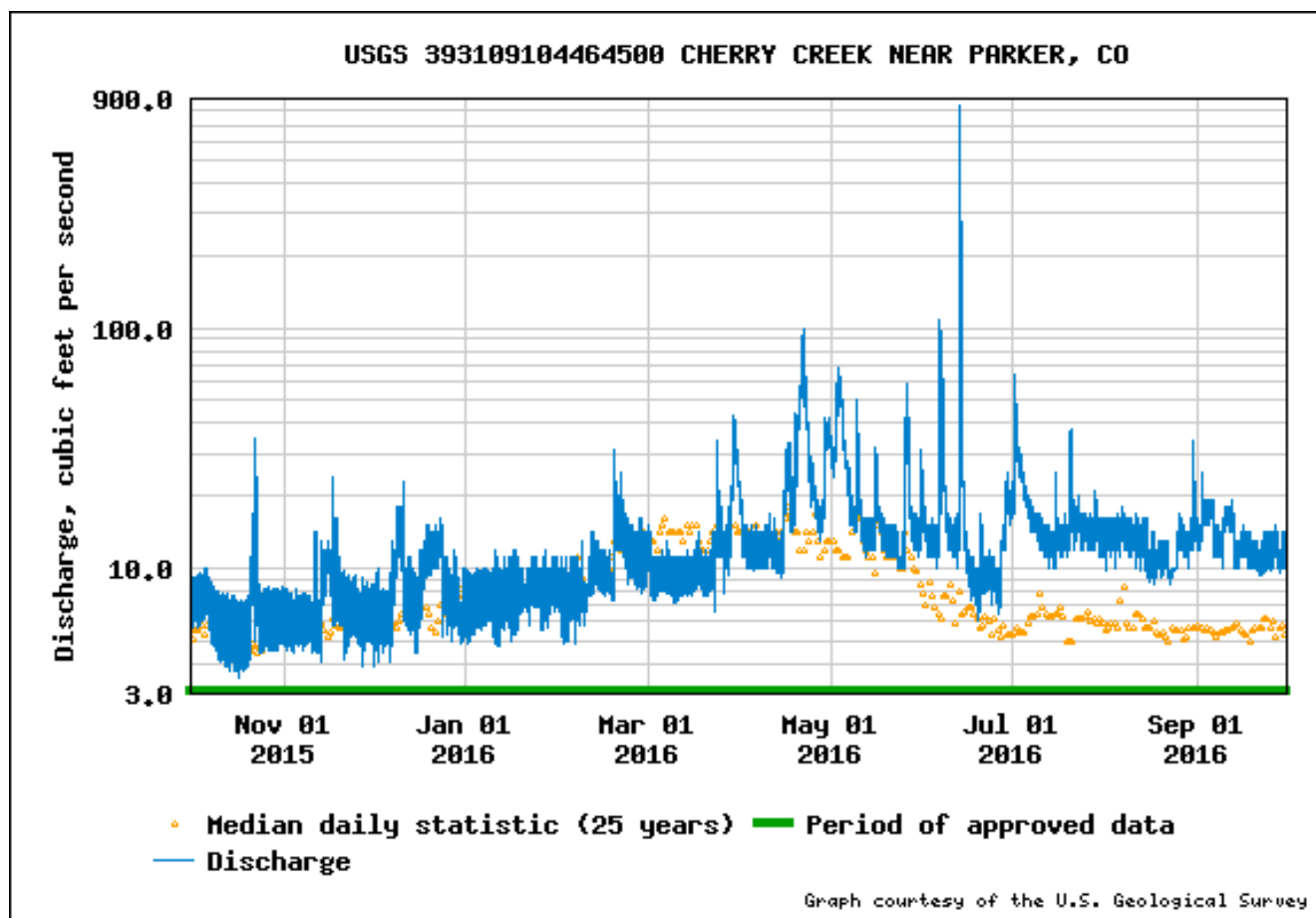


Figure ES-2. WY 2016 Cherry Creek Streamflow near Parker, CO. 2016 data are compared to the past 25 year median daily statistic. April – September 2016 flows were considerably greater than the historic record (Source: USGS, Station 393109104464500, Cherry Creek near Parker, CO).

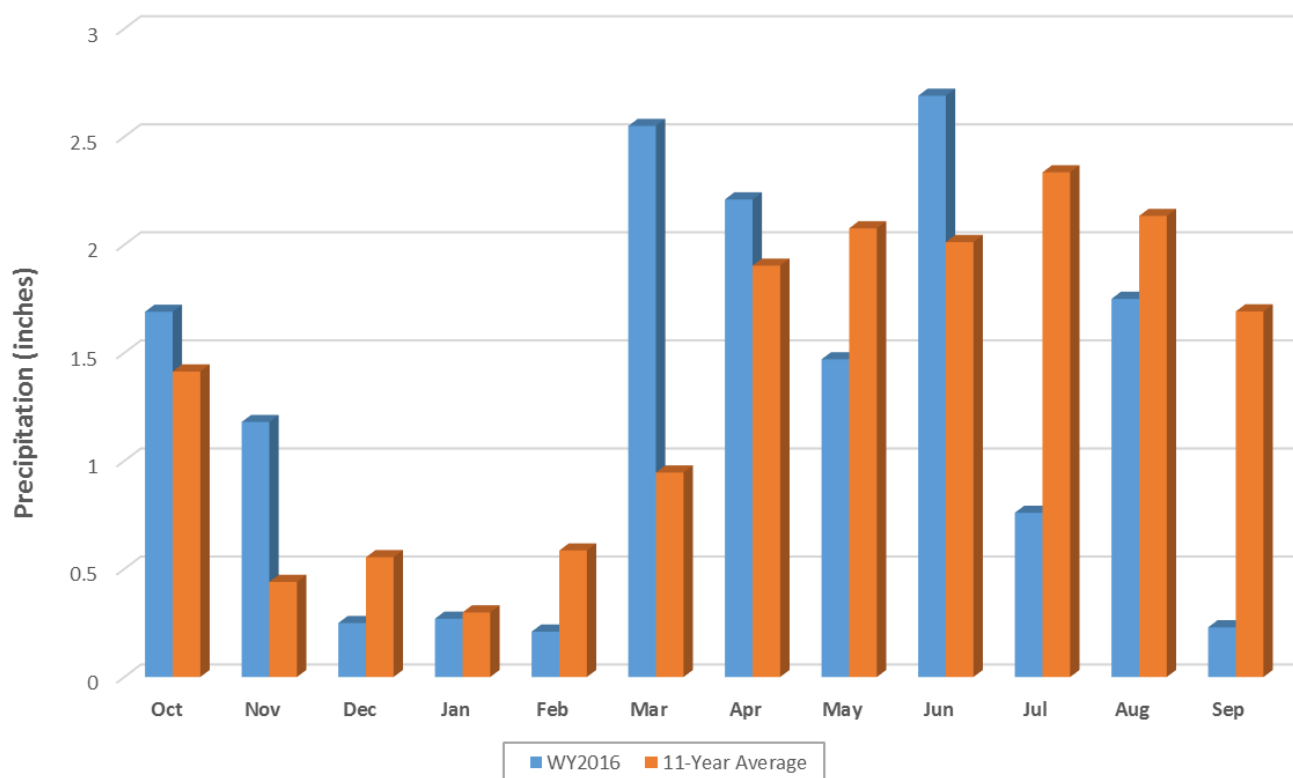


Figure ES-3. Monthly Precipitation near Cherry Creek Reservoir. Comparison of WY2016 precipitation and 11-year average (Data Source: NOAA Precipitation Station at Centennial Airport - KAPA).

Cottonwood Creek PRF passive treatment train approach provided phosphorus reduction during storm events, which could be improved upon with future maintenance, i.e. vegetative harvesting. The passive treatment train approach developed for PRFs in the Cottonwood Creek sub-basin includes a series of wetland detention systems and stream reclamation. This approach provided for a phosphorus reduction strategy, reducing TP concentration during stormflow conditions by 20% (Table ES-1). Total suspended solids concentration (TSS, a quantification of sediment concentration in streamflow) was reduced 77%. This is important, as the phosphorus content in sediments in the creek have been measured to contain high phosphorus content, on average of 0.9 pounds/cubic yard (Ruzzo, 2000). During base flow conditions, there was an increase in TP and TSS concentrations and the loading calculations bear out the instances when there is a net gain (net export) of TP and TSS. Soluble reactive phosphorus (SRP) concentrations were reduced by 25% during base flow conditions, however there was an increased load, or export of SRP, during stormflow events. TN concentrations (and loads) increased during both base flow and stormflow events, resulting in a net gain of nitrogen. Future wetland maintenance on this PRF is recommended. With routine maintenance, i.e. vegetation harvesting, N and P can be further reduced.

Table ES- 1. Pollutant Reduction Effectiveness of the Cottonwood PRFs - 2016 Median Concentrations (µg/L) at Cottonwood Stations, CT-P1 and CT-P2 (Sources of Data: IEH Analytical, Inc. (March 1 2016 -.September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016)).

Analyte	Cottonwood Cr, upstream of PRFs (Station CT-P1)		Cottonwood Cr, downstream of PRFs (Station CT-2)	
	Base Flow	Stormflow	Base Flow	Stormflow
TP, µg/L	42	81	62	65
SRP, µg/L	12	5	9	14
TN, µg/L	1196	1820	1927	1860
TSS, mg/L	11.8	81.5	26	18.5

Cherry Creek nutrient and sediment (TSS) concentrations were elevated upstream of Reservoir.

Total dissolved phosphorus (TDP), TP and TSS concentrations measured upstream of the Reservoir at Cherry Creek Monitoring Station CC-10 (Figure ES-4) were over four times greater than what was measured in Cottonwood Creek at Station CT-2 during routine sampling, and an order of magnitude greater during storm events. Phosphorus was generally present at CC-10 in the dissolved form in WY2016 with the exception of during storm-related high flows. During the higher flow generated by storm runoff, large amounts of sediment (and associated phosphorus) were transported in Cherry Creek. There is a strong relationship between particulate phosphate and suspended sediment conveyed by Cherry Creek.

The flow weighted TP concentration at CC-10 for WY2016 was 250 µg/L, slightly lower than the 2011 – 2015 flow weighted total phosphorus concentration of 263 µg/L (GEI, 2016), yet considerably elevated. The TP inflow concentrations from Cherry Creek remain too elevated to sustain water quality goals within the Reservoir. Therefore, treatment train PRF approaches, located upstream of the Reservoir on Cherry Creek (similar to Cottonwood Creek), may be appropriate for future consideration to reduce TP, SRP, and TSS concentrations of Cherry Creek inflows to the Reservoir.

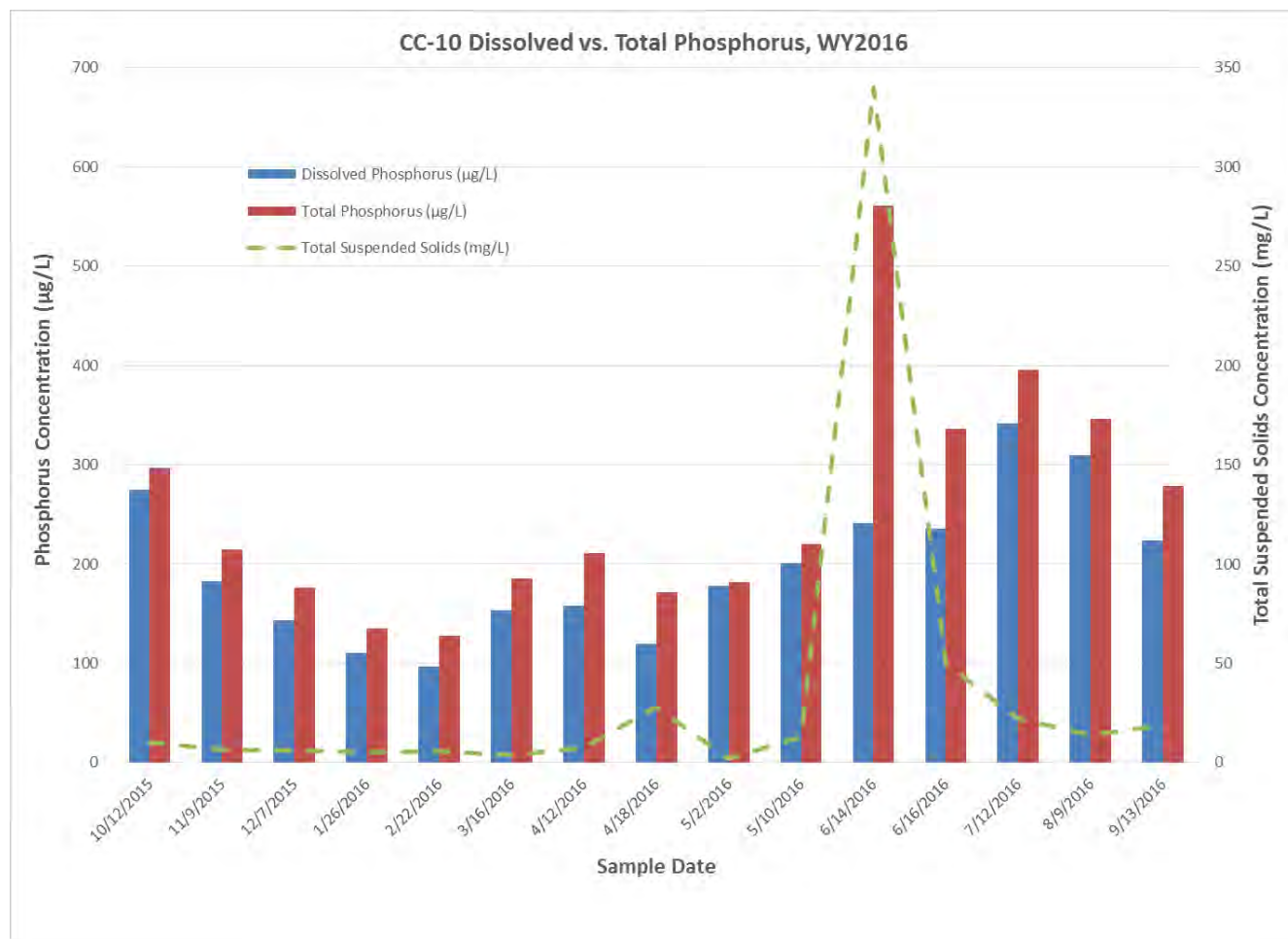


Figure ES-4. Comparison of TP Concentrations of Cherry Creek versus Cottonwood Creek (WY2016). Cherry Creek TP concentration measured at CC-10 (upstream of Reservoir) is on average three times greater than Cottonwood Creek TP concentrations measured upstream of Reservoir at CT-2. (Sources of Data: IEH Analytical (March 1, 2016 - September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016)).

Cherry Creek pH and specific conductance, a surrogate for total dissolved solids (TDS), increased upstream to downstream. The 2016 basin-wide monitoring events indicated an increase in pH and specific conductance in Cherry Creek as surface water moved from the upper basin downstream to the Reservoir (Figure ES-5). As shown, the background pH at Castlewood was 6.1, then increased to pH 8 downstream of CC-6.

In the case of specific conductance, during the May 2016 basin-wide monitoring event values increased approximately 4 fold from the upper monitoring stations (Castlewood and CC-1) to those in Cherry Creek State Park (CC-9 and CC-10) (Figure ES-5). This increase in specific conductance is due, in part, to increased levels of sulfate and chloride in Cherry Creek in the downstream direction.

Review of the historic data from CC-10 suggests that the pH of surface water entering the Reservoir from Cherry Creek appear to be decreasing slightly through time and that specific conductance values at CC-10 appear to have doubled since the mid-2000s (Figure ES-6).

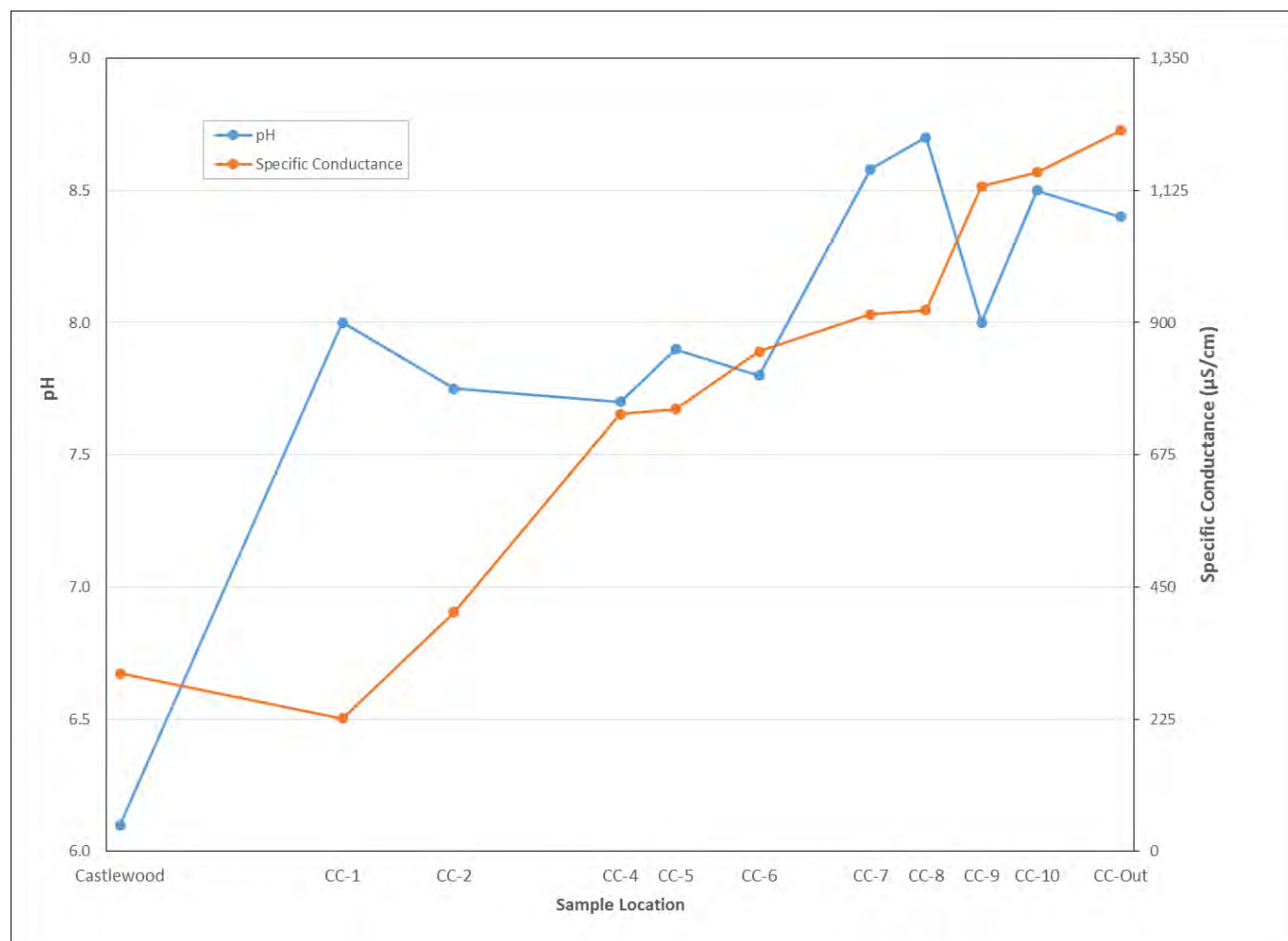


Figure ES-5. Specific Conductance and pH in Cherry Creek Basin, May 2016. (Source of Data: IEH Analytical, Inc.)

The pH of water in lower Cottonwood Creek was consistent with the pH values observed in lower Cherry Creek. However, the concentration of TDS, as inferred by specific conductance values, was higher in Cottonwood Creek than in Cherry Creek. This higher specific conductance is due, in part, to elevated levels of chloride and sulfate present in Cottonwood Creek.

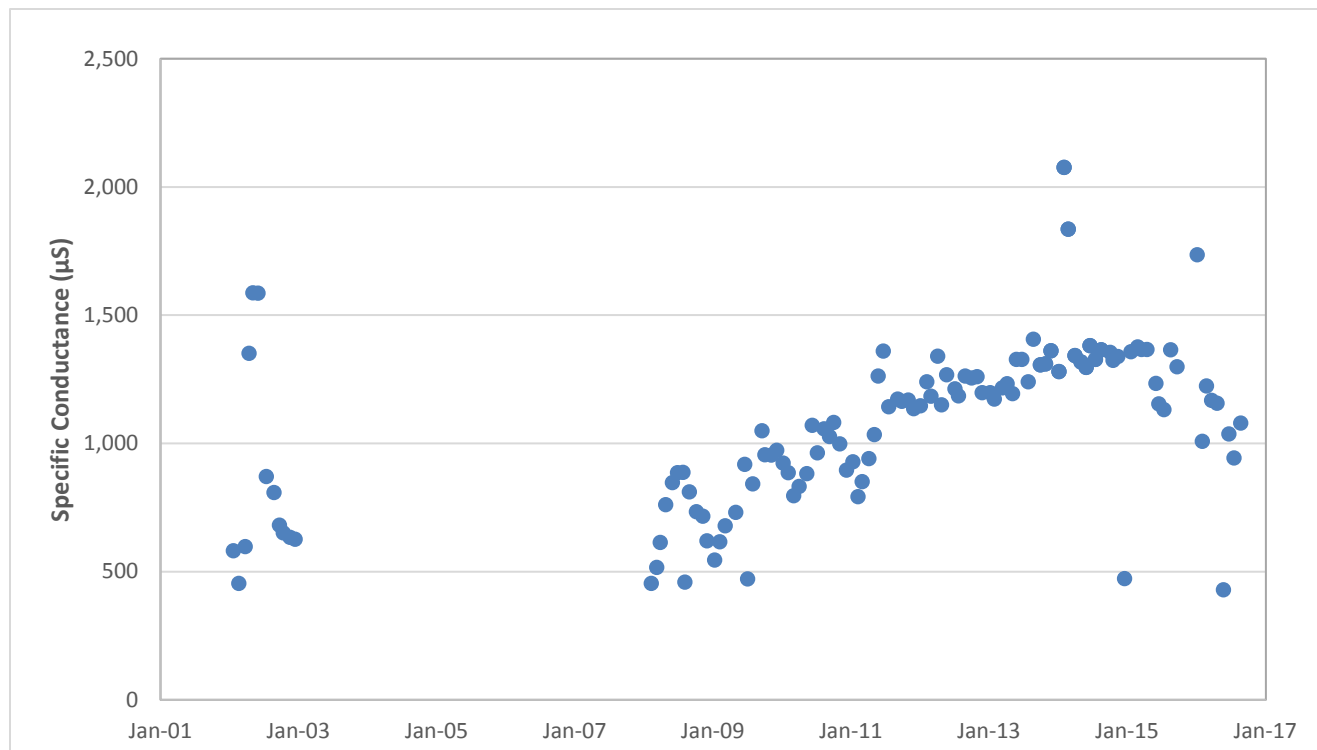


Figure ES-6. Historic specific conductance values at Cherry Creek Monitoring Site CC-10. (Sources of Data: GEI Consultants, Inc. (2001 – February 2016; IEH Analytical, Inc. (March –September 2016)

Alluvial groundwater quality indicated contrast differences in TN and TP concentrations between surface water and ground water media.

A comparison of Cherry Creek surface water and alluvial groundwater data from the May 2016 basin-wide sampling event suggested a difference in TN concentrations between the two media. The median concentrations of TN in May 2016 were 1,500 µg/L in surface water and 300 µg/L in alluvial groundwater. In contrast to TN, comparison of Cherry Creek surface water and alluvial groundwater data from the May 2016 basin-wide sampling event suggests little difference in TP concentrations between the two media, with the exception of well MW-2.

The median concentrations of TP differed little between the two media in May 2016, 207 µg/L in surface water and 214 µg/L in alluvial groundwater. Specific conductance increased in several wells (i.e., MW-1, -5, -6, -9 and Kennedy). It is likely that increases in the concentrations of sulfate and chloride in alluvial groundwater through time contributed to a portion of the observed increase in specific conductance in some wells.

Median soluble reactive phosphorus (SRP) levels in the Cherry Creek alluvial groundwater (2010 – present) were generally similar to median concentrations observed in nearby Cherry Creek surface water (approximately 200 µg/L), over ten times eutrophic levels. The Cherry Creek alluvial SRP data support the TP trend observed in May 2016, although some wells (e.g., MW-2) have historically exhibited a wide range in SRP levels. In general, upstream of the Reservoir the median SRP levels (the horizontal line located in rectangle of each box and whisker plot) in the alluvial groundwater were similar to median concentrations observed in nearby surface water (Figure ES-7), approximately 200 µg/L.

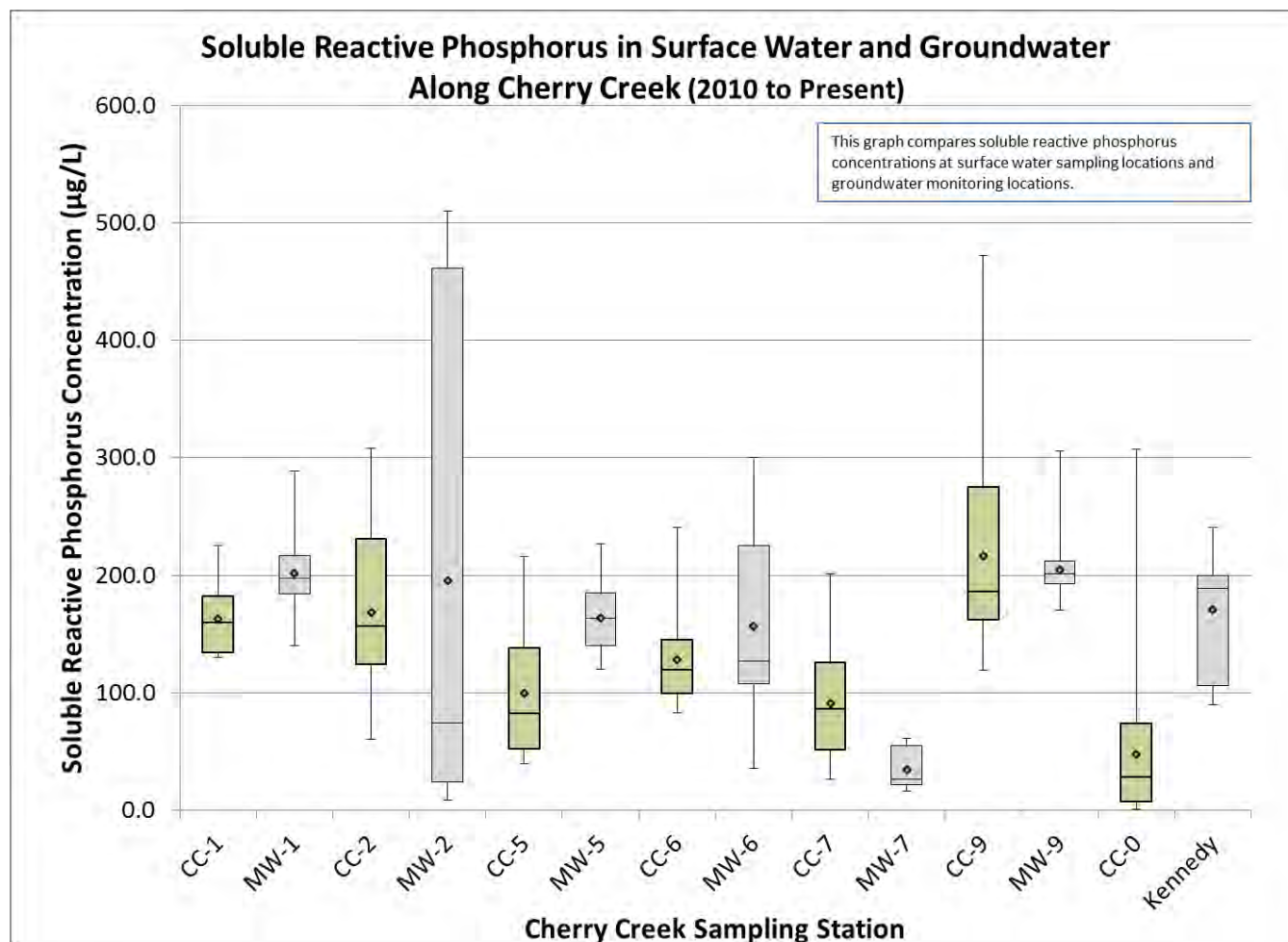


Figure ES-7. Soluble Reactive Phosphorus in Surface Water and Groundwater along Cherry Creek (2010 to Present).

(Sources of Data: GEI Consultants, Inc. (2010 – February 2016); IEH Analytical, Inc. (March 2016 – September 2016))

The observed Cherry Creek surface water inflow SRP concentrations were approximately ten times eutrophic levels, and considered too high for sustaining water quality goals, promoting an over-abundance of algae in the Reservoir.

Due to the geochemistry of the area, higher in phosphorus, the groundwater is expected to have a higher SRP concentration than the surface water. However, what was observed at some sampling stations (i.e. CC-7 and CC-9) is that the groundwater SRP levels were closer in value and less variable than the surface water, likely due in part to nonpoint sources in the surface water that increase P delivery to groundwater.

With exception, the SRP concentrations in surface water released from the Reservoir (CC-0) has historically been lower than Reservoir inflows and that in alluvial groundwater downstream of the Reservoir (alluvial well at Kennedy Golf Course).

Over the past 20 years, the concentration of SRP in the alluvial groundwater upstream of the Reservoir (well MW-9) appears to be gradually increasing (ES-8).

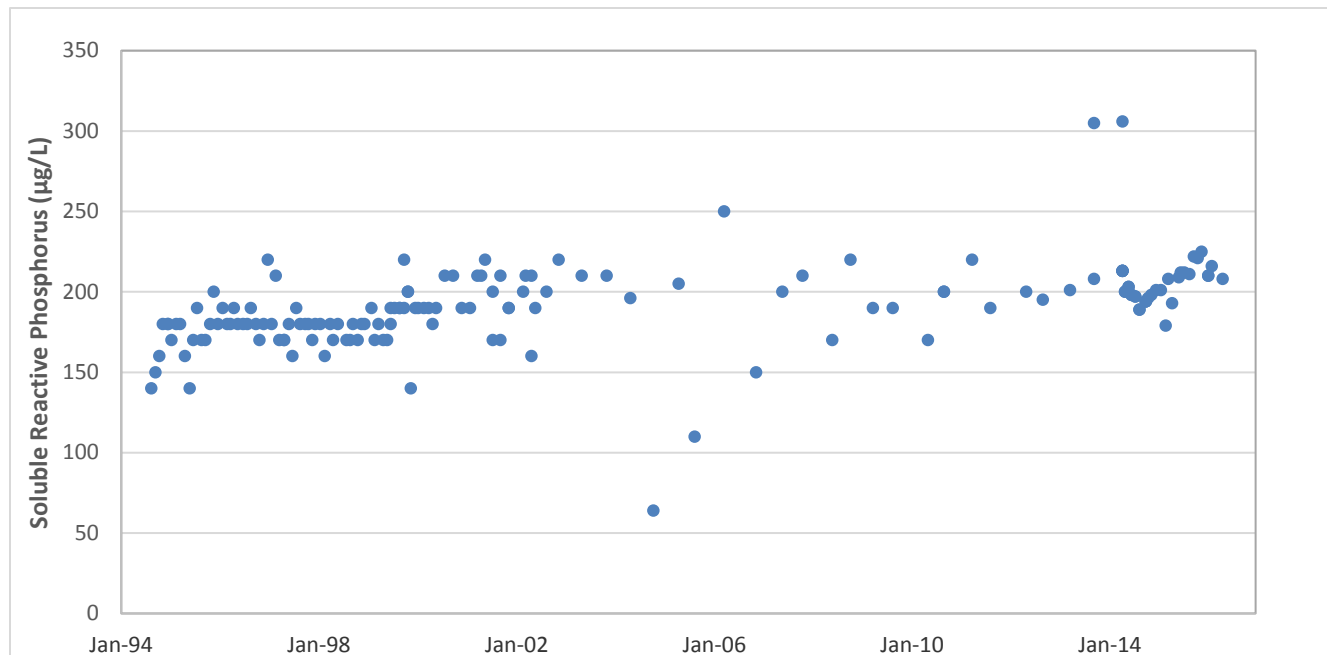


Figure ES-8. Historic SRP Concentrations in Alluvial Well MW-9 (1994 – 2016) (Sources of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (2010 – February 28, 2016); Halepaska and Associates, Inc. (1994 – 2010).

2016 Reservoir Highlights

Reservoir operations were more variable in 2016 and the higher flushing rate provided water quality benefits to the Reservoir. The US Army Corps of Engineers (USACE) operates Cherry Creek Reservoir for flood control purposes. The higher inflows from the Cherry Creek watershed resulted in higher annual pass through volume from the Reservoir outlet works, an average of 15.7 cubic feet per second (cfs), or 11,400 acre-feet. This was over three times the 57-year average daily discharge of 4.6 cfs, or 3,300 acre-feet. The increased flushing rate of the Reservoir helped water quality in 2016. While the Reservoir continued to retain much more nitrogen and phosphorus on a mass basis than it was flushing, the increased flush in the outflow provided a temporal improvement that would have otherwise resulted in greater water quality impacts to the Reservoir.

Phytoplankton and zooplankton data indicated over-productive and nutrient rich Reservoir conditions observed in 2016. Cherry Creek Reservoir continued to exhibit characteristics of an over-productive, nutrient rich Reservoir as indicated by its planktonic communities, density, pH and DO. The phytoplankton taxa included an abundance of Chlorophyta (green algae), Cyanophyta (cyanobacteria), and Bacillariophyta (diatoms) (Figure ES-9). The algal abundance (measured as cell counts/mL) for Cyanobacteria (photosynthetic bacteria, “blue green algae”) and Chlorophyta were all in excess of eutrophic levels, >10,000 cells/mL and > 3,000 cells/mL, respectively. The high cyanobacteria and green algae concentrations caused water quality issues in the Reservoir late May – September, including elevated chl-a concentrations and harmful algal blooms (HABs). The best water quality conditions were observed in the Reservoir on June 14, 2016, as reflected in the plankton data, as well as low concentrations of chl-a and TP, and greater reservoir transparency. This was also during a period of higher than normal inflow and reservoir releases.

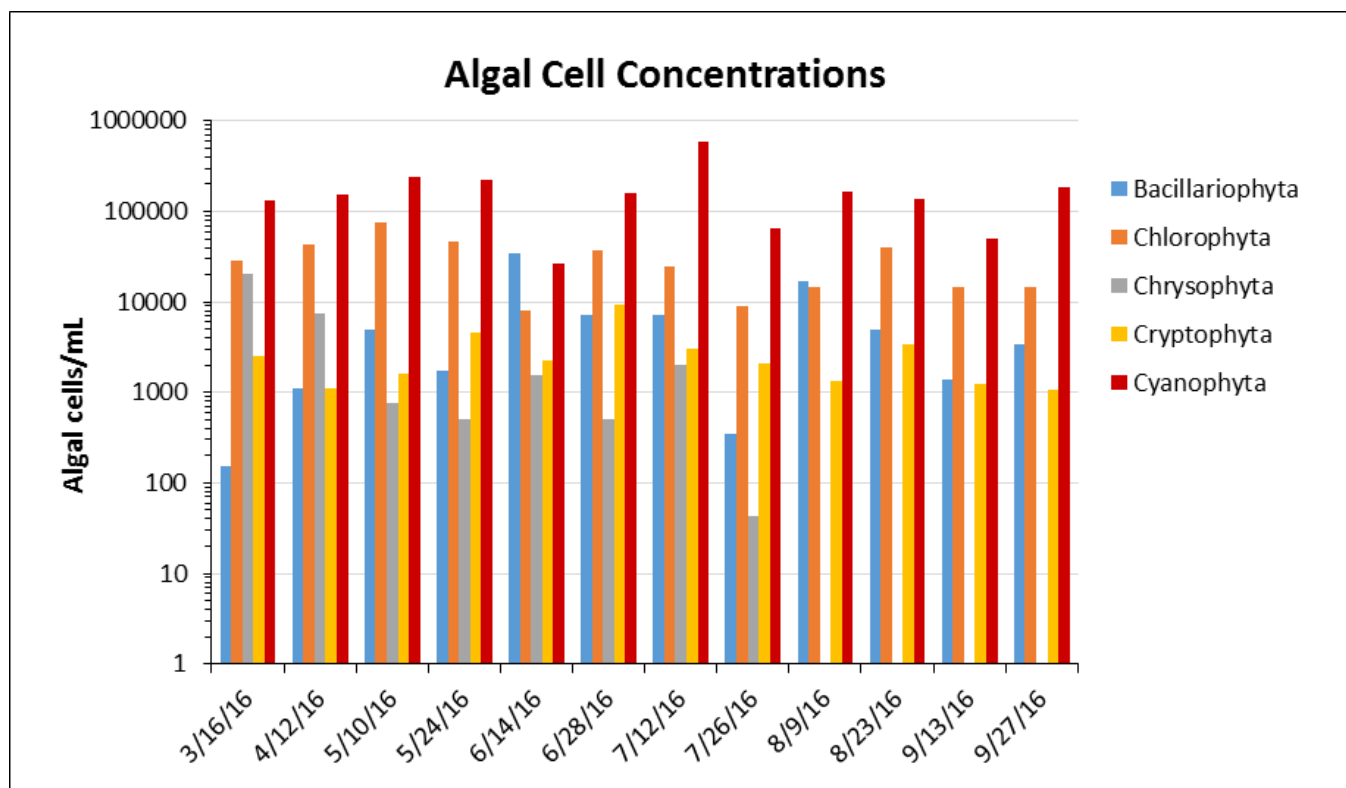


Figure ES-9. Algal Cell Concentrations Measured in Cherry Creek Reservoir in 2016. The top 5 phytoplankton taxa observed in Cherry Creek Reservoir are depicted. The algal abundance (measured as cell counts/mL) for Cyanobacteria (photosynthetic bacteria, “blue green algae”) and Chlorophyta were all in excess of eutrophic levels (Source of Data: PhycoTech, Inc.)

Chl-a accounted for the total phytoplankton community biomass and this biomass was dominated by Chlorophyta (green algae) and Bacillariophyta (diatoms) during the growing season, as depicted in Figure ES-10. A significant amount of biomass energy from phytoplankton and bacteria was also stored in the sediments as organic carbon, which contributed to excess nutrient production during this timeframe.

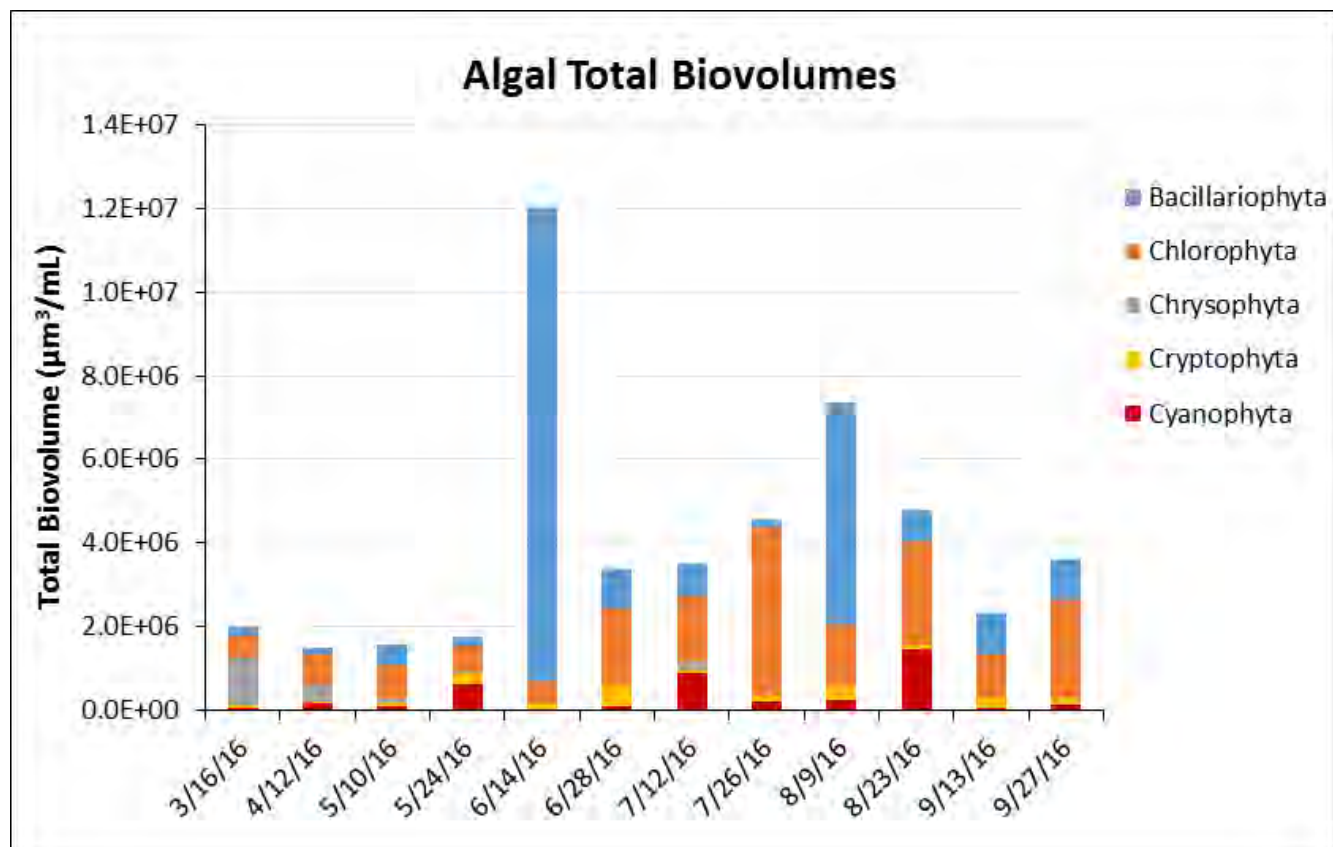


Figure ES-10. Algal Community Biomass. The algal biomass was dominated by Chlorophyta (green algae) and Bacillariophyta (diatoms) during the growing season. (Source of Data: PhycoTech, Inc.)

The 2016 zooplankton community structure was generally illustrative of a hypereutrophic system and not overly productive (biomass) relative to food base for fisheries (Figure ES-11). A generally higher Daphnid biomass was present in June and September, indicating this preferred fish food was available and abundant for the fishery. However, Bosminids, which are ten times smaller than the preferred Daphnids, were prevalent in July 2016, indicating that most of the primary production was not being used by higher aquatic biota during that period, contributing to over enrichment of the Reservoir.

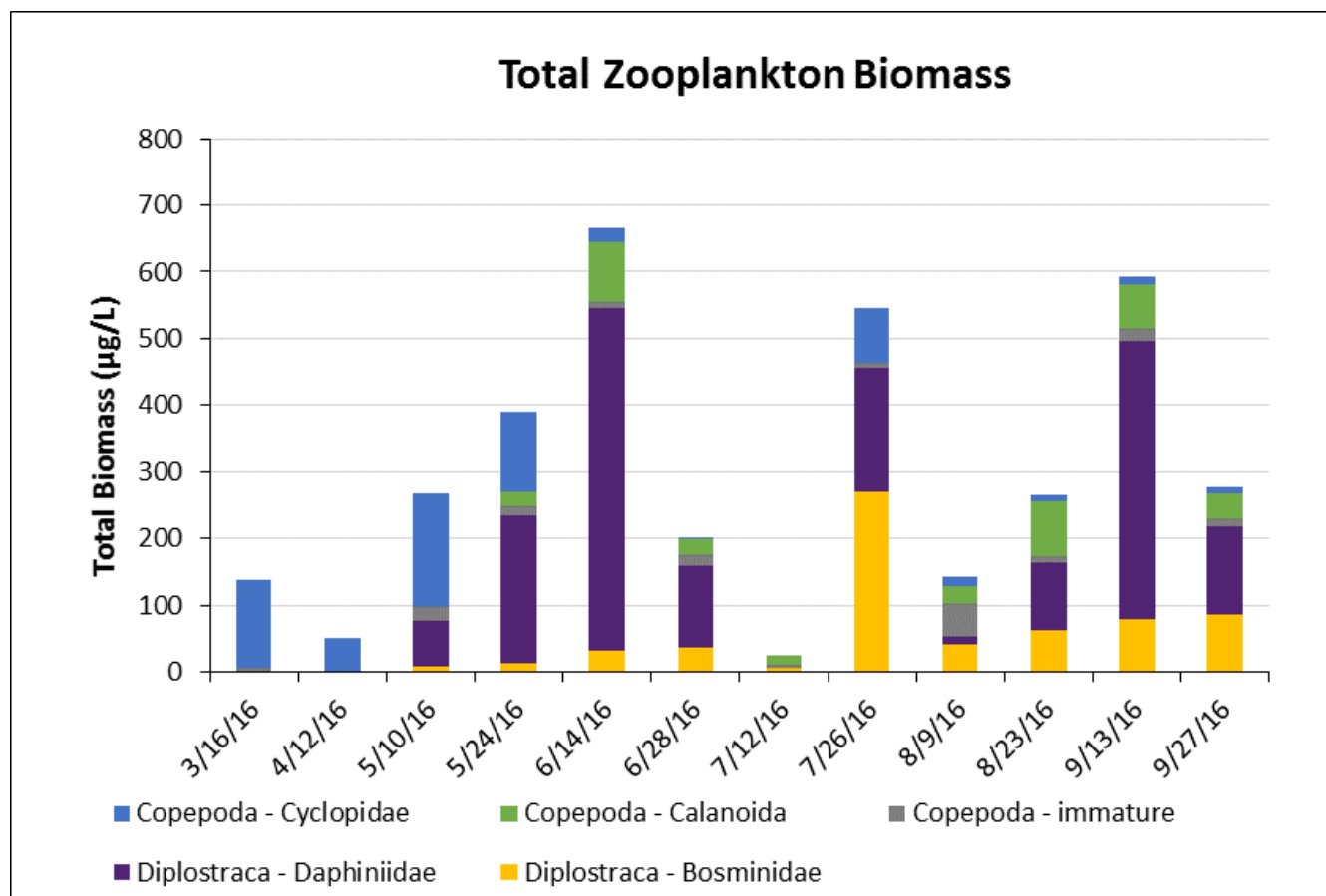


Figure ES-11. Zooplankton Biomass. A generally higher Daphnid biomass was present in June and September, indicating this preferred fish food was available and abundant for the fishery. However, Bosminids, which are ten times smaller than the preferred Daphnids were prevalent in July 2016. (Source of Data: Phycotech, Inc.)

Harmful algal blooms (HABs) observed near Marina and Tower Loop facilitated partnerships and rapid response plan between Authority and Colorado Parks and Wildlife (CPW). In late May/early June, cyanotoxic HABs were observed and measured near the Marina and Tower Loop (Figure ES-12). The spatial distribution of the Microcystin concentrations above 10 µg/L were limited and lower measurements were observed at the swim beach (less than 0.3 µg/L and non-detect (ND)). Low risk Microcystin thresholds for recreation are defined as concentrations less than 10 µg/L (US EPA, 2016; World Health Organization (WHO), 2003; Chorus, et.al, 2000). Warning signage was posted in accordance with WHO criteria.

The HAB occurrence prompted a collaborative partnership between the Authority and CPW for future cyanotoxin sampling and analysis efforts if HABs are observed in the future. The partnership is a big step for the agencies that work to protect recreation uses, aquatic life, and public safety at Cherry Creek Reservoir.

The occurrence of HABs within the Reservoir are likely to continue to occur on the periodic and unpredictable level until phosphorus is reduced in both its external and internal loading dynamics. Fortunately, the dominant cyanobacteria observed in 2016 is not known as a significant toxin producer. However, when conditions are aligned to enable other cyanobacteria to grow that have a greater potential for toxin generation there will be a HAB occurrence. This is particularly true if nutrient and light conditions within the Reservoir are such that they promote nitrogen fixing cyanobacteria to have greater dominance than is currently occurring.

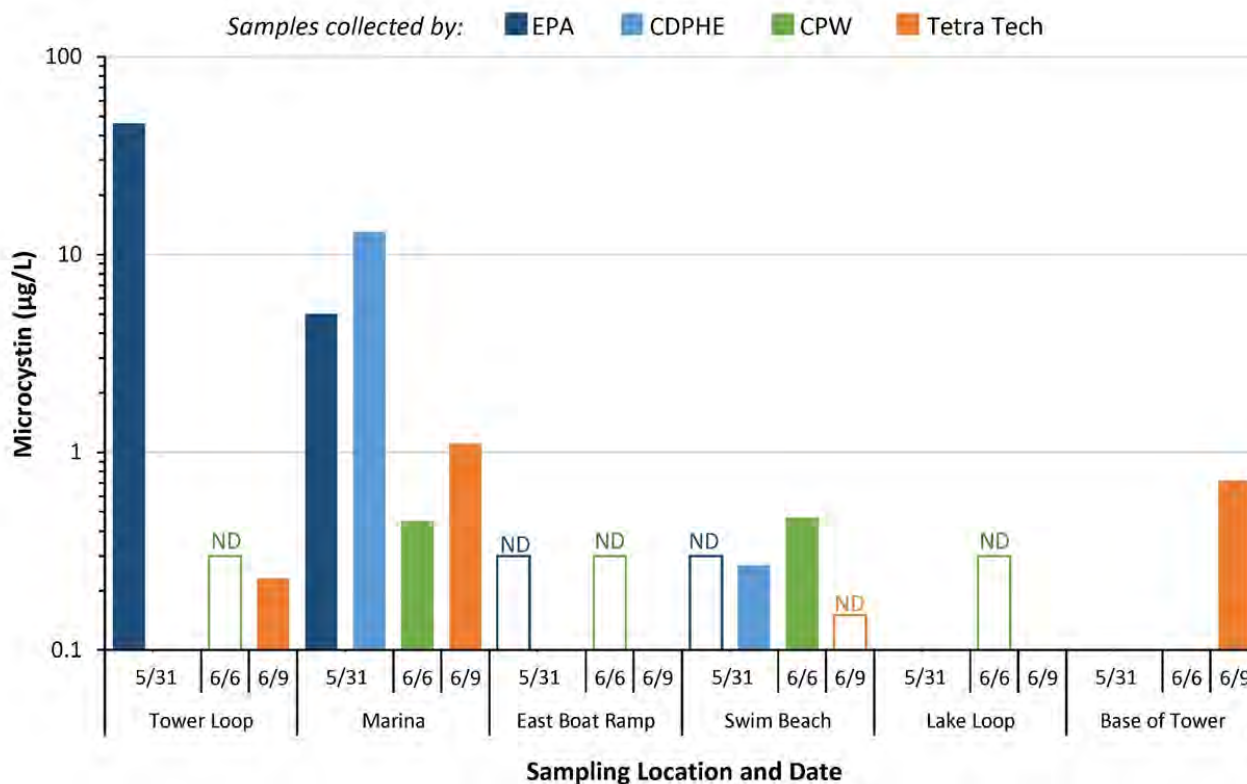


Figure ES-12. Microcystin concentrations in Cherry Creek Reservoir, May 31 - June 9, 2016. A harmful algal bloom was observed on May 31, 2016 by CPW staff. Microcystin concentrations had subsided as non-detect (ND) or less than 1 µg/L by June 9, 2016 at all six sampling locations. Samples were taken by various staff during the period of the HAB and analyzed using different methods. (CPW staff used an Abraxis Dipstick field test for rapid turnaround of Microcystin concentrations. CDPHE lab used ELISA method. EPA lab used ELISA method confirmed by HPLC/MS. Tetra Tech samples were analyzed by GreenWater Lab, using ELISA method confirmed by LC-MS/MS.)

2016 Regulatory Highlights

Temperature, pH, and dissolved oxygen (DO) in Reservoir met water quality standards. The physical data collected in Cherry Creek Reservoir, temperature, DO, and pH, were within the water quality standards for aquatic life in Warm Water 1 Lakes (WQCC Regulation #38, effective 12/31/2016). The 2016 DO profile at Cherry Creek Reservoir station CCR-2 is shown in Figure ES-13. Data demonstrated DO concentrations more than 5 mg/L throughout the majority of the Reservoir providing refuge for fish species. However, lower DO levels, measured at depths near 5 to 7 meters in June through September, were a result of the anoxic conditions that occurred in the reservoir sediments and sediment-water interface that promote internal phosphorus loading. The pH and DO compared to the temperature profiles, indicating that the chemo-stratification that is occurring is due to biological metabolic activity; namely, photosynthetic in the photic zone 0 to 3 meters and respiration at deeper depths.

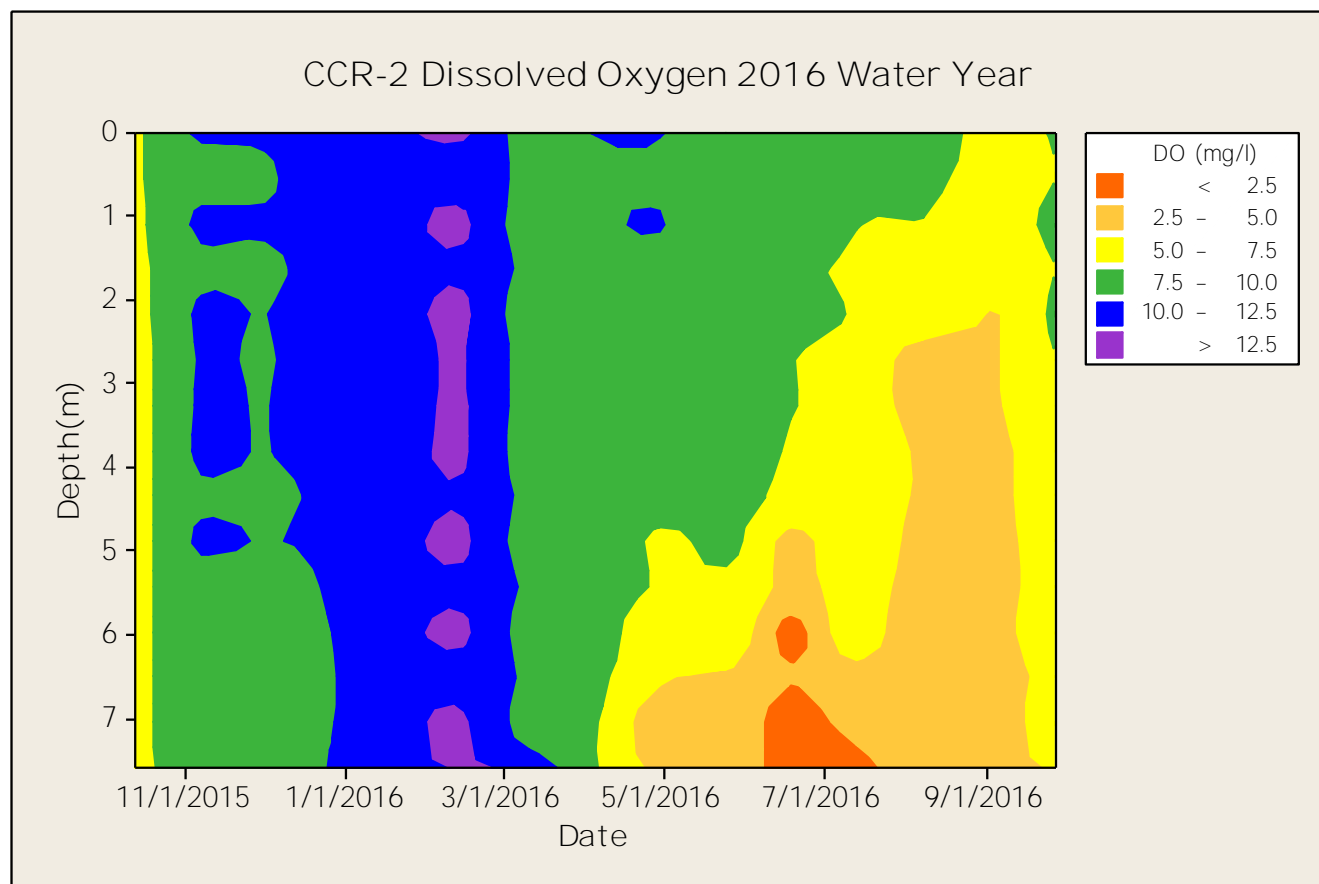


Figure ES-13. DO Profile at Cherry Creek Reservoir Monitoring Station CCR-2 (2016). DO was above 5 mg/L at more shallow depths, providing refuge for the fishery. However, lower DO levels (less than 5 mg/L) were measured at depths near 5 to 7 meters in June through September, a result of the anoxic conditions in the sediment water interface. (Sources of Data: Tetra Tech, (March 1 2016 - September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016))

Chlorophyll-a growing season standard was exceeded. The Reservoir chl-a growing season (July through September) concentration was 23.6 $\mu\text{g/L}$, in exceedance of the 18 $\mu\text{g/L}$ growing season average regulated for chl-a. The seasonal mean concentration is measured in the upper three meters of the water column (photic zone), with an exceedance frequency of once in five years. The Reservoir has exceeded the chl-a standard in four of the last five years (Figure ES-14).

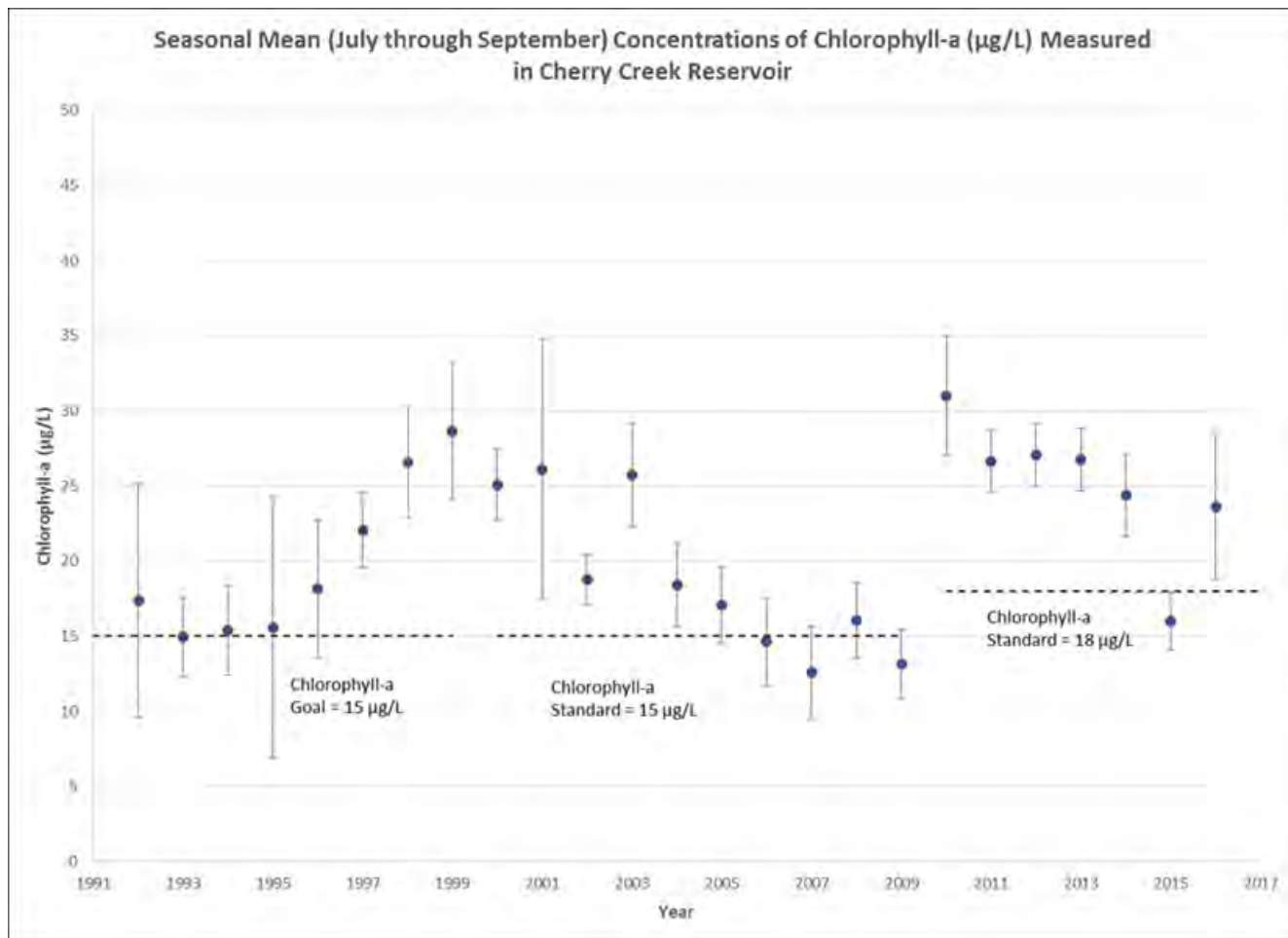


Figure ES-14. Chl-a Growing Season Concentrations in Cherry Creek Reservoir, 1992 – 2016. The chl-a growing season average in 2016 was 23.6 $\mu\text{g/L}$, in exceedance of the water quality standard, 18.0 $\mu\text{g/L}$, with a 1 in 5 year exceedance frequency. (Sources of Data: IEH Analytical (2016); GEI Consultants (2006 – 2015); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).)

Nutrient concentrations in Reservoir were elevated, representative of inflow concentrations, sediment recycling, and algal biomass (as chl-a). Average TP and TN concentrations measured in the Reservoir photic zone during the growing season were 122 $\mu\text{g/L}$ and 897 $\mu\text{g/L}$, respectively. A portion of both TP and TN settled to the bottom sediments, now having several years to recycle several times into the Reservoir before they are flushed in the outflow or sequestered into the Reservoir sediments and no longer available to be recycled. Elevated nutrient concentrations coupled with nutrient recycling in the sediments, supported the growing season chl-a concentrations observed in the Reservoir, 23.6 $\mu\text{g/L}$.

2016 Net Nutrient Loading Highlights

Nearly 3 tons of TP was retained in the Reservoir in 2016. Surface water inflow from Cherry Creek was the dominant source of water (and TP load) to the Reservoir. In WY2016, Cherry Creek provided 64% of the 25,014 acre-ft of water that flowed into the Reservoir, with Cottonwood Creek providing an additional 15%. The relative contribution of the inflows to the Reservoir in WY2016 are illustrated in Figure ES -15. Inflows and outflows to/from the Reservoir were approximately equaled in WY2016, with the year-end reservoir storage with 26 ac-ft more water than it began the water year with.

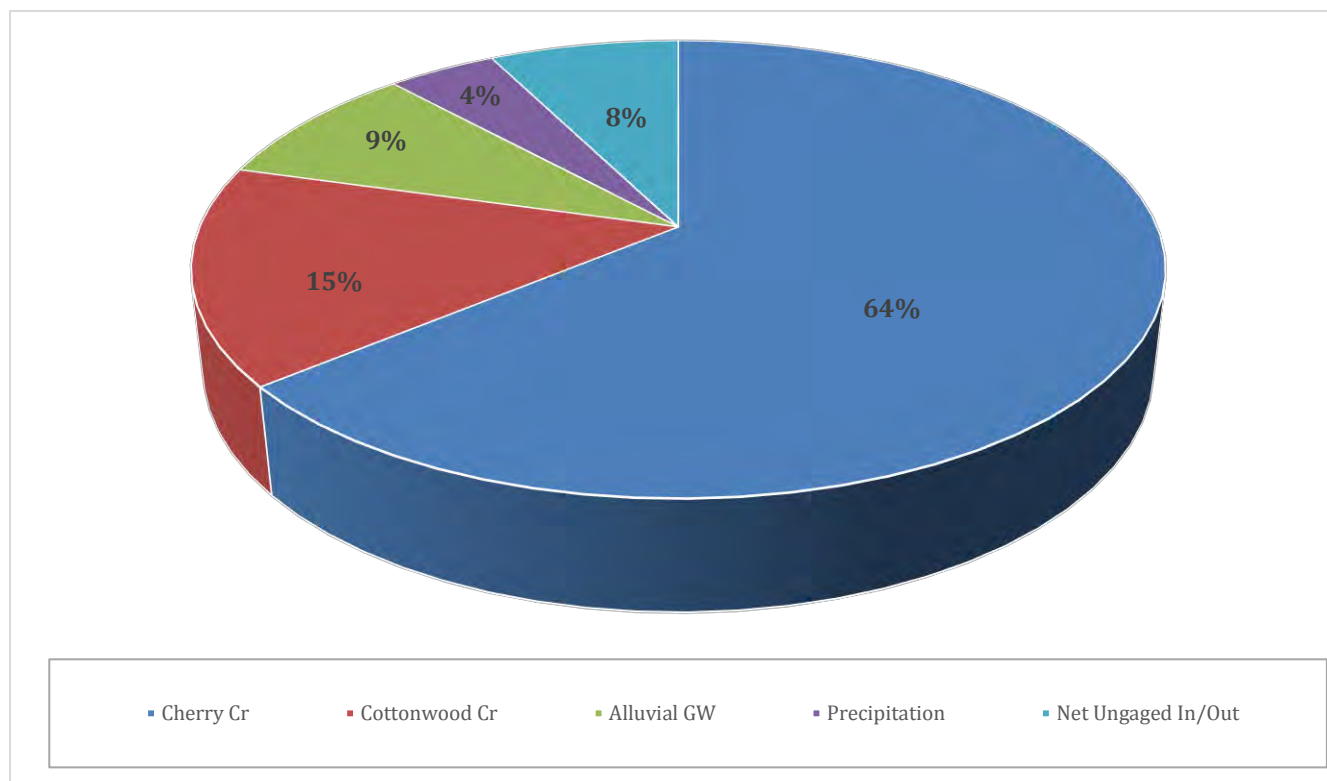


Figure ES-15. Relative Contribution of Cherry Creek Inflows to Reservoir Water Balance in WY2016.

During WY2016 the flow weighted TP concentration was 213 µg/L and an estimated 14,783 pounds (7.4 tons) of phosphorus was delivered to the Reservoir. The relative contributions of the phosphorus loads to the Reservoir in WY2016 are illustrated in Figure ES-16. The relative contribution Cherry Creek to phosphorus loads, 82%, exceeds its relative water contribution, while that of Cottonwood Creek is less. A net 5,627 pounds (2.8 tons) of TP is estimated to have been retained in the Reservoir, available for TP recycling within the Reservoir. TP loads were larger than those observed in long-term trends, with the 2011-2015 median of 200 µg/L.

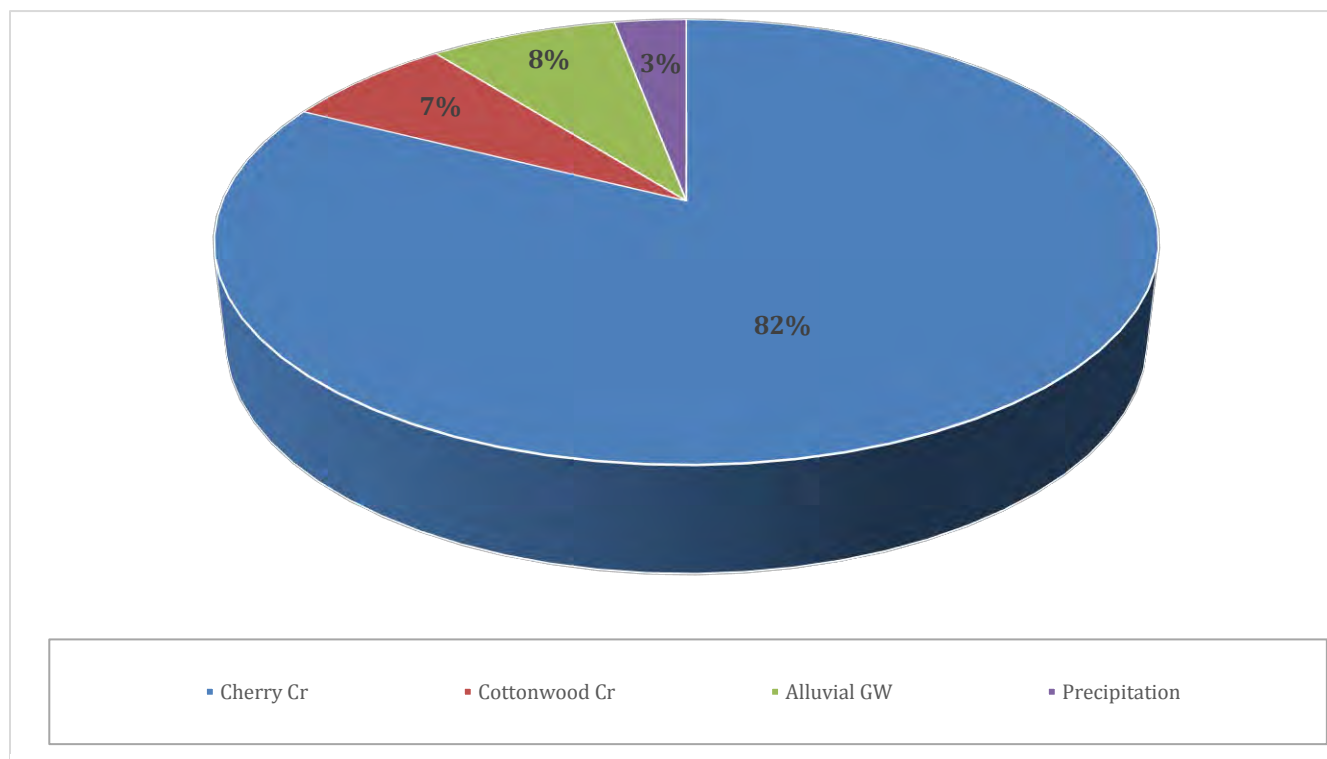


Figure ES-16. Relative Contribution of Cherry Creek Inflows to Reservoir Phosphorus Balance in WY2016.

A net 20,992 pounds (10.5 tons) of nitrogen is estimated to have been retained in the Reservoir in WY2016. An estimated 81,619 pounds (40.8 tons) of nitrogen was delivered to the Reservoir, with a flow weighted concentration of 1,175 µg/L, well below the 2011-2015 median of 1,344 µg/L. The relative contributions of the nitrogen loads to the Reservoir are illustrated in Figure ES-17. The relative contribution of Cherry Creek to nitrogen is roughly equivalent to its relative water contribution, while that of Cottonwood Creek is much greater.

A net 20,992 pounds (10.5 tons) of nitrogen is estimated to have been retained in the Cherry Creek Reservoir in WY2016. In contrast, the overall WY2016 flow-weighted total nitrogen concentration of 1,175 µg/L is higher than the WY2015 value of 1,057 µg/L. Like phosphorus, the WY2016 total nitrogen loads are similar to those calculated in WY2015 and the loads in both WY2015 and WY2016 are larger than those observed in long-term trends.

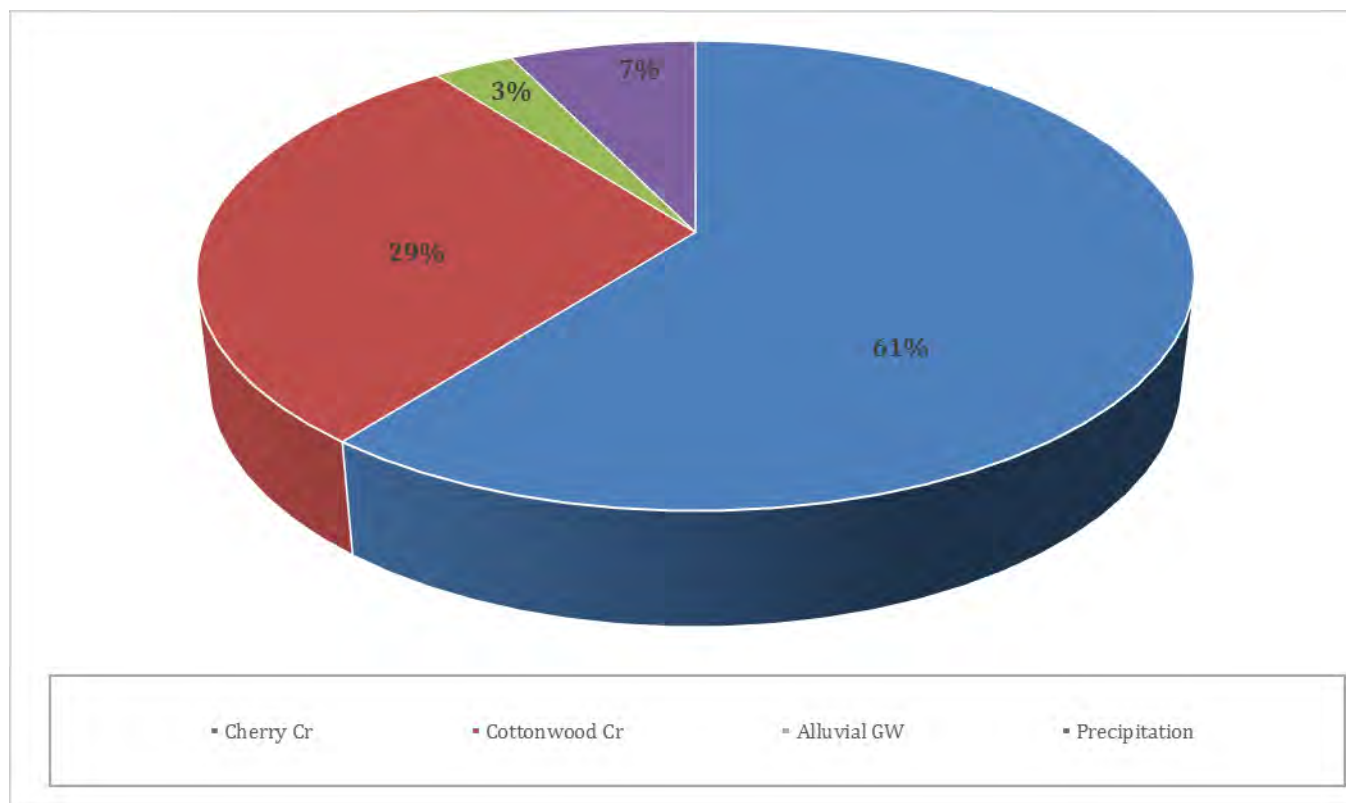


Figure ES-17. Relative Contribution of Cherry Creek Inflows to Reservoir Nitrogen Balance in WY2016.

2017 Next Steps and Recommendations

The Reservoir is getting more productive as time goes on due to the natural progression of man-made lakes, elevated nutrient concentrations observed within the watershed (particularly from Cherry Creek) and recycled nutrients in the Reservoir sediments that are 2 -100 times that of the flushing rate under current conditions in the Reservoir.

Opportunities for water quality improvement exist. Ongoing management of both external (in watershed) and internal (in-reservoir) nutrient concentrations and loads, through strong partnerships with local, state, and federal stakeholders, will support lower productivity in the Reservoir to promote long term protection of beneficial uses.

2017 monitoring recommendations support program objectives. The following next steps are recommended in 2017 to support the monitoring program, data collection and water quality benefits.

- Wetland Harvesting – Commence wetland harvesting and monitoring at Shop Creek PRF (SC-1 and SC-2) to understand the nutrient reduction benefits of this maintenance program. Similar vegetation harvesting is also recommended for the Cottonwood wetlands at CT-2 to promote additional pollutant reduction effectiveness.
- Split Sampling - Continue split sampling of nutrients and chl-a to support QAPP and parametric and nonparametric statistical evaluations to understand and quantify inter-lab variability.
- Replace Stream Gaging Equipment at Strategic Locations - Replace continuous monitoring hardware at CC-10 and CT-2.

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APPENDICES

APPENDIX A – SUMMARY OF CHERRY CREEK BASIN DESIGNATED USES AND WATER QUALITY STANDARDS (REG 38)

APPENDIX B – CHERRY CREEK SAMPLING AND ANALYSIS PLAN/QUALITY ASSURANCE PROTOCOLS AND PRECEDURES, 2016

APPENDIX C – SPLIT SAMPLE ANALYSIS

APPENDIX D – STREAMFLOW DATA, EQUATIONS AND HYDROGRAPHS

APPENDIX E- USACE DATA

APPENDIX F – WATER QUALITY DATA

APPENDIX G – PHYCOLOGY DATA

ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
Ac-ft	Acre-feet
CCR	Code of Colorado Regulations
CDPHE	Colorado Department of Public Health and Environment
CPW	Colorado Parks and Wildlife
cfs	Cubic feet per second
Chl-a	Chlorophyll a
CR72	Control Regulation 72
DO	Dissolved Oxygen
ELISA	Enzyme-Linked Immunosorbent Assays
HPLC/MS	High performance liquid chromatography combined with mass spectrometry
LC-MS/MS	Liquid chromatography followed by a combination of two mass spectrometry analyzers
mg/L	Milligrams per liter
µg/L	Micrograms per liter
ND	Non-detect
%	Percent
POR	Period of record
PRF	Pollutant Reduction Facilities
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Procedures and Protocols
SAP	Sampling and Analysis Program
SM	Standard Methods
SRP	Soluble Reactive Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
USACE	U.S. Army Corps of Engineers
US EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WHO	World Health Organization
WQCC	Water Quality Control Commission

1.0 INTRODUCTION

The Cherry Creek watershed (watershed) includes over 386 square miles of land and 600 stream miles (Figure 1). The 875-acre Cherry Creek Reservoir (Reservoir), located at the downstream terminus, is one of the most productive fisheries and widely enjoyed recreational areas in Colorado. The Reservoir, operated by the U.S. Army Corps of Engineers for flood control, also supports downstream agriculture and water supplies. Protecting the beneficial uses of the Reservoir are paramount.

The Water Quality Control Commission (WQCC) has adopted specific water quality standards for the Reservoir, Cherry Creek, Cottonwood Creek and other watershed tributaries to protect recreation, aquatic life, agriculture and water supply uses. Excerpts from Regulation #38, (5 CCR 1002-38, effective June 30, 2016) summarizing water quality standards pertinent to the Cherry Creek Basin is provided in Appendix A.

In accordance with Cherry Creek Reservoir Control Regulation #72 (5 CCR 1002-72, (CR72), the Authority implements a routine annual water quality monitoring program of the watershed and Reservoir to characterize water quality of inflows and the Reservoir and determine regulatory compliance. This report describes the Authority's monitoring effort, the 2016 data, and evaluation of results.

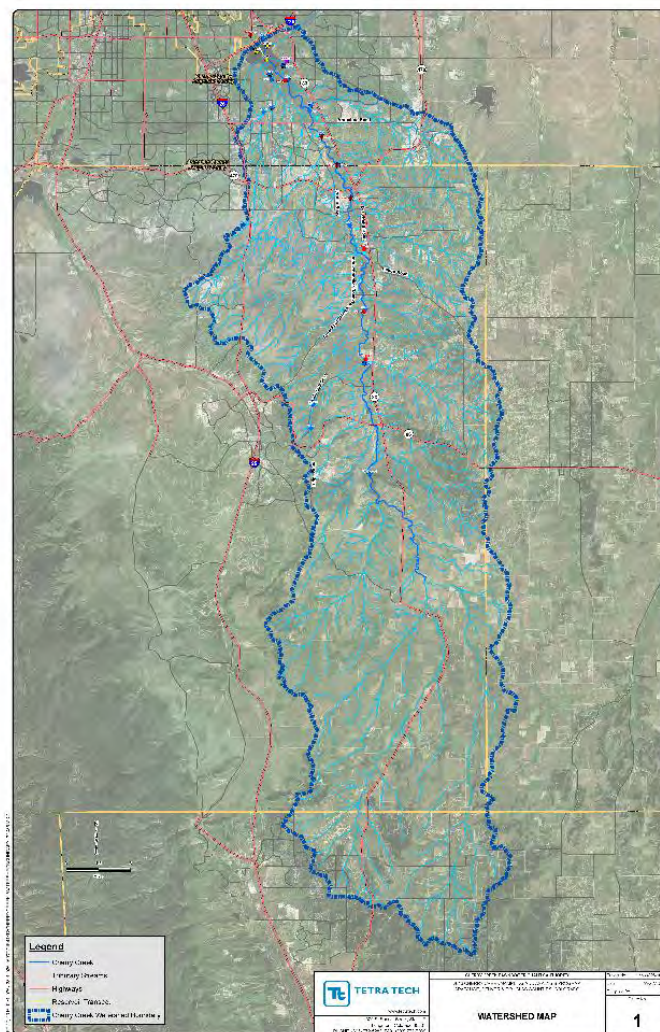


Figure 1. Cherry Creek Basin Watershed Map. The watershed is 386 square miles in size, with over 600 stream miles.

2.0 MONITORING PROGRAM

The monitoring program (“program”) is conducted in accordance with the Cherry Creek Sampling and Analysis Program and Quality Assurance Procedures and Protocols (SAP/QAPP, updated May 2016; Appendix B). The program includes characterization of the Reservoir water quality, inflow volumes, alluvial water quality, nonpoint source flows, and pollutant reduction facilities (PRF). The reservoir, precipitation, and watershed (surface water, groundwater, and PRF) sampling locations are depicted on Figure 2. Tables 1, 2, and 3 summarize program analytes at each monitoring site and sampling frequency.

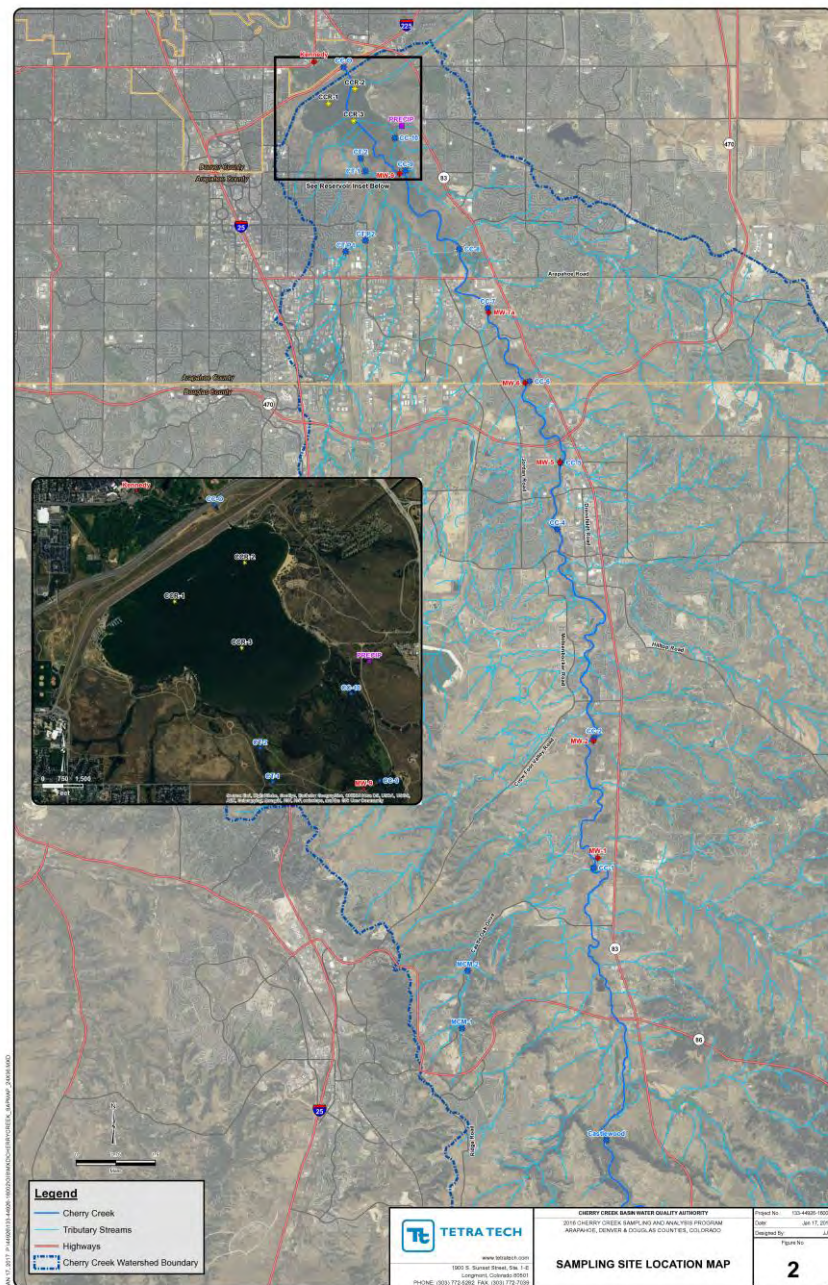


Figure 2. Sampling Location Map (Source: Tetra Tech, Inc.)

Table 1. Reservoir Sampling Parameters, Frequency, and Sites

Analyte	Monthly Nutrient-Biological Samples (Photic Zone)		Monthly Nutrient Profile (4m-7m)	Bi-monthly Sonde & Nutrient Samples (May- Sept)
	CCR-1, CCR-3	CCR-2	CCR-2	CCR-1, CCR-2, CCR-3
Total Nitrogen	√	√	√	√
Total Dissolved Nitrogen	√	√	√	√
Ammonia as N	√	√	√	√
Nitrate + Nitrite as N	√	√	√	√
Total Phosphorus	√	√	√	√
Total Dissolved Phosphorus	√	√	√	√
Orthophosphate as P	√	√	√	√
Total Organic Carbon		√	√	√
Dissolved Organic Carbon		√	√	√
Total Volatile Suspended Solids	√	√		√
Total Suspended Solids	√	√		√
Chlorophyll <i>a</i>	√	√		√
Phytoplankton		√		√
Zooplankton		√		√

Table 2. Rain Gage Sampling Parameters

Analyte	CCR-Precip
Total Nitrogen	√
Total Dissolved Nitrogen	√
Ammonia as N	√
Nitrate + Nitrite as N	√
Total Phosphorus	√
Total Dissolved Phosphorus	√
Orthophosphate as P	√

Table 3. Stream and Groundwater Sampling Parameters, Frequency, and Sites

Analyte	Monthly Surface Water Samples	Storm Event Surface Water ISCO Samples	Bi-annual Surface Water Samples	Bi-annual Groundwater Samples
	9 sites (CC-0, CC-10, CC-7-EcoPark, CT-1, CT-2, CT-P1, CT-P2, MCM-1, MCM-2)	6 sites (CC-10, CC-7-EcoPark, CT-1, CT-2, CT-P1, CT-P2,)	8 sites (Castlewood, CC-1, CC-2, CC-4, CC-5, CC-6, CC-8, CC-9)	8 sites (MW-1, MW-2, MW-3c, MW-5, MW-6, MW-7a, MW-9, Kennedy)
Total Nitrogen	√	√	√	√
Total Dissolved Nitrogen	√	√		
Ammonia as N	√	√	√	√
Nitrate + Nitrite as N	√	√	√	√
Total Phosphorus	√	√	√	√
Total Dissolved Phosphorus	√	√	√	√
Orthophosphate as P	√	√	√	√
Chloride			√	√
Sulfate			√	√
Total Organic Carbon				√
Dissolved Organic Carbon				√
Total Volatile Suspended Solids	√	√		
Total Suspended Solids	√	√		

2.1 MONITORING OBJECTIVES

The program was designed to understand and quantify the relationships between nutrient loading (both in-lake and external) and Reservoir productivity. The routine monitoring of surface water and groundwater is implemented to promote the concentration based management strategy for phosphorus control in the basin, and determination of the total annual flow-weighted concentration of nutrients to the Reservoir, evaluation of watershed nutrient sources and transport mechanisms, and effectiveness of PRFs and BMPs in the basin.

The specific objectives of the program include the following:

- Assess protection of beneficial uses and compliance with water quality standards.
- Determine base flow and storm flow concentrations for nitrogen and phosphorus in tributary inflows, as well as concentrations in the Reservoir and the outflow.

- Determine the hydrological inflows and nutrient loads entering the Reservoir, including Reservoir exports.
- Determine the annual flow-weighted phosphorus concentration and changes to the concentrations entering the Reservoir from streams and precipitation and the phosphorus export from the Reservoir via the outlet structure.
- Determine biological productivity in the Reservoir, as measured by algal biomass (chl-a concentration), and species composition of the plankton community.
- Evaluate relationships between the biological productivity and nutrient concentrations within the Reservoir and total inflows.
- Assess the effectiveness of pollutant reduction facilities (PRFs) on Cottonwood Creek and McMurdo Gulch to reduce phosphorus loads into the Reservoir.

The program has also supported other complimentary Authority activities over the years, such as calibration of the Reservoir water quality model, determining water quality effectiveness of Authority owned PRFs and additional non-specified monitoring determined by the Authority to be supportive of Authority long term goals for the Reservoir and watershed that promote protection of beneficial uses and preservation and enhancement of water quality.

2.2 SAP/QAPP

The SAP/QAPP (Sample and Analysis Plan/Quality Assurance Project Plan) provides the foundation for all sampling and analysis program activities, including sampling methods, QA/QC (quality assurance/quality control) protocols, etc. All monitoring and analytical work are performed in accordance with this document, provided in Appendix B.

In 2016, a variety of field procedure refinements were implemented (e.g., improve sampling methodology for plankton samples, discontinuance of certain monitoring locations due to access issues, etc.). The QAPP documents the 2016 refinements and approaches used to manage change in the dynamic program. The refinements to the program recognize opportunities to enhance the integrity of the data to promote sound science and limnology, while maintaining the dynamic nature of the program and changes that are warranted from time to time based on:

- Monitoring objectives being met,
- New objectives being formulated,
- Changes to sampling methodology,
- Duplicative efforts and opportunities to reduce costs,
- Meeting regulatory objectives or regulatory changes,
- Opportunities to improve quality of data and sampling methodology to reflect sound science and limnology.

2.2.1 Laboratory Analyses

Analytical services were provided by a variety of accredited laboratories in accordance with laboratory QA/QC protocols outlined in the QAPP prepared by each respective laboratory to meet state certification requirements. Table 4 summarizes laboratories utilized during the 2016 program.

Table 4. Laboratories Responsible for Analyzing Samples (2016 Labs)

Laboratory/Manager	Analytical Services
IEH Analytical, Inc., Damien Gadowski, Ph.D.	Nutrients, inorganics, organics, and chl-a.
PhycoTech, Inc., Ann St. Amand, Ph.D.	Phytoplankton and Zooplankton, identification, enumeration, concentration, biovolume and biomass.
GEI Consultants, Inc., Ecological Division, Ms. Sarah Skigen	Nutrients, inorganics, organics, and chl-a.
GreenWater Laboratory, Inc., Mark Aubel, Ph.D.	Cyanotoxins

As part of the QA/QC protocol, nutrient and chl-a samples were split between IEH Analytical and GEI Consultants to understand lab variability and data comparability. A preliminary evaluation of the comparability of TP and TN between labs (with limited sample size) are within margin of error, approximately 20%. However, chl-a, TDP, and SRP concentrations were more variable amongst the two laboratories.

For chl-a there are noted differences between laboratories in standard method of analysis (SM 10200 H (IEH) and modified SM 10200 H with hot ethanol extraction (GEI)) and sampling containers provided by the lab (amber glass (IEH) and clear plastic cubitainer (GEI)) that may contribute to differences in results. The chl-a standard methods of analysis employed by IEH and GEI are both approved by the Colorado Department of Public Health and Environment (WQCC Regulation No. 85, effective 9/30/12). The amber glassware used by IEH may mitigate the potential post-collection chl-a growth. The chl-a concentrations are consistently lower with IEH (amber glassware) and may bear out the differences in sample preservation.

Over the course of the coming years, additional split sampling of nutrients and chl-a is recommended to increase sample size between labs to facilitate parametric and non-parametric statistical evaluations of data and compare results between labs to help us understand the inter-laboratory variability and relationship between historic data and current data for nutrient parameters and chl-a (see Appendix C, Split Sample Analysis).

3.0 DATA AND RESULTS

The monitoring program is comprised of data and results from the (1) watershed (including water quality and quantity of surface water, groundwater, stormwater, and pollutant reduction effectiveness of PRFs) and (2) Reservoir. The 2016 water quality data and results are described herein and made available on the Authority's website, www.cherrycreekbasin.org.

3.1 WATERSHED

The watershed-wide water quality monitoring program evaluated the location, timing, and magnitude, quantity and quality, of nutrient sources to the Reservoir. The surface water and groundwater monitoring program data contains the following elements:

- Routine surface water sampling results, including PRF effectiveness.

- Storm event sampling results.
- Groundwater sampling results.

During WY2016, 18 surface water sites were monitored on a monthly to semi-annual basis (Table 3) and some were included in a storm event monitoring program.

The USACE performed its annual operational check and flushing of the of the Reservoir outlet works on June 1, 2016. The USACE individually operated the gates between 0900 and 1400 on June 1 and the discharge in Cherry Creek downstream of the Reservoir increased from approximately 50 cfs to approximately 1,300 cfs in five separate pulses. An estimated 218 ac-ft of water, above that which would have been released had the discharge be held steady at 50 cfs, was released from the Reservoir during the test. The Reservoir level decreased 0.22 feet as a result of the releases.

3.1.1 Surface Water

During WY2016 the Cherry Creek surface water monitoring sites were routinely sampled monthly or twice per year (Table 3). Additionally, six of the monitoring sites were included in the storm event program. In the WY2016 storm event program, runoff generated from storm events was sampled up to seven times at four locations in Cottonwood Creek and two locations in lower Cherry Creek.

3.1.1.1 Stream Flows

The U.S. Geological Survey (USGS) has operated two gaging stations on Cherry Creek upstream of the Reservoir for numerous years. The Cherry Creek near Franktown gage (number 0671200) has a 76 year period of record (POR) and the Cherry Creek near Parker gage (number 393109104464500) has a 25 year POR. The Authority operates two gaging stations upstream of the Reservoir at surface water monitoring sites CC-7 (Eco Park) and CC-10. The Authority's gage locations are illustrated on Figure 2.

The USGS's Cherry Creek near Franktown gage is located just upstream of the Authority's Castlewood monitoring location and has a drainage area of 169 mi². The WY2016 flows at the USGS Franktown gage totaled 4,395 ac-ft, with an average daily discharge rate of 6.1 cfs. The WY2016 average rate was approximately 30% higher than the long-term (WY1940-WY2016) average daily rate of 4.6 cfs. The WY2016 daily hydrograph for the Cherry Creek near Franktown gage is illustrated, along with the 76 year POR mean daily flow, on Figure 3.

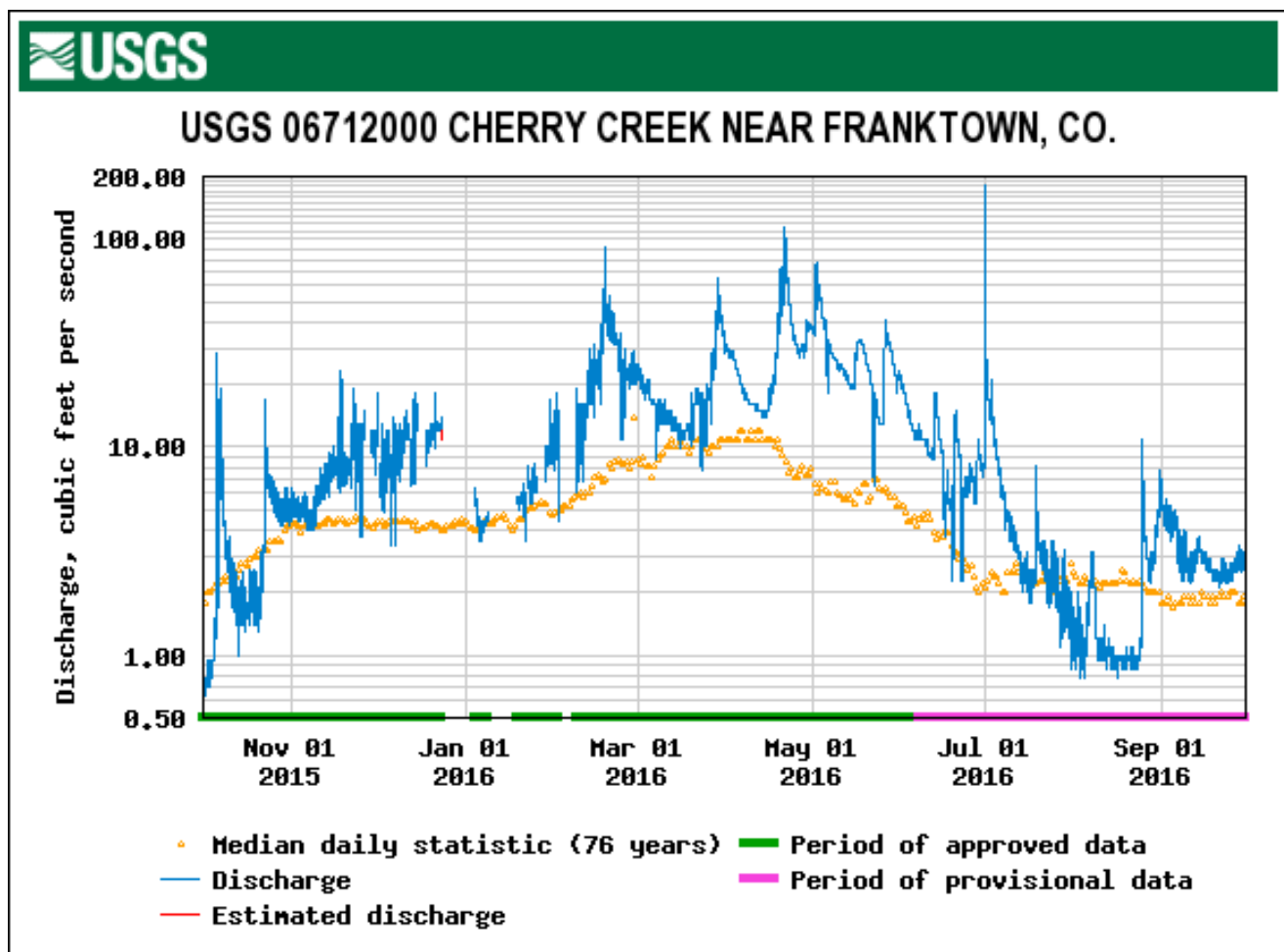


Figure 3. WY2016 Hydrograph and Historical Median Flows for USGS Gage near Franktown (Source: <http://waterdata.usgs.gov/nwis/uv?06712000>)

The USGS Cherry Creek near Parker gage is located approximately nine miles upstream of the Reservoir, about ½ mile upstream of Authority monitoring site CC-4, and has a drainage area of 287 mi². The WY2016 flows at the USGS Parker gage totaled 4,908 ac-ft, with an average daily discharge rate of 6.8 cfs. The WY2016 average rate was approximately 21% higher than the long-term (WY1992-WY2016) average daily rate of 5.6 cfs. The WY2016 daily hydrograph for the USGS Parker gage is illustrated, along with the 25-year POR mean daily flow, on Figure 4.

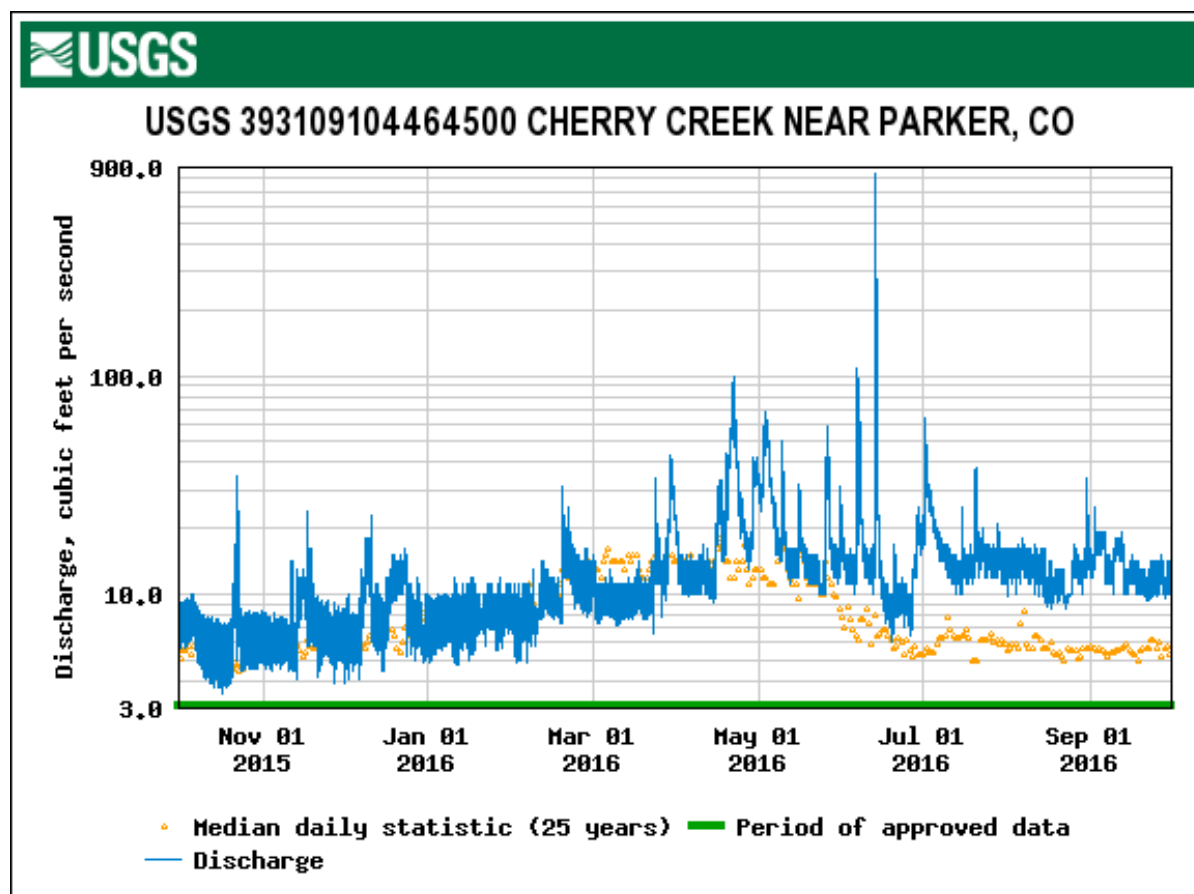


Figure 4. WY2016 Hydrograph and Historical Median Flows for USGS Gage near Parker (Source: <http://waterdata.usgs.gov/nwis/uv?393109104464500>)

Above average flows were measured at both USGS gaging stations in WY2016. These flows are in contrast to the slightly below average precipitation measured at the nearby Centennial Airport weather station (KAPA) in WY2016, 15.3 inches, which was 93% of average. Even more anomalous, the July through September precipitation total was only 44% of average (Figure 5), yet streamflow at the USGS gage near Parker remained approximately twice the historical mean for this period (Figure 4). However, review of precipitation data for the entire basin (<http://water.weather.gov/precip/>) suggests that the southern (upper) portion of the basin may have received substantially more precipitation in WY2016 than the northern portion of the basin where the Authority's monitoring efforts are focused.

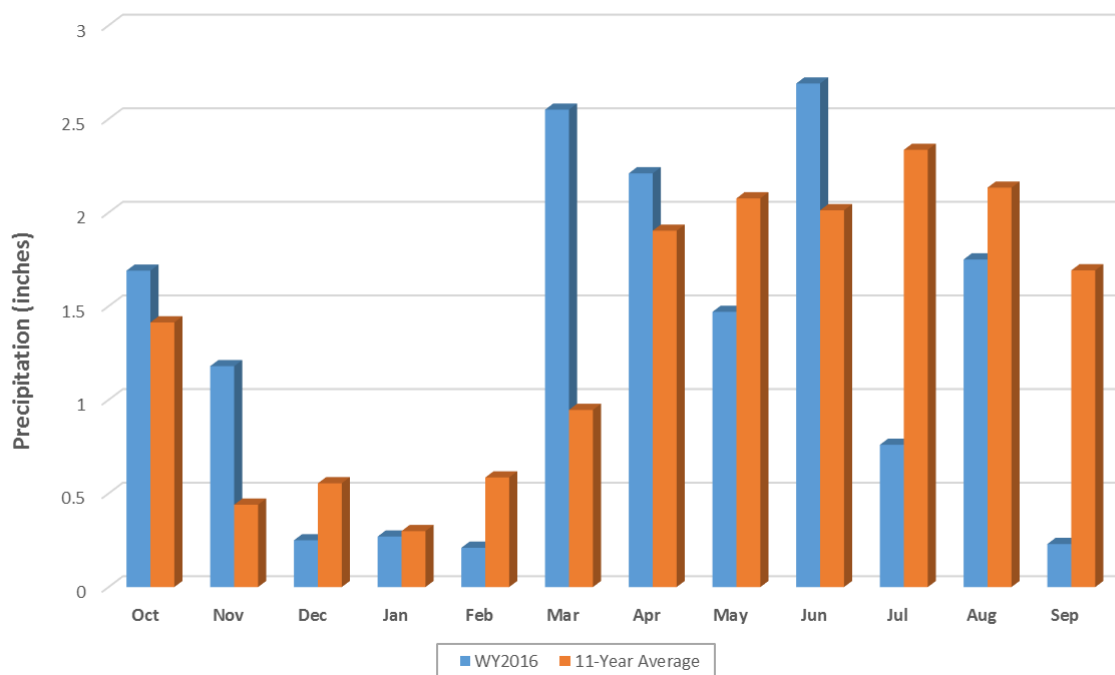


Figure 5. Monthly Precipitation near Cherry Creek Reservoir (Data Source NOAA Precipitation Station at Centennial Airport - KAPA).

The Authority operates and maintains two continuous recording stations on Cherry Creek at CC-7 (Eco Park) and CC-10 (Figure 2). Data for these stations are provided in Appendix D. The estimated WY2016 flows at the Authority's CC-10 monitoring site totaled 16,002 ac-ft, with an average daily discharge rate of 22 cfs (Figure 6). These values are approximately 3.25 times greater than those observed 9 miles upstream at the USGS gage near Parker (Figure 4).

The Authority also operates continuous recording equipment at the four monitoring sites on Cottonwood Creek. Monitoring sites CT-P1 and CT-P2 monitor the inflow and outflow, respectively, of the PRF located west of Peoria Street. Monitoring sites CT-1 and CT-2 monitor the inflow and outflow, respectively, of the PRF located just upstream of the Reservoir inside the Park boundary (the "Perimeter Pond"). Streamflow data and hydrograph equations for these stations are provided in Appendix D. The estimated WY2016 flows at the Authority's CT-2 monitoring site totaled 3,854 ac-ft, with an average daily discharge rate of 5.3 cfs. The WY2016 daily hydrograph for the CT-2 gage, which reflects the flow of water entering the Reservoir from Cottonwood Creek, is illustrated on Figure 7.

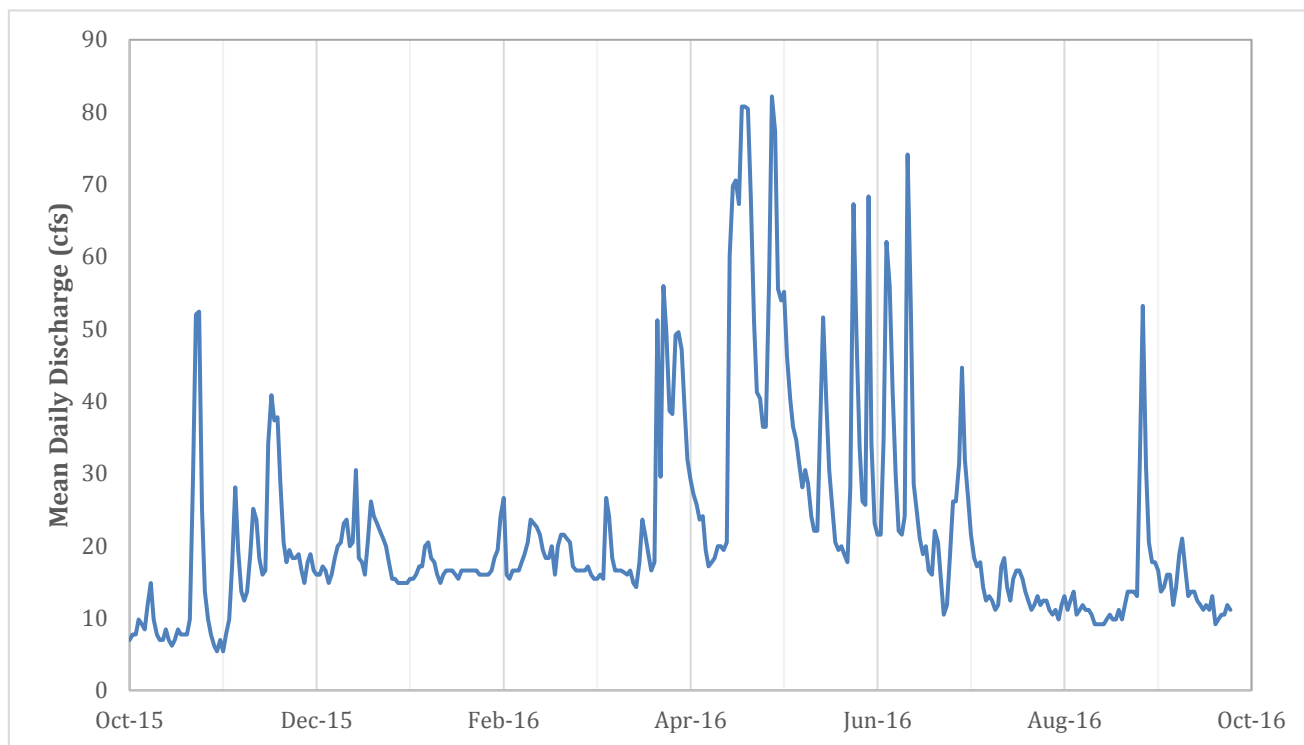


Figure 6. WY2016 Hydrograph for the Authority's Cherry Creek CC-10 Gage (Source of Data: ISCO Samplers, Data uploaded by GEI Consultants (October 2015 – February 2016) and Tetra Tech, Inc. (March 2016 – September 2016))

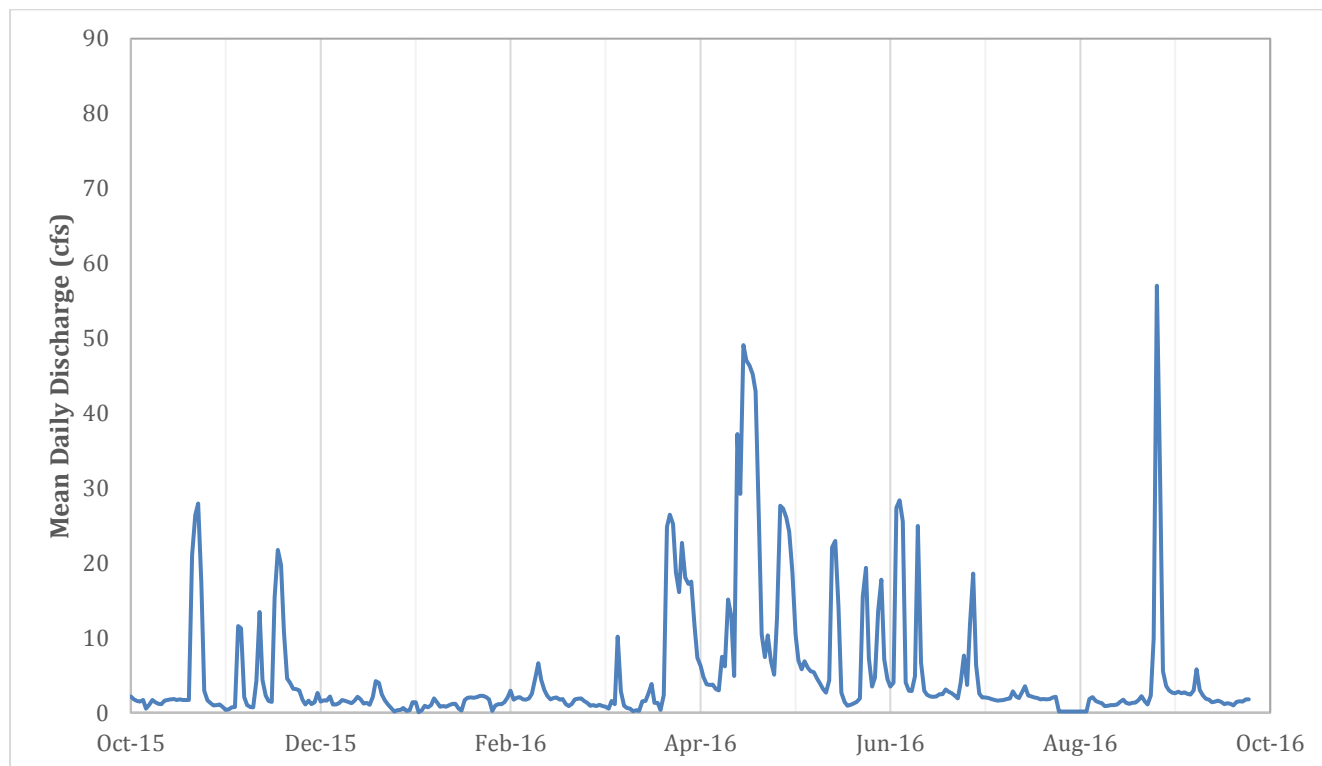


Figure 7. WY2016 Hydrograph for the Authority's Cottonwood CT-2 Gage (Source of Data: ISCO Samplers, Data uploaded by GEI Consultants, Inc. (October 2015 – February 2016) and Tetra Tech, Inc. (March 2016 – September 2016))

The USACE also calculates net daily inflow into the Cherry Creek Reservoir by estimating the change in reservoir storage and then accounting for losses (measured releases from outlet works, estimated evaporation) and gains (precipitation based on reservoir surface area). The USACE's net daily inflow combines the flows from Cherry Creek, Cottonwood Creek, other minor tributaries, and alluvial groundwater gains/losses. The USACE's WY2016 daily inflow estimates are included in Appendix E.

The continuous recording equipment (ISCO samplers) at many of the Authority's monitoring sites malfunctioned during WY2016 and some units had parts replaced during the course of the year at the recommendation of the ISCO representative. Periods of flow data had to be estimated when the equipment was offline. Because of the age of some of the ISCO recorders (up to 17 years old) and the importance of accurate data, particularly at key inflow stations CC-10 and CT-2, it is prudent for the Authority to consider purchasing new equipment at key monitoring locations in 2017.



Photo 1 – Cherry Creek Sampling Team collecting streamflow data in Cottonwood Creek (CT-P1).

3.1.1.2 Cherry Creek Water Quality

The Cherry Creek sub-basin is significantly larger than the Cottonwood Creek sub-basin, 234,000-acres and 9,050-acres, respectively. The larger Cherry Creek sub-basin area, with greater runoff volume and different land uses resulted in a different water quality character in comparison with the Cottonwood Creek sub-basin. The Cherry Creek basin had higher TP, however, Cottonwood Creek basin had higher TDS, TN, chloride, and sulfate. WY2016 water quality data are provided in Appendix F.

The pH and specific conductance (surrogate for total dissolved solids (TDS)) of water in Cherry Creek both increase as surface water moves from the upper basin downstream to the Reservoir. In the case of specific conductance, during the May 2016 basin-wide monitoring event values increased approximately 4 fold from the upper monitoring stations (Castlewood and CC-1) to those in Cherry Creek State Park (CC-9 and CC-10) (Figure 8).

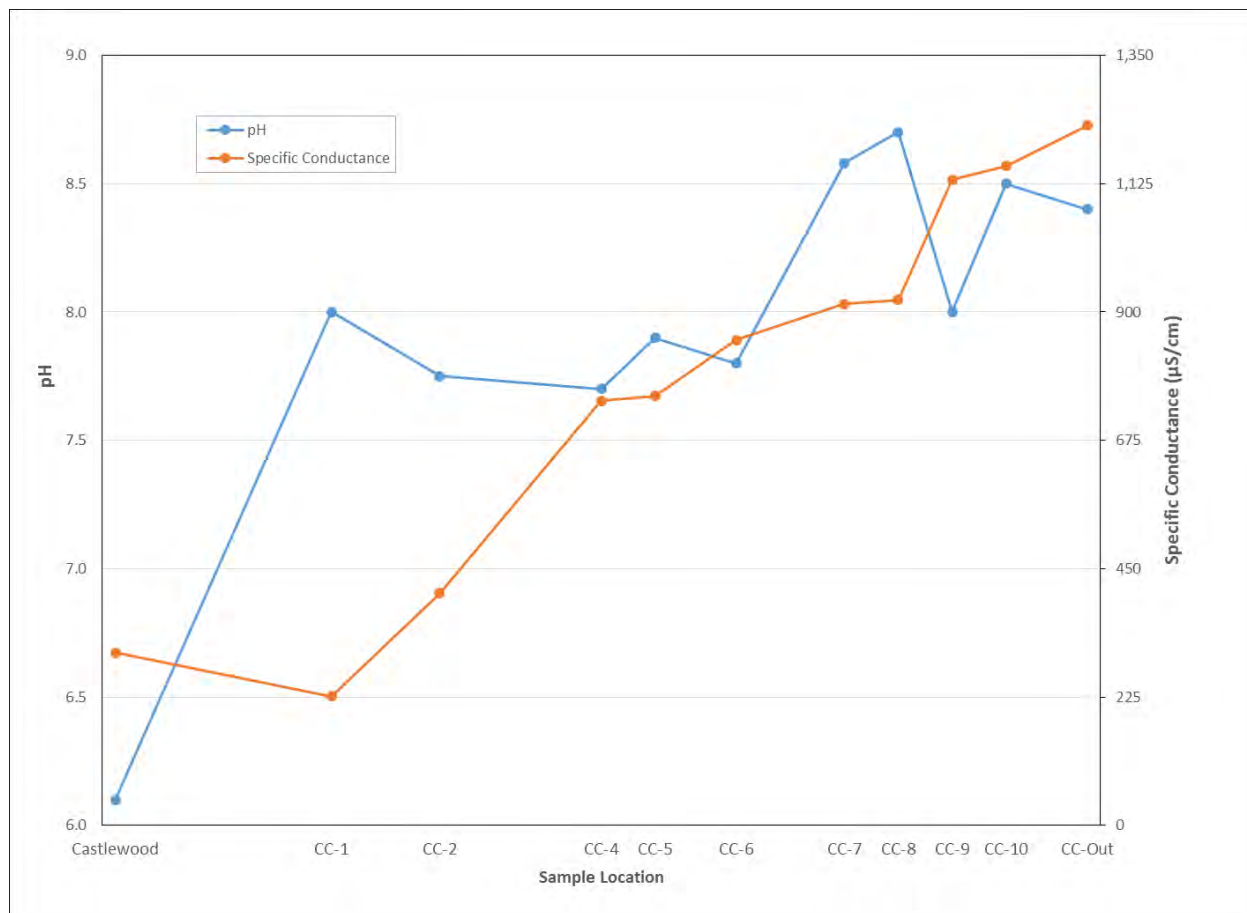


Figure 8. Specific Conductance and pH in Cherry Creek Basin, May 2016. (Source of Data: IEH Analytical, Inc.)

Review of the historic pH values measured at CC-10 suggests that the pH of surface water entering the Reservoir at CC-10 appears to be decreasing through time (Figure 9) although the WY2016 values are higher than the overall trend.

Review of the historic specific conductance values measured at CC-10 also indicate that surface water quality in Cherry Creek is evolving (Figure 10). Since the mid-2000s, specific conductance values at CC-10 appear to have doubled although the WY2016 values are slightly lower than the recent trend.

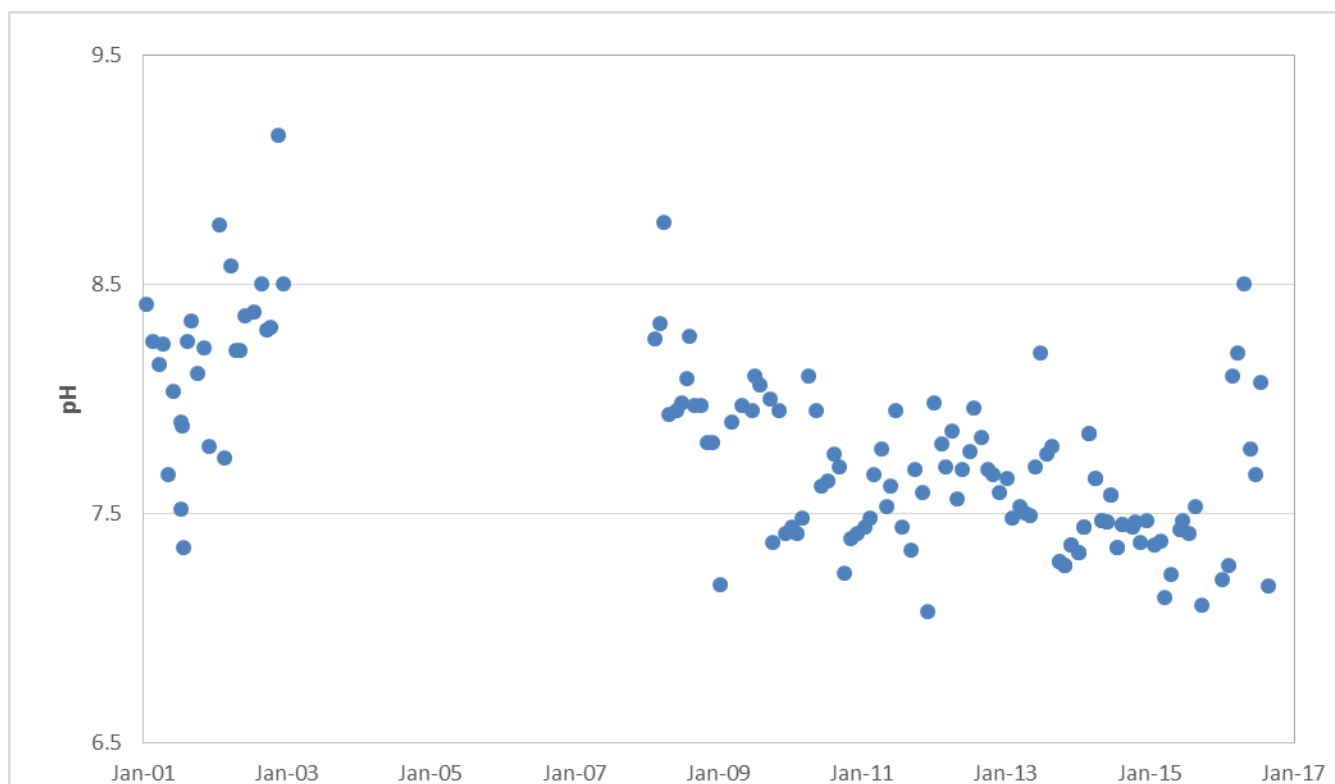


Figure 9. Historic pH values at Cherry Creek Monitoring Site CC-10. (Sources of Data: GEI Consultants, Inc. (2001 – February 2016; IEH Analytical, Inc. (March –September 2016)

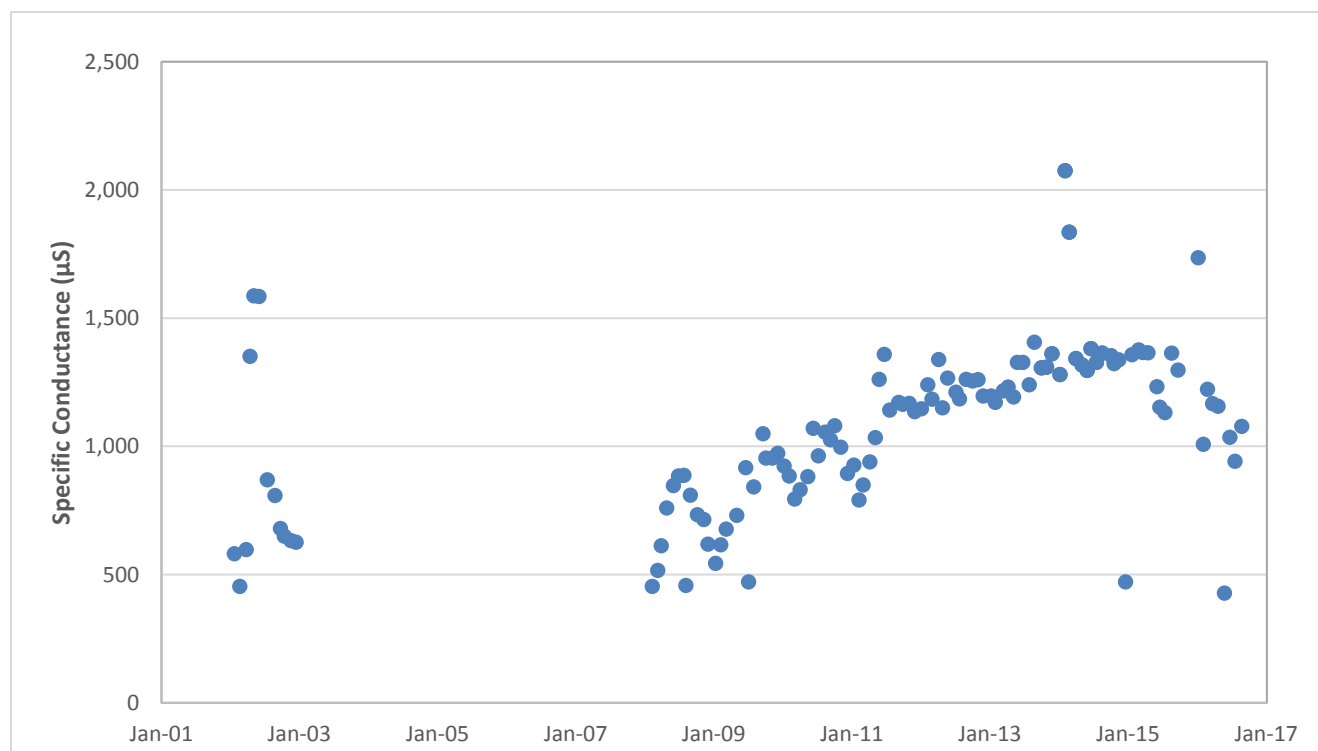


Figure 10. Historic specific conductance values at Cherry Creek Monitoring Site CC-10. (Sources of Data: GEI Consultants, Inc. (2001 – February 2016; IEH Analytical, Inc. (March –September 2016)

Data from the May 2016 basin-wide surface water sampling event indicated that the concentrations of chloride and sulfate increased downstream through the basin (Figure 11). These concentration increases accounted for at least a portion of the increase in specific conductance previously noted (Figure 8).

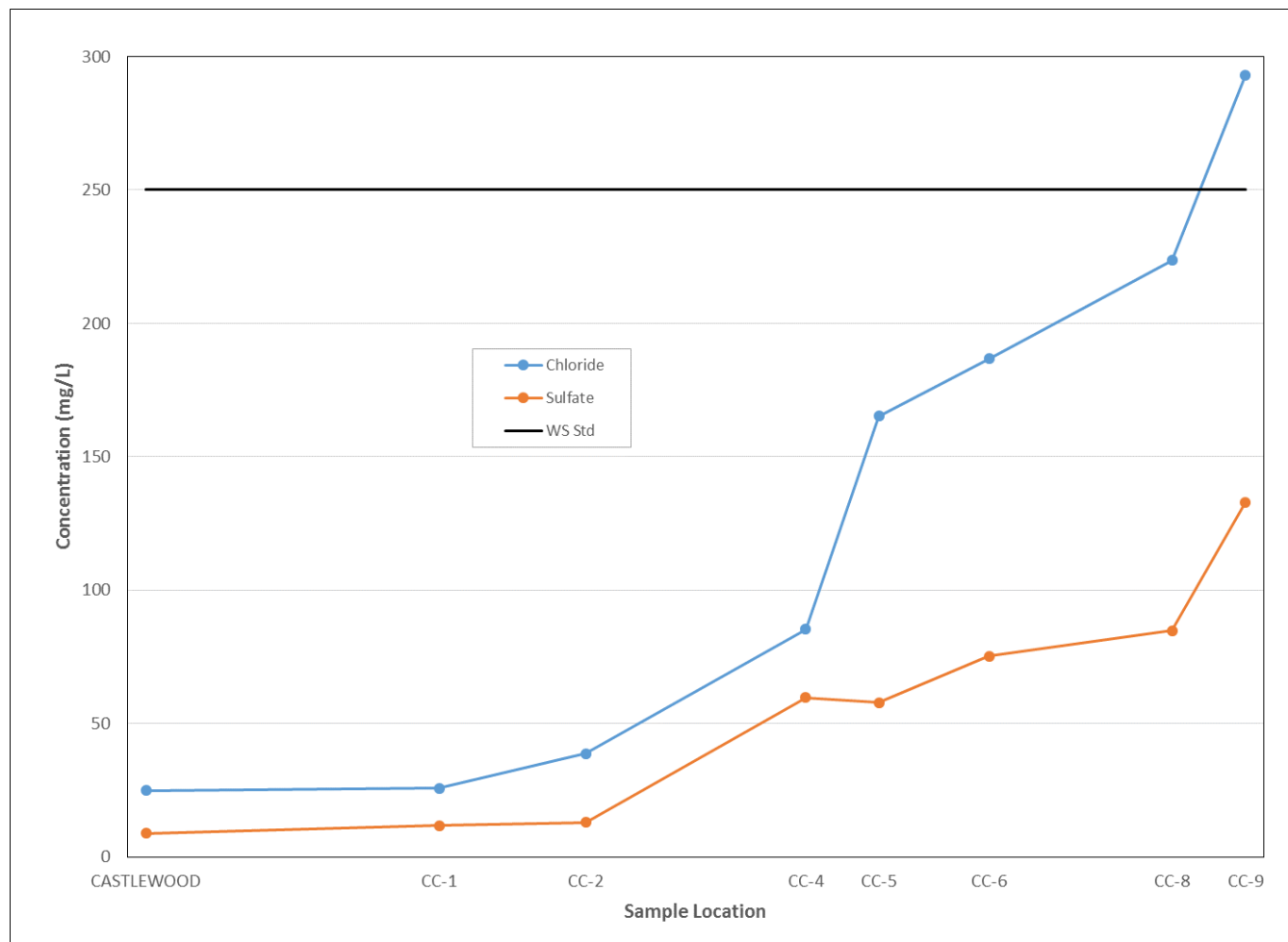


Figure 11. Chloride and Sulfate Concentrations in Cherry Creek Basin, May 2016. Secondary drinking water supply standards for each is 250 mg/L. (Source of Data: IEH Analytical, Inc.)

As illustrated in Figure 11, the May 2016 chloride value measured at CC-9 exceeded the surface water (water supply) standard of 250 mg/L (5 CCR 1002-38, Appendix 38-1, Stream Segment COSPCH01). Surface water samples currently collected from Authority monitoring sites CC-7, CC-10 and CC-Out are not analyzed for chloride or sulfate (Table 3) and data from these sites are, therefore, not available to include in Figure 11. However, chloride and sulfate were analyzed in five monthly samples collected at CC-10 from October 2015 through February 2016 and all values were below the 250 mg/L. The sources of chloride and sulfate may be attributable to chemical addition (ferric chloride or aluminum sulfate (alum) used in wastewater treatment processes to reduce phosphorus concentrations in discharges to meet permit requirements. However, chloride and sulfate are also used as tracers for septic system and pasture sources and this is often tied to nitrogen increases which was also observed in the basin. During the May 2016 basin-wide surface water sampling event, the level of total phosphorus remained relatively constant upstream of the Reservoir while total nitrogen increased from

the Castlewood State Park downstream to Parker (CC-4) and then remained relatively constant to the Cherry Creek State Park, when levels decreased (Figure 12).

In May 2016, the levels of both TP and TN leaving the Reservoir (CC-Out) were lower than those entering the Reservoir (Figure 12). As will be quantified in Section 4, this is due to the retention of nutrients in the Reservoir and is the result of a significant portion of the nutrient inflow load settling to the bottom sediments. The relative Reservoir concentration was high but less than the inflow due to sedimentation, and that was reflected in the outflow concentration.

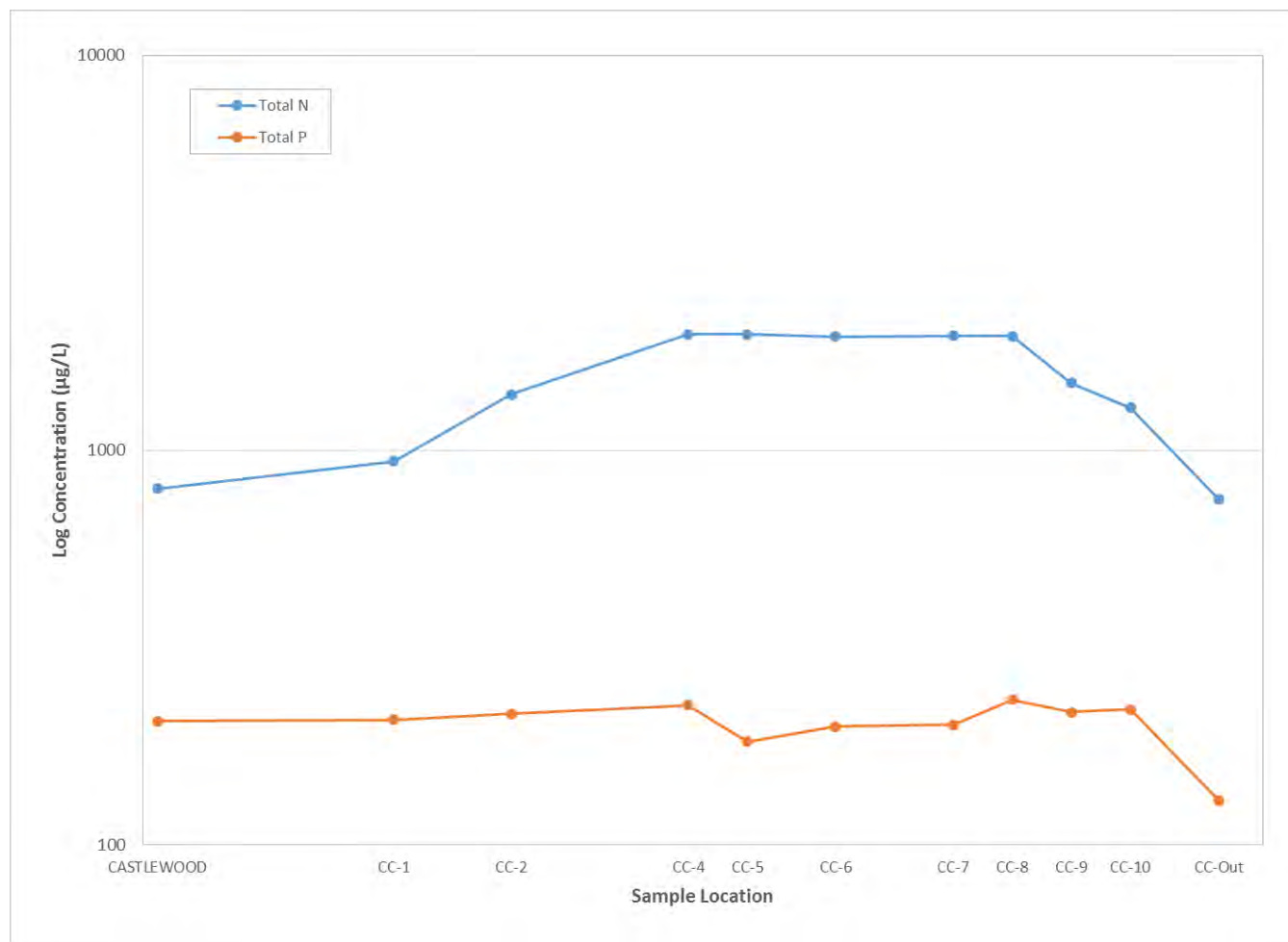


Figure 12. TN and TP Concentrations in Cherry Creek Basin, May 2016. (Source of Data: IEH Analytical, Inc.)

During the October 2015 basin-wide surface water sampling event, TP levels were slightly higher than those observed the following spring and also fluctuated (Figure 13). TN data are not available for all sites from October 2015.

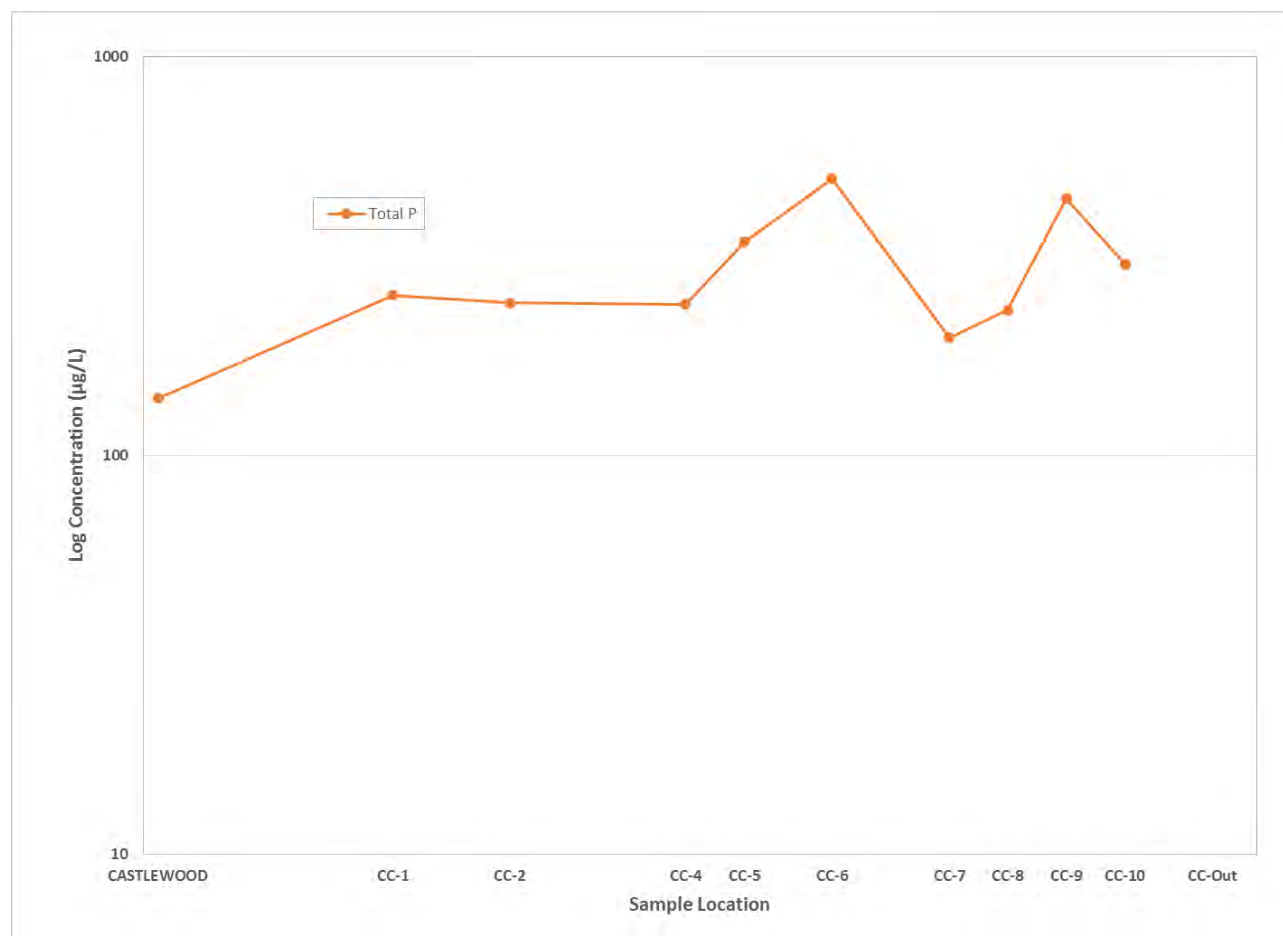


Figure 13. TP Concentrations in Cherry Creek Basin, October 2015. (Source of Data: GEI Consultants, Inc.)

In May 2016, ammonium accounted for less than 6% of the TN present in Cherry Creek, with nitrate/nitrite comprising a larger component of the total nitrogen load. Soluble reactive phosphorus (SRP) comprised the majority of the total phosphate in both the October 2015 and May 2016 basin-wide surface water sampling events. The relative distribution of the various nitrogen and phosphorus species measured during the May 2016 basin-wide surface water sampling event are illustrated in Figure 14. The relative distribution of the phosphorus species measured during the October 2015 basin-wide surface water sampling event is illustrated in Figure 15.

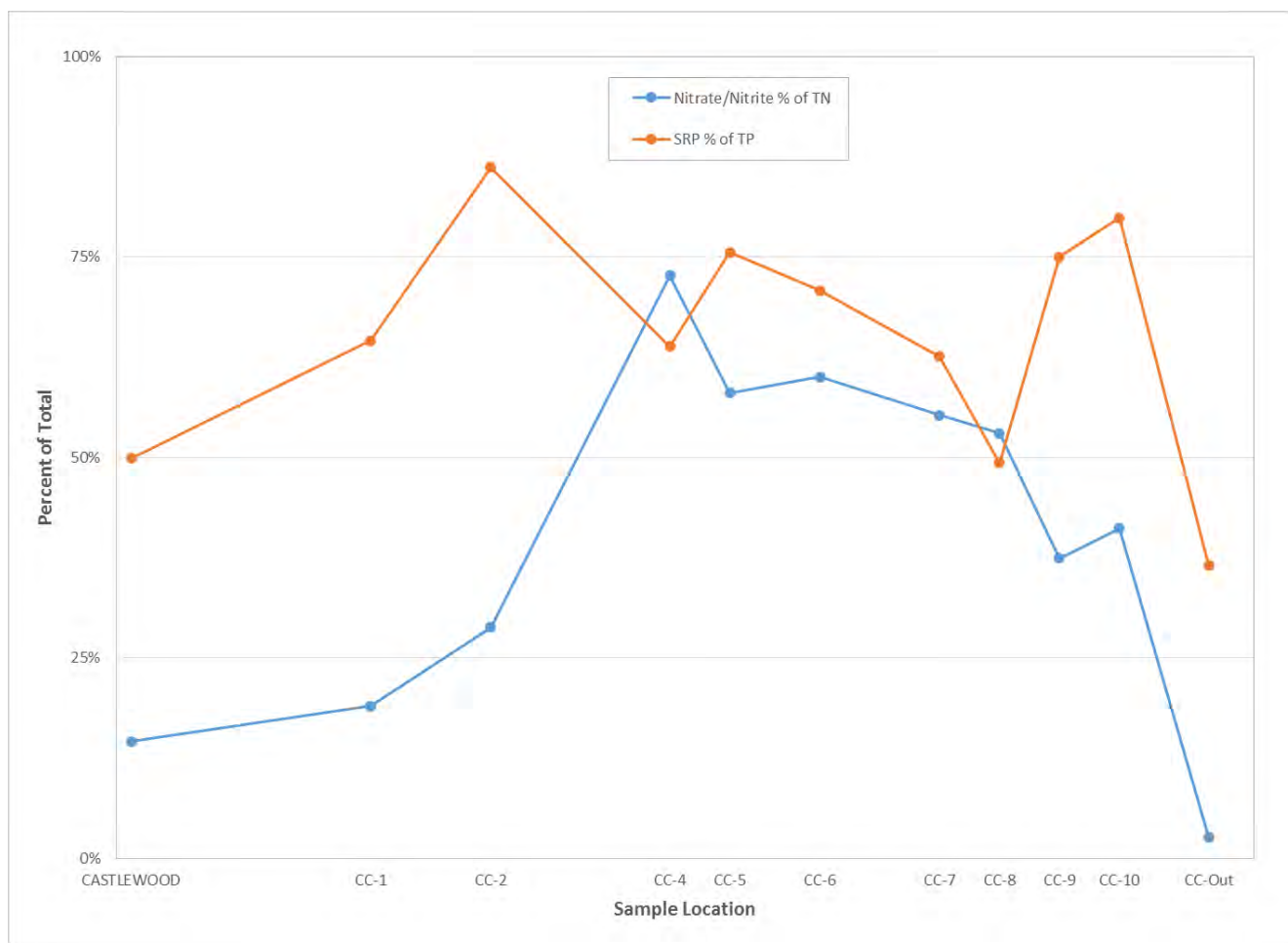


Figure 14. Nitrogen and Phosphorus Species in Cherry Creek Basin, May 2016 (Source of Data: IEH Analytical, Inc.)

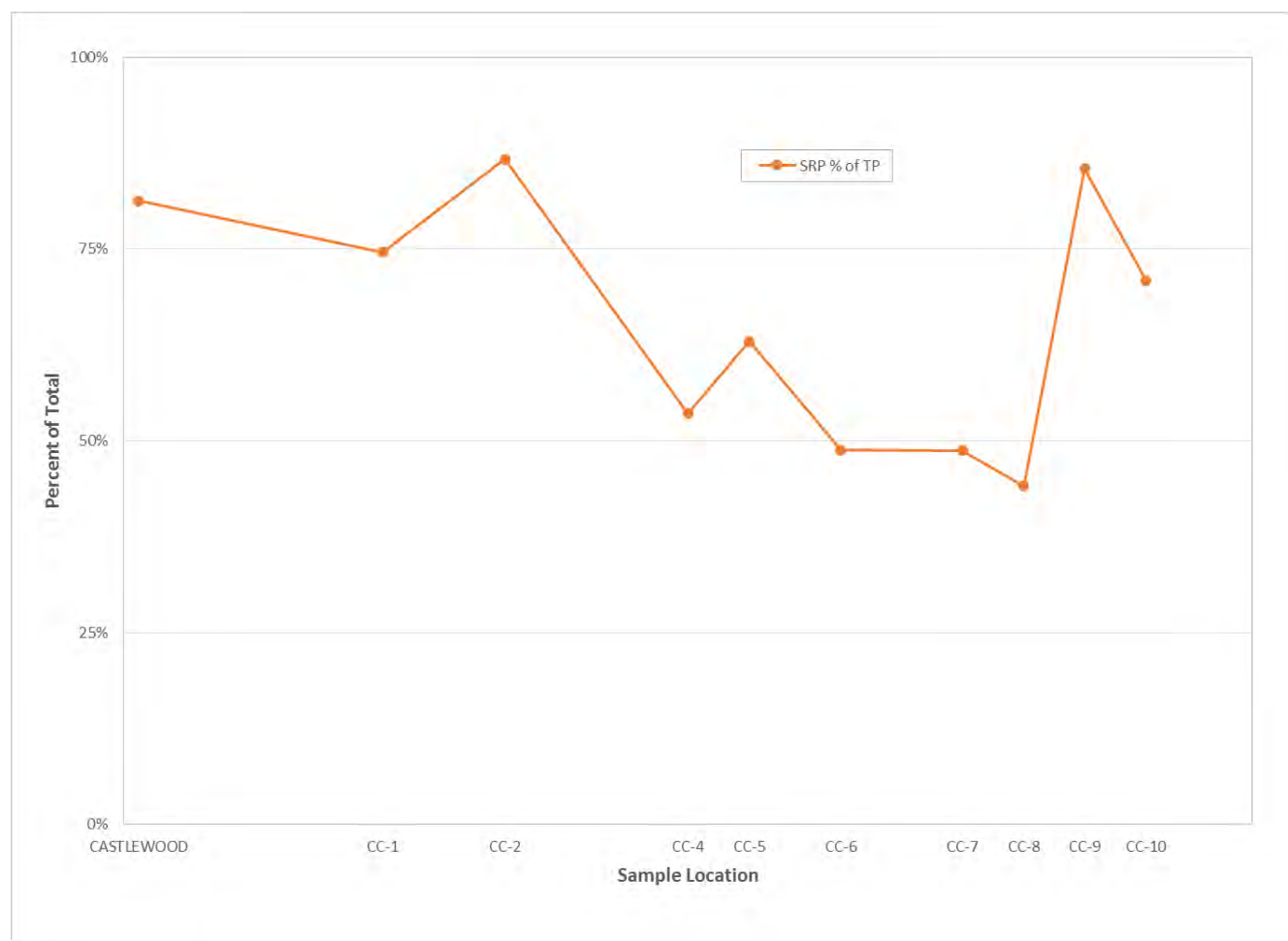


Figure 15. Phosphorus Species in Cherry Creek Basin, October 2015. (Source of Data: GEI Consultants, Inc.)

Just upstream of the Reservoir, phosphorus was generally present at CC-10 in the dissolved form in WY2016, which includes SRP, with the exception of during storm-related high flows (e.g., June 14, 2016). During the higher flows generated by storm runoff, large amounts of sediment (and associated phosphorus) are transported in Cherry Creek (Figure 16).

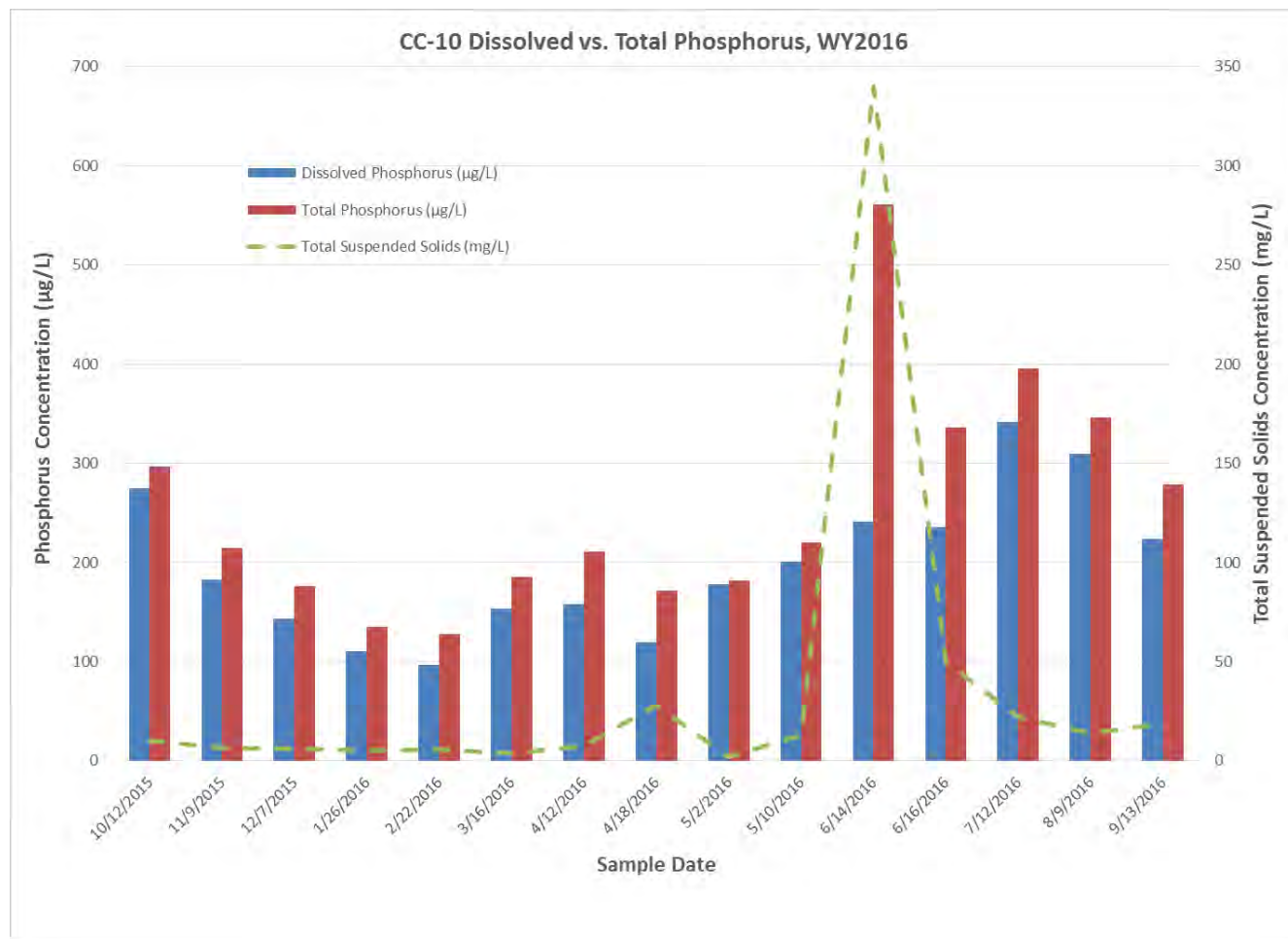


Figure 16. Comparison of Dissolved and Total Phosphorus and TSS at CC-10, WY2016. (Sources of Data: GEI Consultants, Inc. (October 2015 – February 2016) and IEH Analytical, Inc. (March 2016 – September 2016))

There is a strong relationship between particulate phosphate and suspended sediment conveyed by Cherry Creek. Particulate phosphate is calculated as the difference between the total and the dissolved phosphorus concentrations (or the difference in the height of the red and blue bars in Figure 16). The relationship between particulate phosphate and TSS at CC-10 in WY2016 is illustrated in Figure 17.

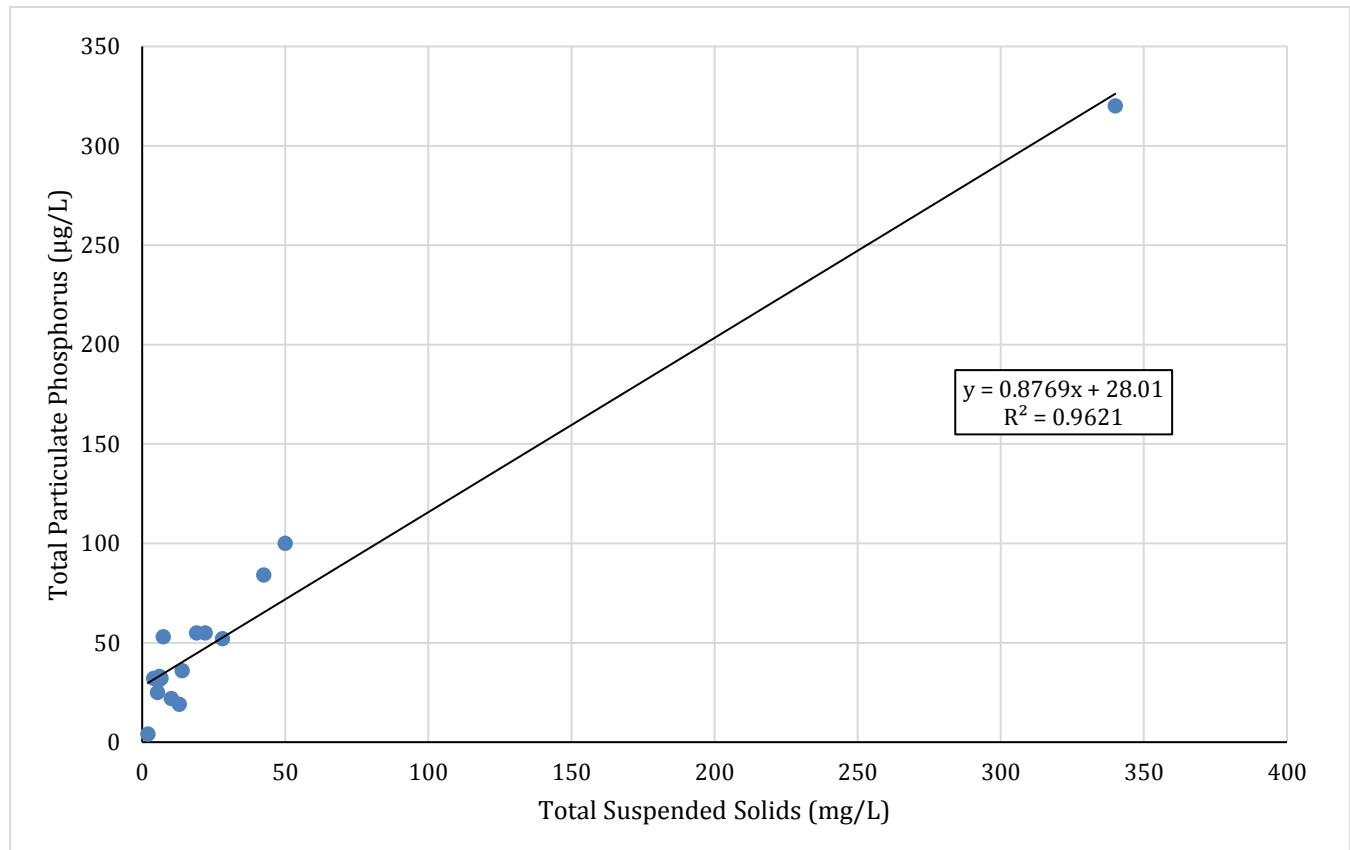


Figure 17. Particulate Phosphate versus TSS at CC-10, WY2016. (Sources of Data: GEI Consultants, Inc. (October 2015 – February 2016) and IEH Analytical, Inc. (March 2016 – September 2016))

The positive relationship between phosphorus and suspended sediment concentrations is reflected in the difference between the median total phosphorus concentrations in samples collected at CC-10 during storm events versus those in samples collected during routine (non-storm) sampling events. Summary statistics for total phosphorus concentrations at CC-10 in WY2016 under these two flow regimes are provided in Table 5.

Table 5. Summary Statistics for Total Phosphorus Samples Collected at CC-10 during Base Flow (Routine) and Storm Events, WY2016.

Total Phosphorus Statistic	Base Flow Sampling Events (Routine, Non- Storm)	Storm Sampling Events
Count	11	5
Minimum (µg/L)	128	172
Maximum (µg/L)	561	336
Mean (µg/L)	250	261
Median (µg/L)	215	301

The flow weighted total phosphorus concentration at CC-10 for WY2016 was 250 µg/L. The WY2016 value is slightly lower than the recent (2011 – 2015) flow weighted total phosphorus concentration of 263 µg/L published in GEI (2016) but much higher than the WY2016 flow weighted total phosphorus concentration of 87.6 µg/L calculated at site CT-2 in lower Cottonwood Creek (Section 3.1.1.3).

Nitrogen was predominately present at CC-10 in the dissolved form in WY2016 with the exception of during storm-related high flows (Figure 18). However in contrast to phosphorus, there is not a strong relationship between particulate nitrogen and TSS.

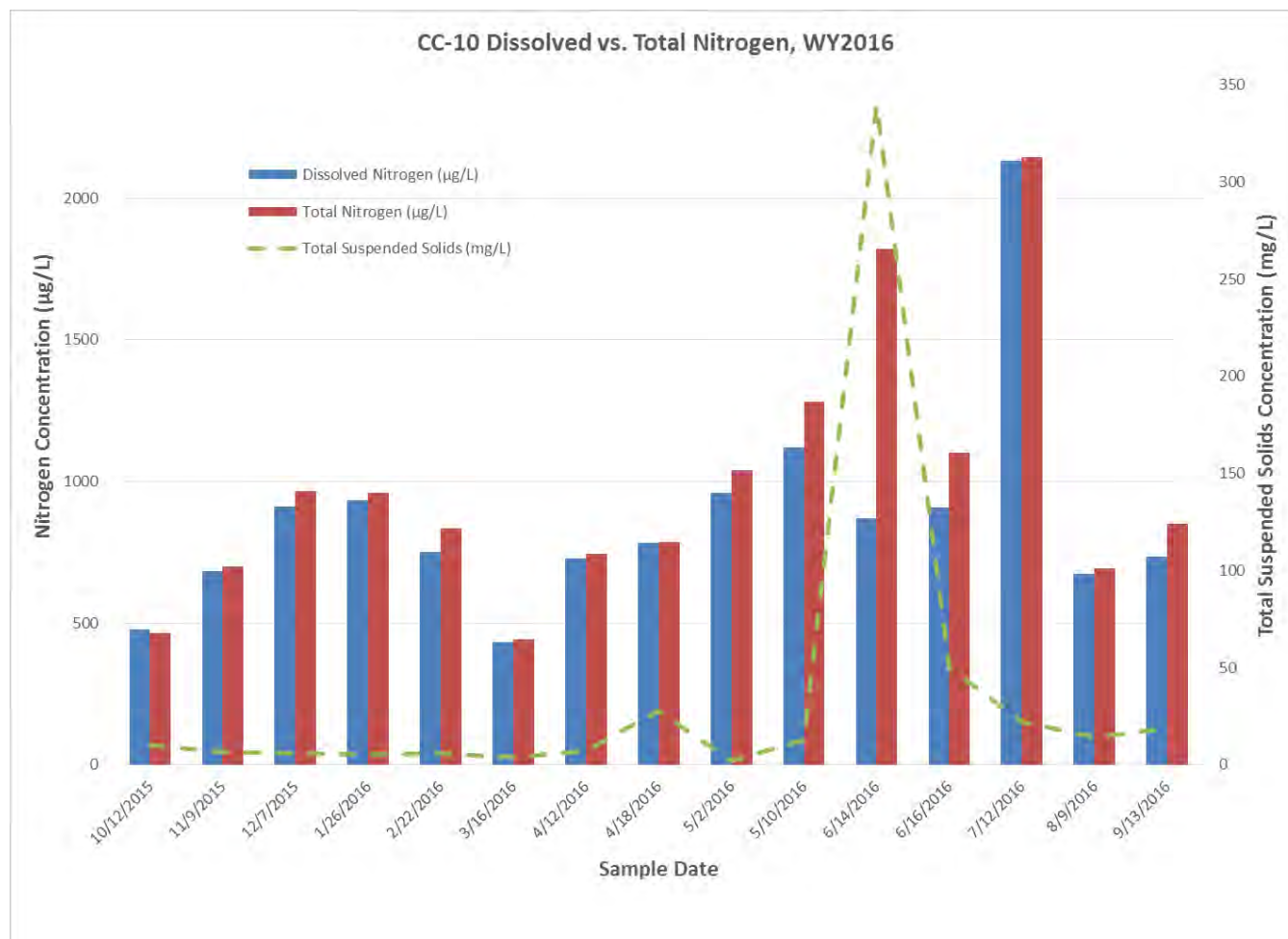


Figure 18. Comparison of Dissolved and Total Nitrogen and TSS at CC-10, WY2016. (Sources of Data: GEI Consultants, Inc. (October 2015 – February 2016) and IEH Analytical, Inc. (March 2016 – September 2016))

Summary statistics for total nitrogen concentrations at CC-10 in WY2016 under these storm and non-storm (routine sampling) flow regimes are provided in Table 6.

Table 6. Summary Statistics for Total Nitrogen Samples Collected at CC-10 during Base Flow (Routine) and Storm Events, WY2016. (Sources of Data: GEI Consultants, Inc. (October 2015 – February 2016) and IEH Analytical, Inc. (March 2016 – September 2016))

Total Nitrogen Statistic	Base Flow Sampling Events (Routine, Non- Storm)	Storm Sampling Events
Count	11	5
Minimum (µg/L)	444	562
Maximum (µg/L)	1,820	1,100
Mean (µg/L)	897	882
Median (µg/L)	833	924

The flow weighted TN concentration at CC-10 for WY2016 was 1,012 µg/L. The WY2016 value is lower than the recent (2011 – 2015) flow weighted TN concentration of 1,261 µg/L published in GEI (2016) and approximately half the WY2016 flow weighted TN concentration of 2,020 µg/L calculated at site CT-2 in lower Cottonwood Creek (Section 3.1.1.3).

3.1.1.3 Cottonwood Creek Water Quality

The quality of surface water in lower Cottonwood Creek just above the Reservoir (monitoring site CT-2) is discussed in this section. The water quality at the other Cottonwood Creek monitoring sites is discussed in Section 3.1.1.4 in the context of PRF performance. WY2016 water quality data are provided in Appendix F.

The pH of water in lower Cottonwood Creek ranged from 7.1 to 8.2, with a median value of 8. This pH range is consistent with the pH values observed in lower Cherry Creek (see Figure 9). However, the concentration of dissolved solids, as inferred by specific conductance values, was higher in Cottonwood Creek than in Cherry Creek. In WY2016, the specific conductance at CT-2 ranged from approximately 1,500 to 3,200 µS/cm with a median value of 1,750 µS/cm (compared to Cherry Creek specific conductance values at CC-10 in Figure 10). This higher specific conductance is due, in part, to elevated levels of chloride and sulfate present in Cottonwood Creek. Specially, the concentration of chloride exceeded 250 mg/L in four of five WY2016 samples collected at CT-2 while the concentration of sulfate exceeded 250 mg/L in all five WY2016 samples collected at CT-2. Cottonwood Creek has a chloride standard of 250 mg/L and water supply (WS) standard for sulfate (5 CCR 1002-38, Appendix 38-1, Stream Segment Cospch04B).

The concentrations of TP and TN measured at CT-2 in WY2016 are shown in Figure 19. The level of nitrogen present in lower Cottonwood Creek is higher than that observed in Cherry Creek, but the level of phosphorus is an order of magnitude lower in Cottonwood Creek than in Cherry Creek (compare Figure 19 to Figures 12 and 13).

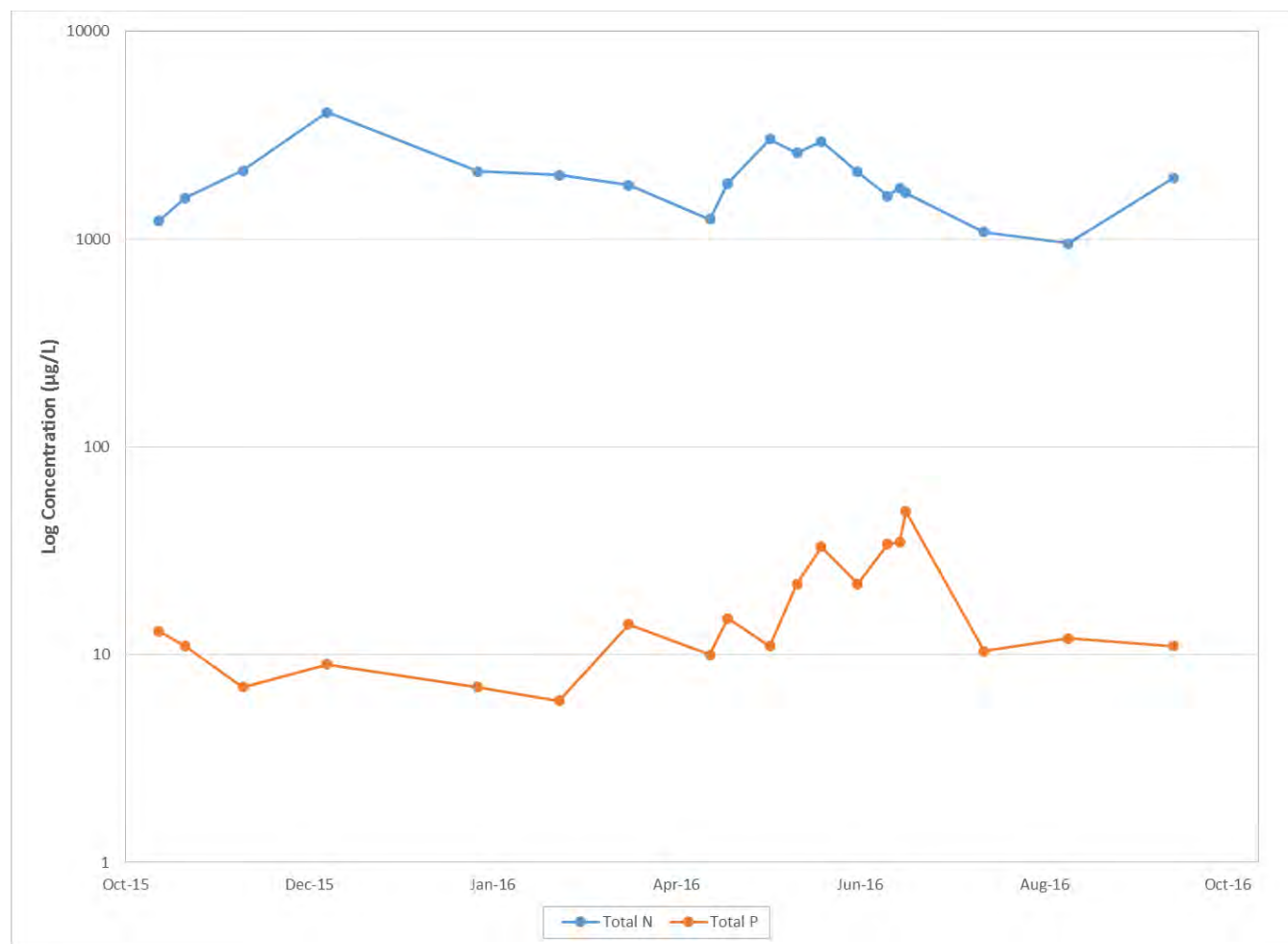


Figure 19. Comparison of Total Nitrogen and Total Phosphorus at CT-2, WY2016

Consistent with the mode of transport in Cherry Creek, there is a moderately strong relationship between particulate phosphorus and TSS in Cottonwood Creek (Figure 20).

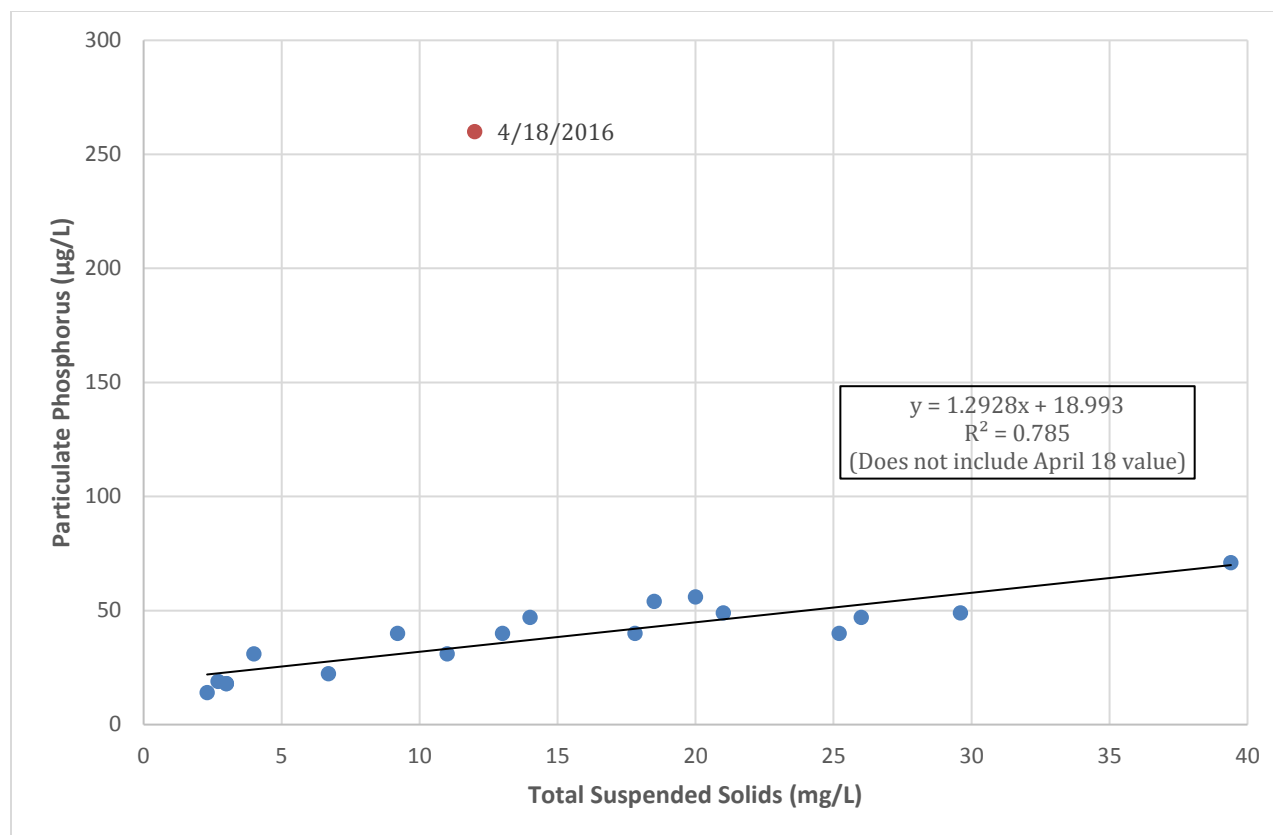


Figure 20. Particulate Phosphate versus TSS at CT-2, WY2016 (Sources of Data: GEI Consultants, Inc. (October 2015 – February 2016; IEH Analytical, Inc. (March 2016 – September 2016).

Summary statistics for total nitrogen and total phosphorus concentrations at CT-2 in WY2016 under storm and non-storm (routine sampling) flow regimes are provided in Table 7.

Table 7. Summary Statistics for TN and TP Samples Collected at CT-2 during Routine and Storm Events, WY2016.

Statistic	Total Phosphorus		Total Nitrogen	
	Base Flow Sampling Events (Routine, Non-Storm)	Storm Sampling Events	Base Flow Sampling Events (Routine, Non-Storm)	Storm Sampling Events
Count	12	7	11	7
Minimum (µg/L)	43	29	954	1,584
Maximum (µg/L)	78	275	4,085	3,030
Mean (µg/L)	59	84	2,009	2,116
Median (µg/L)	58	65	2,034	1,860

The flow weighted TP concentration at CT-2 for WY2016 was 87.6 µg/L, which is higher than the recent (2011 – 2015) flow weighted TP concentration of 75 µg/L published in GEI (2016) but far below the WY2016 flow weighted TP concentration of 1,261 µg/L calculated at site CC-10 in lower Cherry Creek (Section 3.1.1.2). The flow weighted TN concentration at CT-2 for WY2016 was 2,020 µg/L, which is also higher than the recent (2011 – 2015) flow weighted TN concentration of 1,592 µg/L published in GEI (2016) and approximately twice the WY2016 flow weighted TN concentration of 1,012 µg/L calculated at site CC-10 in lower Cherry Creek (Section 3.1.1.2).

3.1.1.4 Pollutant Reduction Facility Performance

The passive treatment train approach developed in the Cottonwood Creek sub-basin includes a series of wetland detention systems and stream reclamation (PRFs). The Authority collects water quality samples under both routine (monthly) and storm (spring and summer) flow conditions at four monitoring sites on Cottonwood Creek. Monitoring sites CT-P1 and CT-P2 monitor the inflow and outflow, respectively, of the PRF located west of Peoria Street (the “Peoria Pond”). Monitoring sites CT-1 and CT-2 monitor the inflow and outflow, respectively, of the PRF located just upstream of the Reservoir inside the Park boundary (the “Perimeter Pond”). Data for these stations are provided in Appendix F.

Historically, the Authority has evaluated the effectiveness of the Peoria and Perimeter Ponds separately. Beginning in WY2016, the combined effectiveness of these two PRFs is evaluated. This holistic approach will provide an assessment of the PRFs but will also account for water quality changes between the two PRFs, thus providing an assessment of the net impact of the passive treatment approach on nutrient concentrations in Cottonwood Creek.

In WY2016, the passive treatment approach provided for an effective phosphorus reduction strategy under stormflow conditions, reducing TP concentrations by 20% (Table 8). Total suspended solids concentration (TSS, a quantification of sediment concentration in streamflow) was also reduced 77% during storm flows. This TSS reduction is important, as the phosphorus content in sediments in Cottonwood Creek have been measured to contain high phosphorus content, on average of 0.9 pounds/cubic yard (Ruzzo, 2005), as illustrated in Figure 20. During base flow conditions, there was an increase in TP and TSS concentrations and the loading calculations in Appendix F bear out the instances when there is a net gain (net export) of TP and TSS. Soluble reactive phosphorus (SRP) concentrations were reduced by 25% during base flow conditions, however there was an increase, or export of SRP, during stormflow events. TN concentrations (and loads) increased during both base flow and stormflow events, resulting in a net gain of nitrogen. Future wetland maintenance on this PRF, particularly around the Perimeter Pond, is prudent. With routine maintenance, i.e. vegetation harvesting, N and P will be further reduced.

Table 8. Pollutant Reduction Effectiveness of the Cottonwood PRFs – Passive treatment train approach reduced TP by 20% during stormflows and reduced SRP by 25% during base flow conditions, 2016 Median Values at Cottonwood Stations, CT-P1 and CT-P2. (Sources of Data: IEH Analytical (March 1 2016 -.September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016).

Analyte	Cottonwood Cr, upstream of PRFs (Station CT-P1)		Cottonwood Cr, downstream of PRFs (Station CT-2)	
	Base Flow	Stormflow	Base Flow	Stormflow
TP, µg/L	42	81	62	65
SRP, µg/L	12	5	9	14
TN, µg/L	1,196	1,820	1,927	1,860
TSS, mg/L	11.8	81.5	26	18.5

The PRF developed in McMurdo Gulch is a stream reclamation project. The Authority collected water quality samples only under routine flow (base flow) conditions at two monitoring sites on McMurdo Gulch. Monitoring site MCM-1 is located upstream of the steam reclamation project area while monitoring site MCM-2 is located downstream of the stream reclamation project area. Streamflow, water quality, and load calculations for these stations are provided in Appendix F.

In WY2016, the McMurdo Gulch Stream Reclamation Project reduced the median TP and median SRP concentrations by 14% and 30%, respectfully (Table 9). TN and TSS concentrations were essentially unchanged through the stream reclamation project area in McMurdo Gulch in WY2016. (Table 8). However, as shown in the loading analysis (Appendix F), an increase in pollutant load was observed during some months for TN, TP, and TSS, resulting in a net export of pollutant loads between the upstream and downstream stations.

Table 9. Pollutant Reduction Effectiveness of the McMurdo Gulch – Stream Reclamation approach reduced TP concentrations by 14% and SRP by 30% during base flow conditions, Median Values at McMurdo Gulch, Stations MCM-1 and -2. (Sources of Data: IEH Analytical (March 1 2016 -.September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016).

Analyte	McMurdo Gulch Upstream of PRFs (Station MCM-1)	McMurdo Gulch Downstream of PRFs (Station MCM-2)
	Base Flow	Base Flow
TP, µg/L	351	300
SRP, µg/L	276	192
TN, µg/L	495	476
TSS, mg/L	4.0	4.1

3.1.2 Groundwater

The Cherry Creek alluvial groundwater is currently scheduled to be monitored twice per year (Table 3). Many of the wells in the Authority's alluvial groundwater monitoring network have been regularly sampled since 1994. The wells are located throughout the basin, including just upstream (MW-9) and just downstream (Kennedy) of the Reservoir (Figure 2). The depths of the wells ranges from approximately 27 to 60 feet. Alluvial groundwater samples were collected from by GEI monthly from well MW-9 from October 2015 through February 2016. Tetra Tech collected samples from all seven (7) Authority wells in May 2015. WY2016 water quality data are provided in Appendix F.

3.1.2.1 Groundwater Levels

Groundwater levels are scheduled to be measured twice per year (spring and fall). Monitoring well MW-9 was also equipped with a continuous water level and temperature monitoring device from April 14, 2016 through the end of the water year. The Kennedy well is owned by the City and County of Denver and their employees "purge" the well prior to sampling; consequently, water levels obtained from the Kennedy well are not representative of static groundwater levels as Denver personnel initiate well pumping prior to arrival of Authority sampling personnel.

Hydrographs illustrating the groundwater levels in the Authority's alluvial wells are provided in Appendix D. The historic groundwater level data for the Authority monitoring wells provided on these hydrographs dates from the mid-1990s through WY2016. In general, the trends in groundwater levels in the Authority wells is similar during the first decade of monitoring; groundwater levels in all wells decreased from highs in the early- to mid-1990s to lows in the early- to mid-2000s. Beginning in the early- to mid-2000s the groundwater levels in some of the wells exhibit different trends. From upstream to downstream, these general trends are summarized below.

- After decreasing from the mid-1990s through the early-2000s, alluvial groundwater levels observed in well MW-1 have increased slightly but are not back to the mid-1990 levels. The depth to groundwater in this well, current about 25 feet below ground surface, is much deeper than the other Authority wells where groundwater levels are less than 10 feet below ground surface.
- After decreasing from the mid-1990s through the mid-2000s, alluvial groundwater levels observed in wells MW-2 and 5 have increased to the highest levels historically measured.
- After decreasing from the mid-1990s through the early- to mid-2000s, alluvial groundwater levels in wells MW-6 and MW-9 fluctuated with no major apparent recent trends.

Well MW-9 was also equipped with a continuous data logger starting on April 14, 2016 to monitor shorter-term changes in alluvial groundwater levels and temperature. The WY2016 continuous water level data collected from well MW-9 are illustrated in Figure 21.



Figure 21. WY2016 Mean Daily Alluvial Groundwater Elevation in Well MW-9. (Sources of Data: Tetra Tech, Inc. (April 2016 – September 2016))

As anticipated, the alluvial groundwater level monitored at MW-9 exhibits seasonality with groundwater levels decreasing over a foot from springtime highs to fall lows. WY2016 daily average groundwater level and temperature measurements from MW-9 are provided in Appendix F.

3.1.2.2 Groundwater Quality

Based on the review of the historic pH and specific conductance data collected from the Authority wells, the quality of the alluvial groundwater appears to be slowly evolving through time. The pH of the alluvial groundwater is generally near neutral, predominately ranging from approximately 6.5 to 7.5. The data from some wells (i.e., MW-1, -2, -5 and -9) suggest a slight decrease in pH over the past 20 years. The historic pH values measured in samples collected from well MW-9 are illustrated in Figure 22.

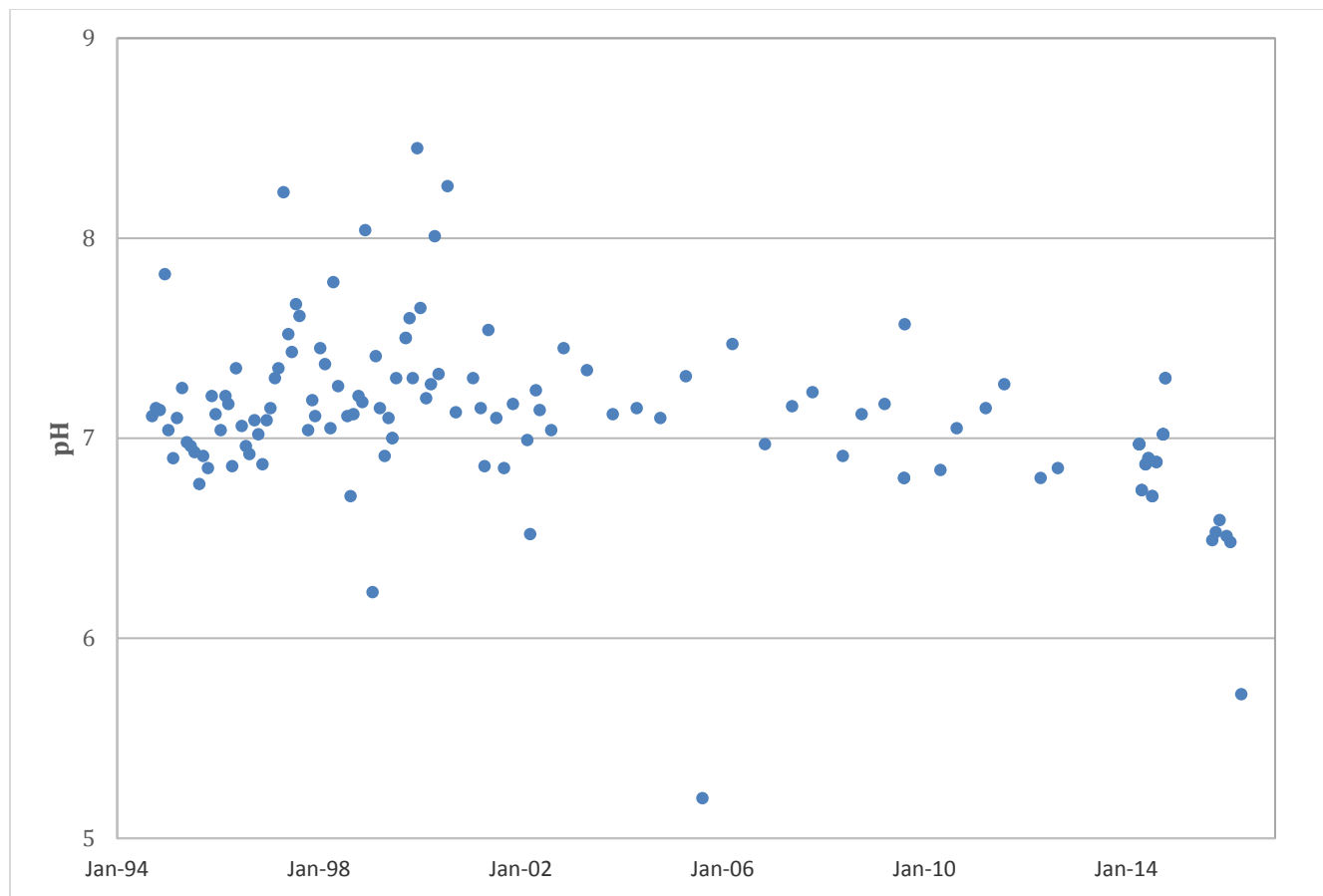


Figure 22. Historic pH values in Well MW-9. (Source of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1994).

The pH values in well Kennedy, located downstream of the Reservoir, have remained relatively constant through time.

Specific conductance, a surrogate of the total dissolved solids (TDS) content of the alluvial groundwater, has increased in several wells (i.e., MW-1, -5, -6, -9 and Kennedy). The historic specific conductance values measured in samples collected from well MW-9 are illustrated in Figure 23.

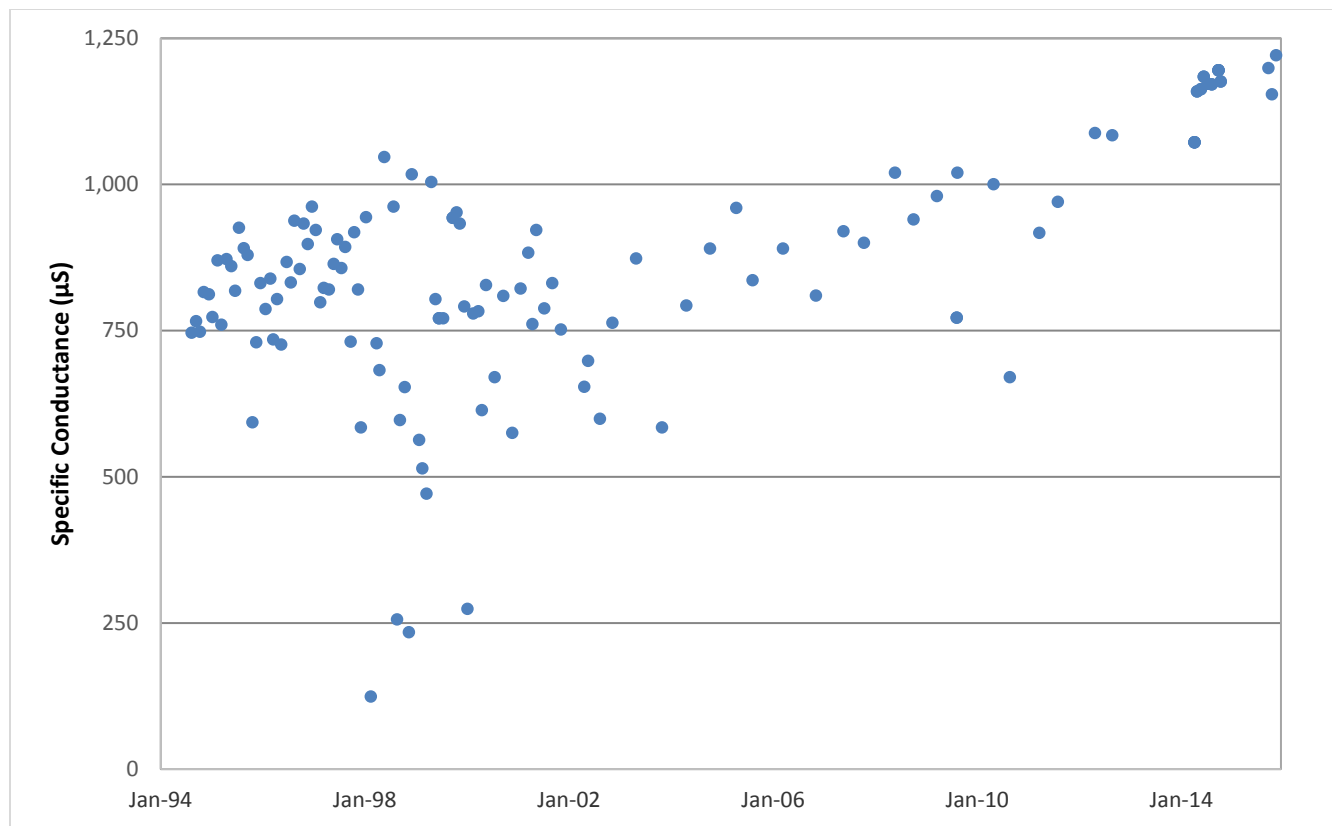


Figure 23. Historic specific conductance values in Well MW-9. (Source of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1994).

Based on the results of the May 2016 groundwater sample, median sulfate and chloride concentrations in the alluvial groundwater samples were 100 mg/L and 277 mg/L, respectively. It is likely that increases in the concentrations of both these anions through time contributes to a portion of the observed increase in specific conductance in some wells.

Data from the May 2016 basin-wide alluvial groundwater sampling event indicated that the concentration of sulfate in all the wells was below the applicable state groundwater (domestic water supply) standard (5 CCR 1002-41.8, Table 2). However, as illustrated in Table 10, chloride concentrations in four of the seven alluvial wells sampled exceeded the applicable domestic water supply standard of 250 mg/L (ibid.). As mentioned in Section 3.1.1.2, this is a marker for septic system and land use impacts on groundwater.

Table 10. Chloride Concentrations in Alluvial Wells, May 2016

Well Number	Chloride (mg/L)*
MW-1	609
MW-2	279
MW-5	208
MW-6	205
MW-7A	277
MW-9	290
Kennedy	231

*Bolded concentrations exceed groundwater standard of 250 mg/L

Comparison of Cherry Creek surface water and alluvial groundwater data from the May 2016 basin-wide sampling event suggests a difference in total nitrogen concentrations between the two media (Figure 24). The median concentrations of TN in May 2016 were 1.5 mg/L in surface water and 0.3 mg/L in alluvial groundwater. The exception to this pattern was well MW-1, where the total nitrogen level was much greater than that in the adjacent surface water. Note that nitrate/nitrite concentration in well MW-1, 8.29 mg/L, was below the state groundwater (domestic water supply) standard (5 CCR 1002-41.8, Table 1).

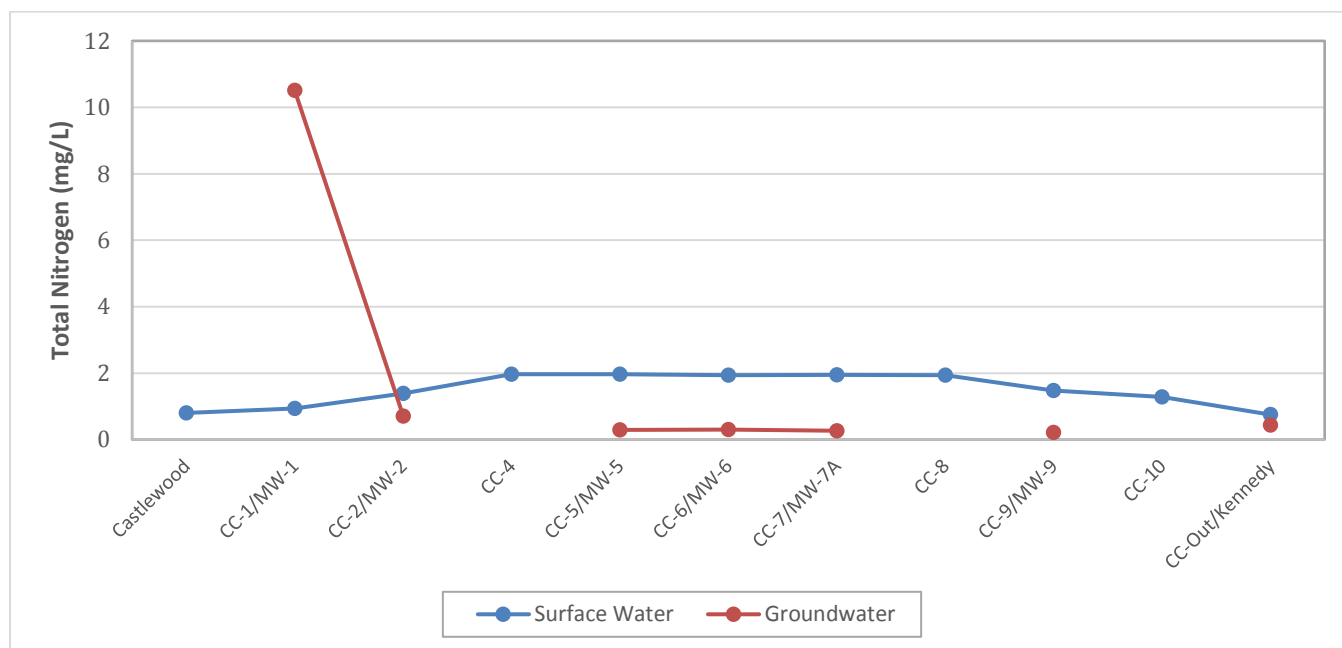


Figure 24. Total Nitrogen concentrations in Cherry Creek Surface Water and Alluvial Groundwater, May 2016. (Source of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (October 2015 – February 2016))

In contrast to TN, comparison of Cherry Creek surface water and alluvial groundwater data from the May 2016 basin-wide sampling event suggests little difference in total phosphate concentrations between the two media, with the exception of well MW-2 (Figure 25). The median concentrations of total phosphorus differed little between the two media in May 2016, 207 µg/L in surface water and 214 µg/L in alluvial groundwater.

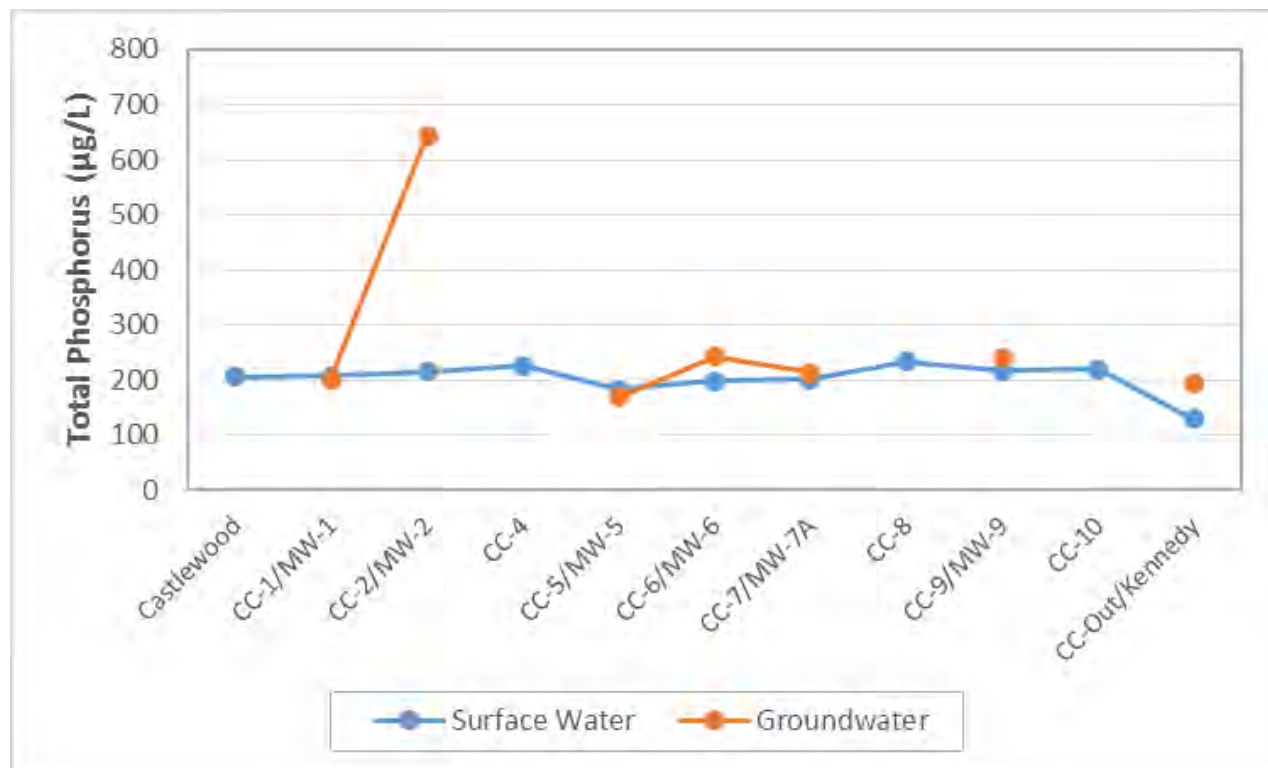


Figure 25. TP concentrations in Cherry Creek Surface Water and Alluvial Groundwater, May 2016 (Source of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (October 2015 – February 2016))

Recent (2010 to present) SRP data supported the TP trend observed in May 2016, although some wells (e.g., MW-2) historically exhibited a wide range in SRP levels. In general, upstream of the Reservoir the SRP levels in the alluvial groundwater are similar to that in nearby surface water (Figure 27). However the SRP level in surface water released from the Reservoir (CC-Out) has historically been lower than that in alluvial groundwater downstream of the Reservoir (alluvial well Kennedy) (Figure 26).

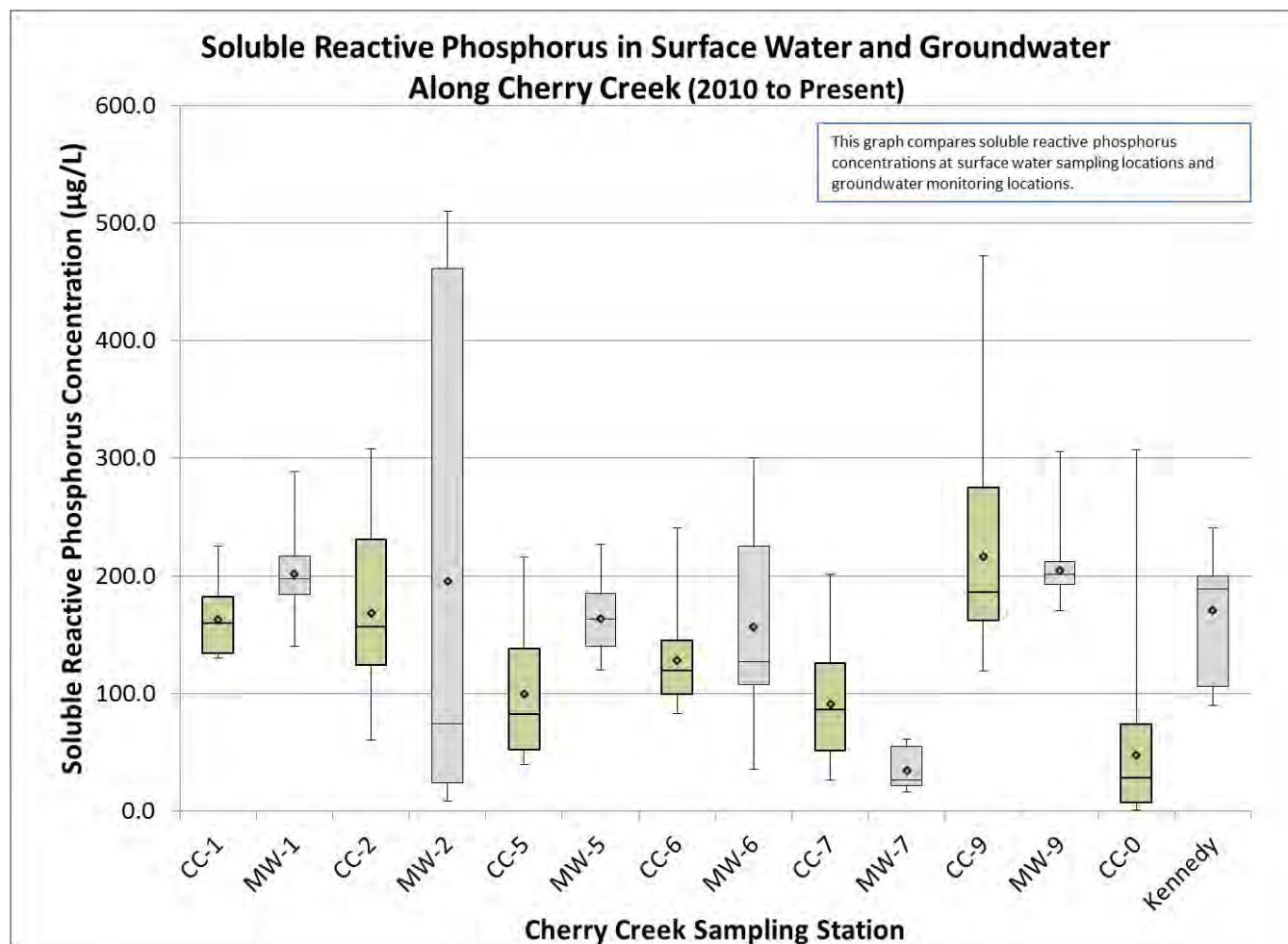


Figure 26. Soluble Reactive in Surface Water and Groundwater along Cherry Creek (2010 to Present) Sources of Data: GEI Consultants, Inc. (Jan 2010 – Feb 2016); IEH Analytical, Inc. (March 2016 – September 2016)

Over the past 20 years, the concentration of SRP in the alluvial groundwater upstream of the Reservoir appears to be gradually increasing, adding to the Reservoir nutrient source pool (Figure 27).

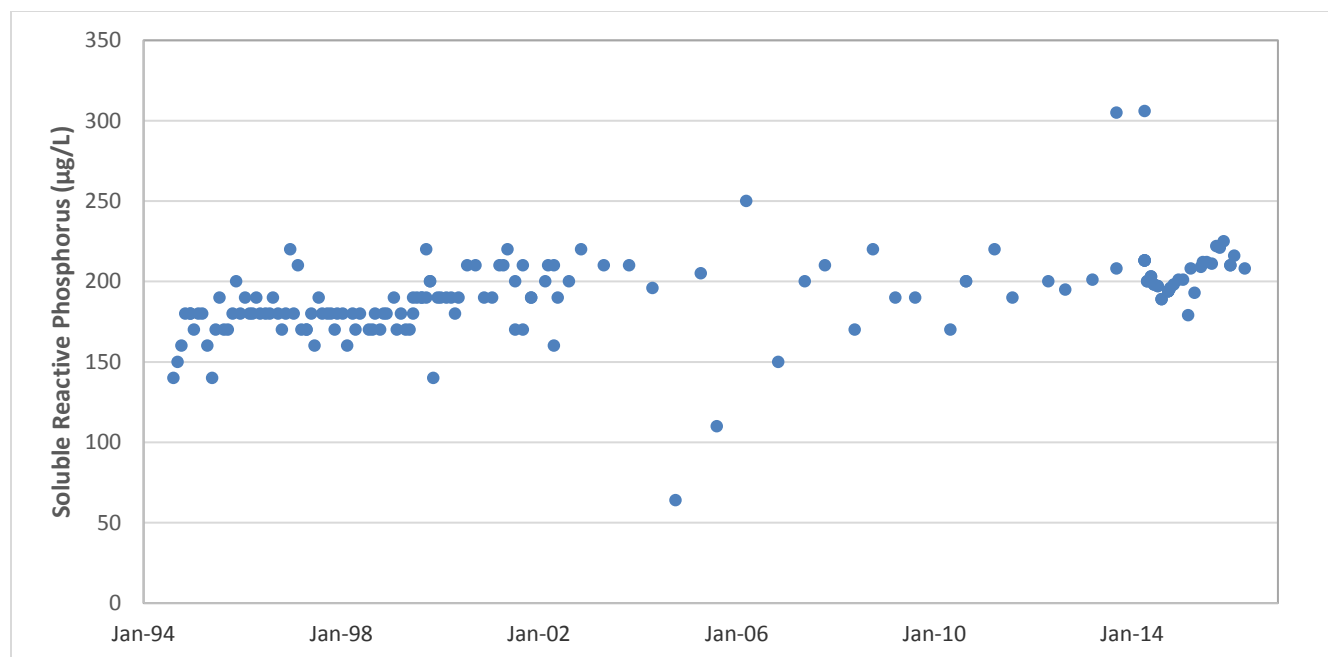


Figure 27. Historic SRP Concentrations in Alluvial Well MW-9 (1994 – 2016) (Sources of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (2010 – February 28, 2016); Halepaska and Associates (1994 - 2010).

Well MW-9 was sampled and analyzed for the total and dissolved forms of organic carbon (TOC and DOC, respectively) six (6) times during WY2016. The WY2016 TOC and DOC results are illustrated in Figure 28 along with historical data from the well.

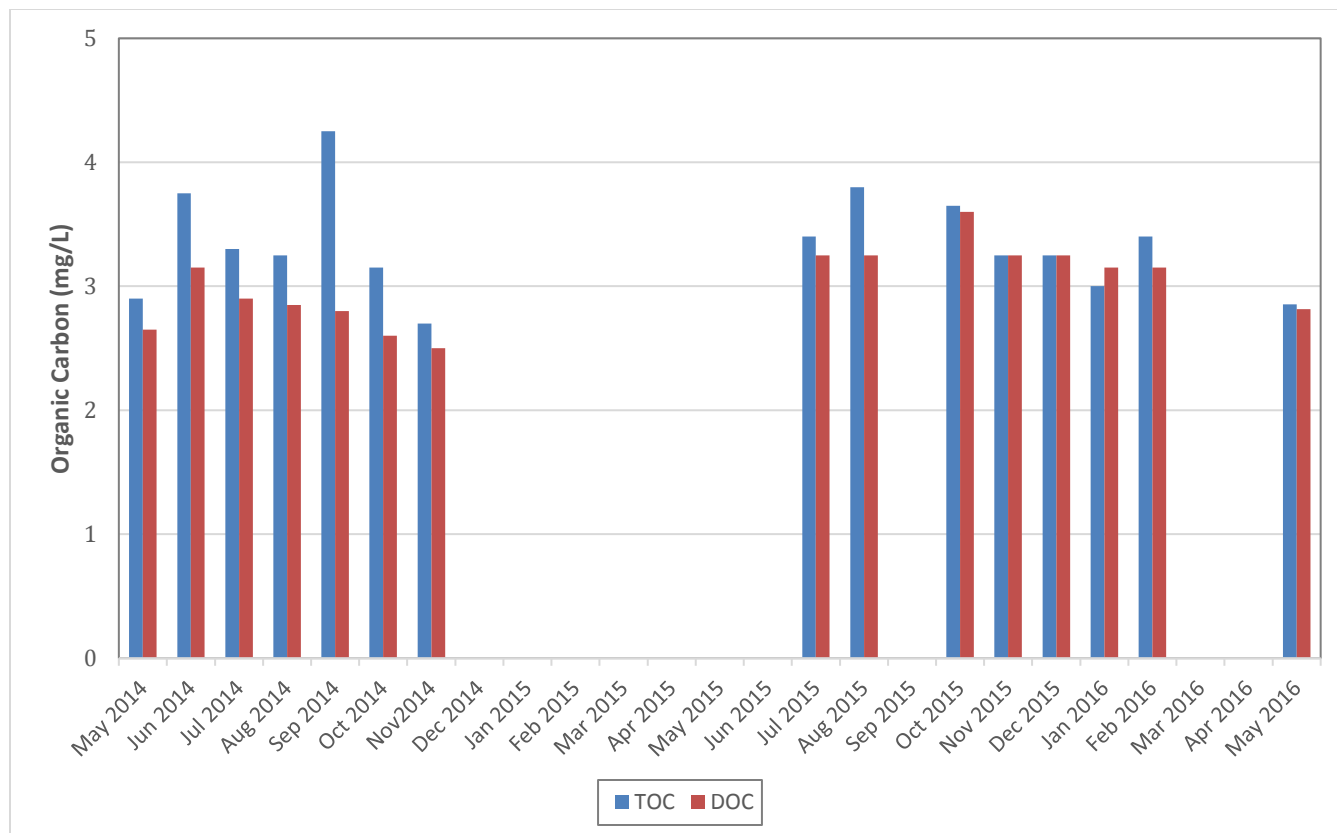


Figure 28. Total and Dissolved Organic Carbon Data from MW-9. Sources of Data: GEI Consultants, Inc. (May 2014 – February 2016; IEH Analytical, Inc. (March 2016 – September 2016)

The long-term TOC concentrations in the alluvial groundwater samples collected from well MW-9 range from 2.7 mg/L to 4.3 mg/L, averaging 3.3 mg/L. The TOC concentrations measured in the six samples collected in WY2016 exhibited the slightly lower average of 3.2 mg/L.

As illustrated in Figure 28, historically the dissolved fraction comprises between 66% and 100% of the total organic carbon present in the alluvial groundwater samples collected from well MW-9, with a long-term average of 91%. In WY2016, essentially all the organic carbon (99%) was present in the dissolved fraction.

3.2 RESERVOIR

Monitoring at the Reservoir has focused on data to support regulatory requirements and attaining beneficial uses; aquatic life, recreation and indirect downstream uses, water supply and agriculture. As such, the primary constituents of concern are phosphorus, nitrogen, and chl-a. Nutrients, TP and TN, are often the contributing or limiting factor in the growth of algae (Cole 1979; Horne and Goldman 1994; Wetzel 2001; Cooke, et al. 1993). Excessive amounts of these nutrients in aquatic systems often result in algal blooms that create an imbalance in the Reservoir, aesthetic problems, as well as potentially unsuitable conditions for aquatic life. High external loads from the watershed, coupled with internal phosphorus loading in the Reservoir itself, impact water quality in the Reservoir. Chl-a, a regulated indicator of algae level, affects aquatic life, fishing, swimming and other recreational uses. Ultimately, lower nutrient concentrations are necessary to greatly reduce algal biomass as measured by chl-a.

The phycology data provides an excellent biological indicator of what plankton species are thriving and helps determine ecological stressors, overall health of the Reservoir, and an understanding of the basis for some water quality issues. Other physical parameters described in this section, transparency, dissolved oxygen, temperature, and pH, support protection of aquatic life and recreational uses.

3.2.1 Transparency

Secchi disk depth and a LI-COR water sensor provided a measurement of Reservoir water clarity or transparency in WY2016. Transparency is a basic indicator of the health of an aquatic ecosystem and the level of biological productivity.

Figure 29 depicts mean Secchi disk depth in the Reservoir at CCR-2 during WY2016. The mean Secchi disk depth was as high as 1.7 meters (m) in mid-June, representing the highest clarity condition which coincided with:

- Highest precipitation events and Reservoir flushing rates,
- Lowest phytoplankton cell counts and chl-a concentration (7.6 µg/L), and
- Lowest TP concentration (4.6 µg/L).

The end of July Secchi disk depth measurements of approximately 0.6 meters represented hypereutrophic conditions and reduced clarity. The greatest chl-a and TP concentrations were also measured during this timeframe (34 µg/L and 154 µg/L, respectively). Secchi disk depth from 1992 to present is depicted in Figure 30. Over the past 25 years the Secchi disk depth has declined, although the statistical relationship is poor ($R^2 = 0.29$). Since 2000 there is no statistical change in Secchi disk depth ($R^2 = 0.05$).

The LI-COR sensor measured light attenuation to determine transparency and the depth at which 1% of photosynthetically active radiation penetrated the water column (i.e., photic zone depth). The depth of 1% light attenuation ranged from 1.1 m in late July/August timeframe to a maximum depth 6.5 m in mid-June. Figure 31 depicts the direct relationship between Secchi disk depth and 1% light attenuation ($R^2 = 0.70$). A stronger relationship is observed with Secchi disk depth up to 1.8 m and 1 % light attenuation up to 5 m.

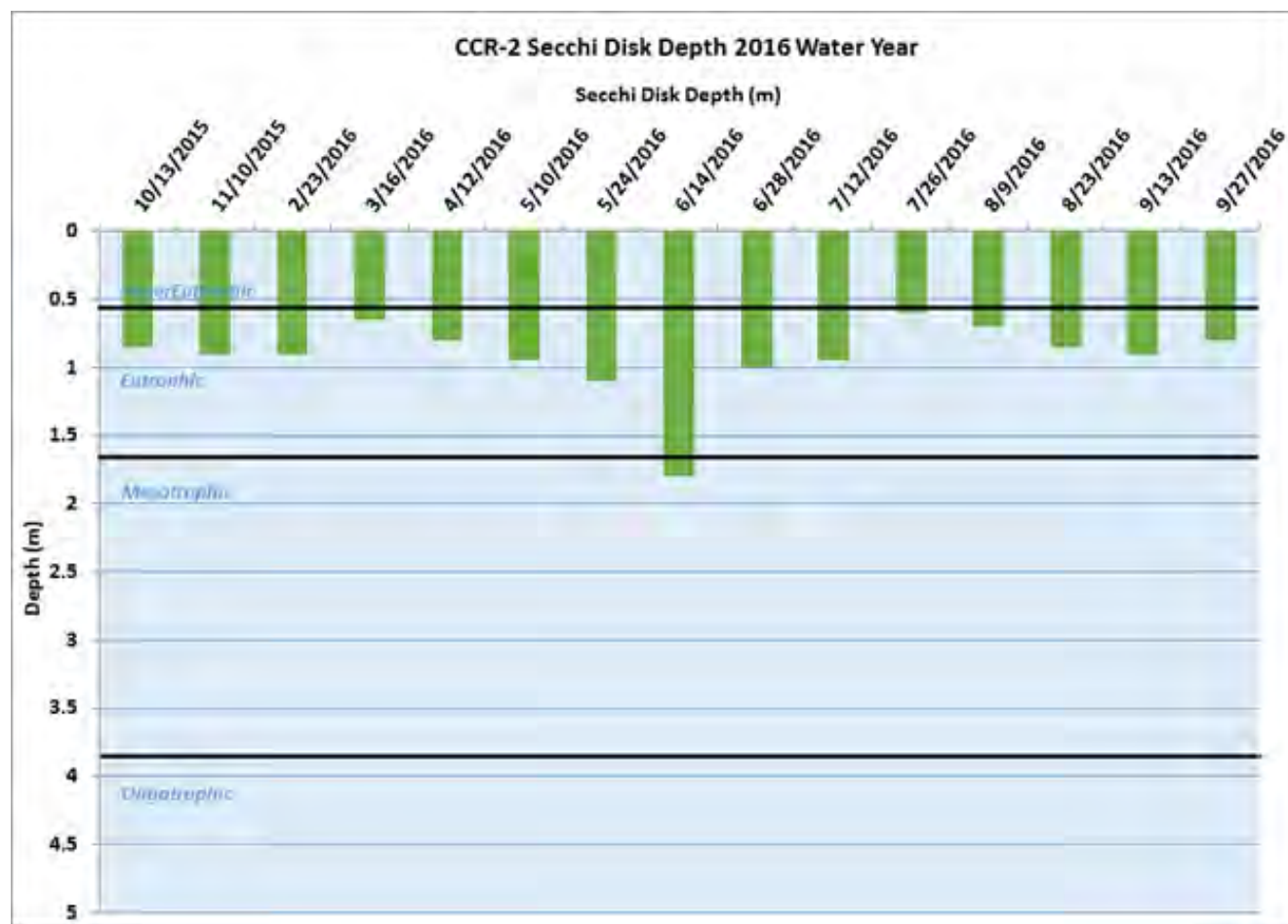


Figure 29. WY2016 Secchi Disk Depth in Cherry Creek Reservoir, Station CCR-2 (Source of Data: IEH Analytical, Inc. (March 1 2016 – September 30, 2016); GEI Consultants, Inc. (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).

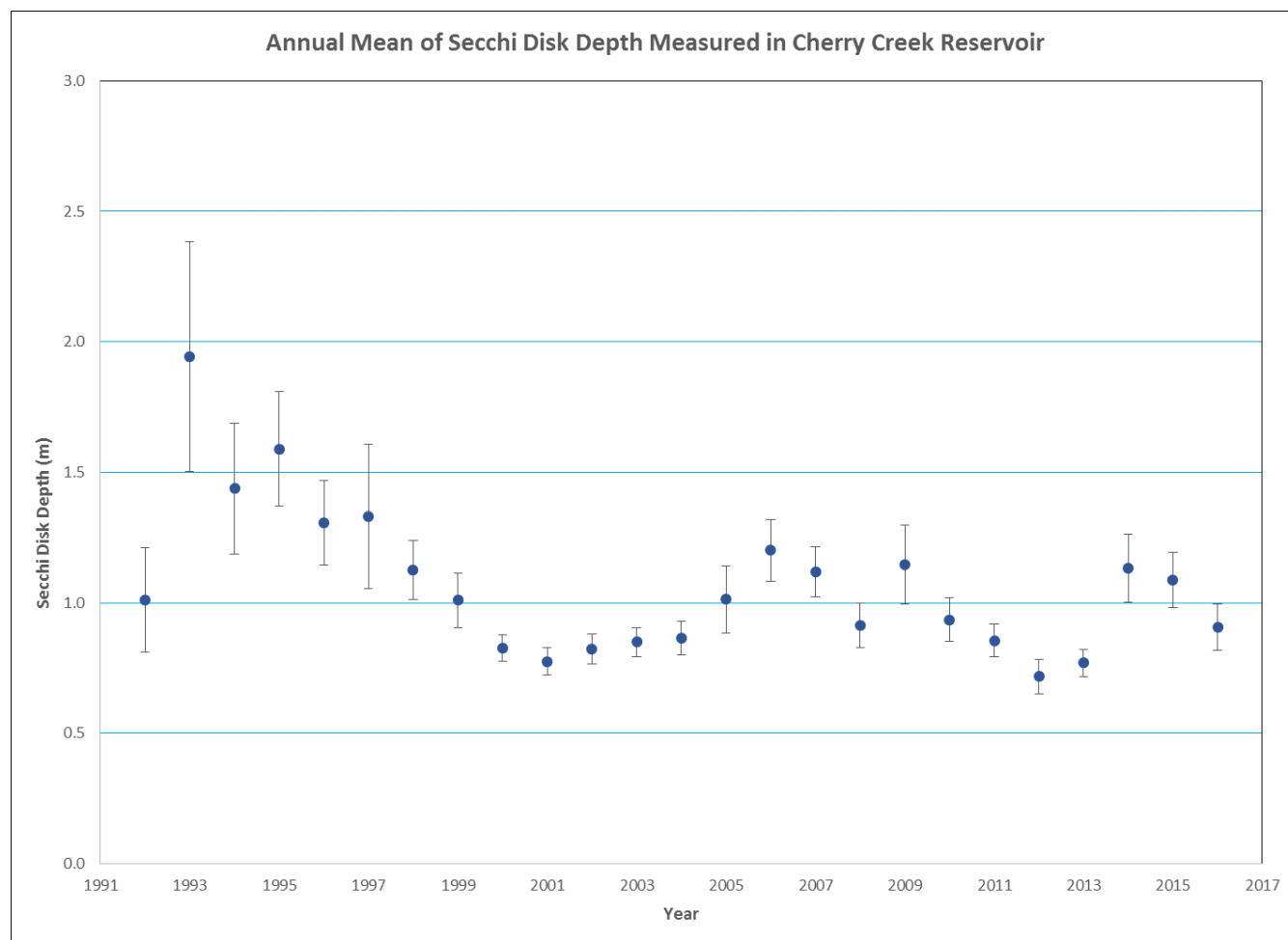


Figure 30. Annual Mean Secchi Disk Depth Measured in Reservoir, 1992 – 2016. The Secchi Disk depth decreased 1992 – 2000. There is no trend in the data from 2001 – 2016. (Sources of Data: IEH Analytical, Inc. (March 1, 2016 – September 30, 2016); GEI Consultants, Inc. (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).

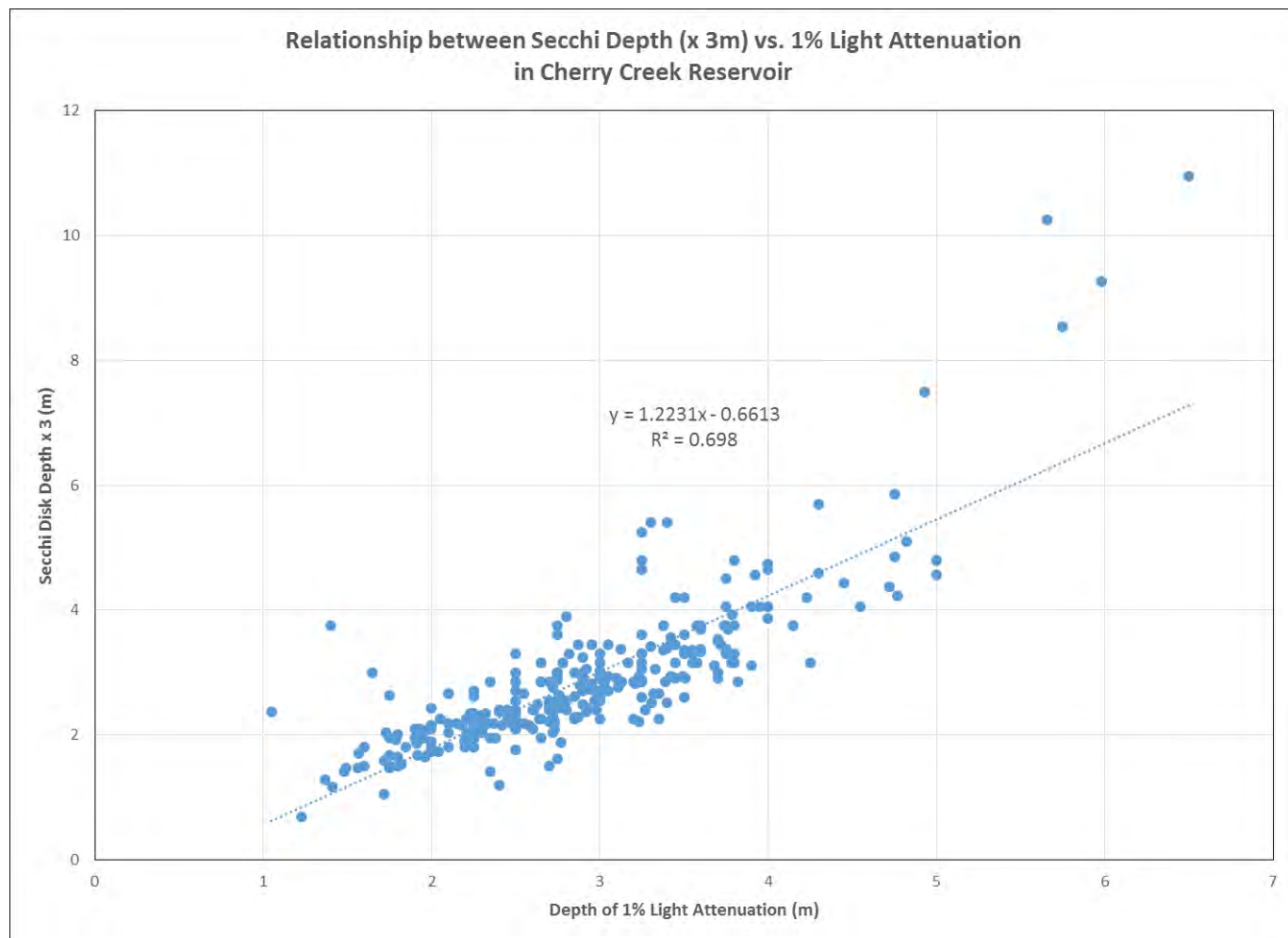


Figure 31. Relationship between Secchi Disk Depth X 3 (m) and Depth of 1% Light Attenuation in Reservoir (m) –

There is a direct relationship between Secchi disk depth and 1% light attenuation ($R^2=0.70$). A stronger relationship is observed with Secchi Disk depth up to 1.8 m and 1 % light attenuation of 5 m. (Sources of Data: IEH Analytical, Inc. (March 1, 2016 – September 30, 2016); GEI Consultants, Inc. (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).

3.2.2 Total Phosphorus

The WY2016 TP concentrations measured in the photic zone ranged between 48 µg/L and 175 µg/L (Figure 32). The growing season mean TP concentration was 126 µg/L. The lowest TP concentration of 48 µg/L was measured on June 14, 2016, after the HABs were observed May 31, 2016 – June 9, 2016. This is most likely due to the increase in precipitation and outflow effectively flushing some of the algal biomass with organic-P out of the Reservoir, coupled with sedimentation of the algal bloom biomass that transported TP to the Reservoir sediments.

Data collected throughout the growing season indicated an abundance of TP in the Reservoir, resulting in a eutrophic reservoir that continues to age and even show hypereutrophic tendencies. Therefore, it appears the light and hydraulic residence time (flushing rate) were the limiting factors in controlling phytoplankton productivity.

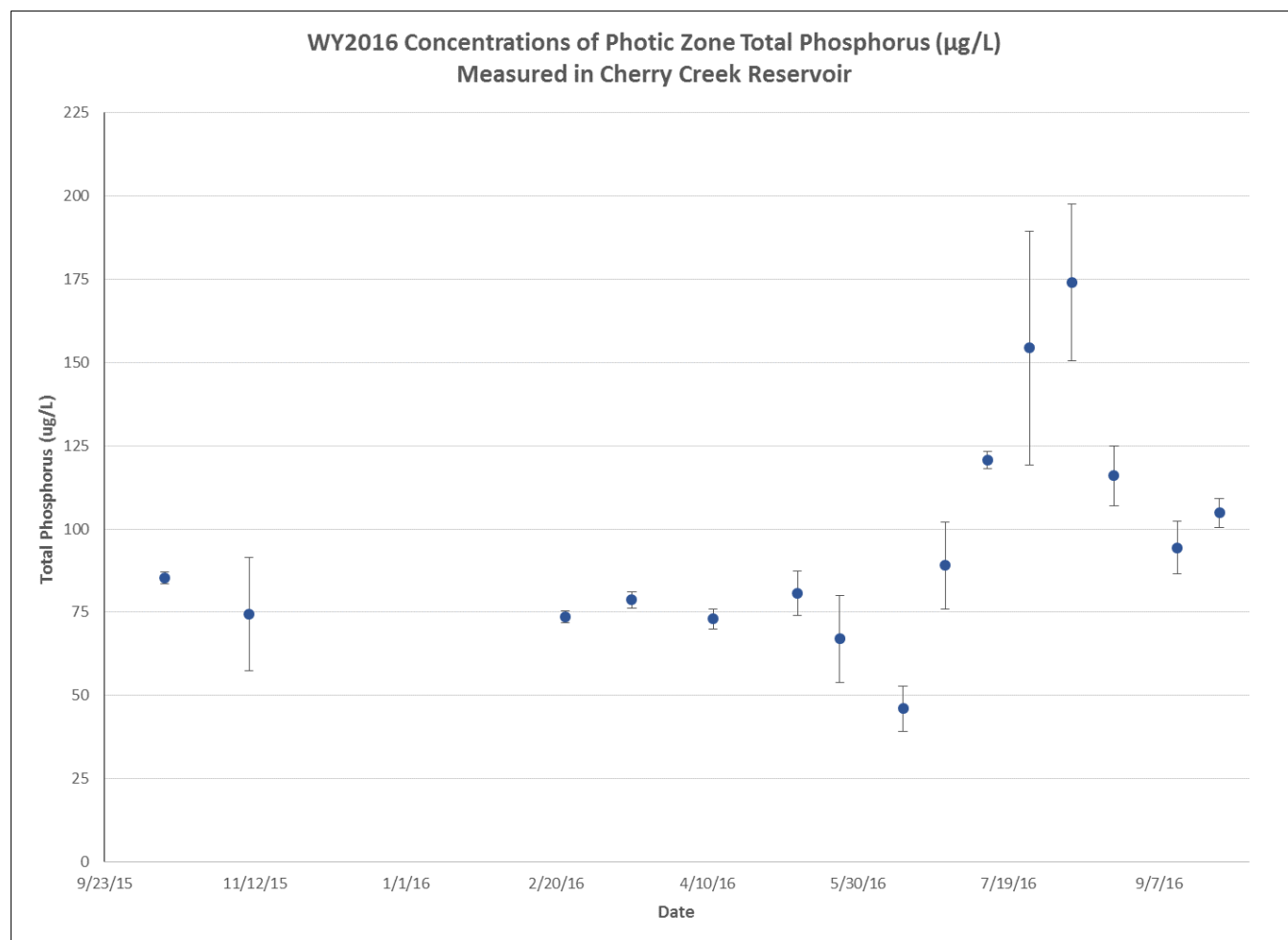


Figure 32. Total Phosphorus in Cherry Creek Reservoir – As measured in photic zone at all reservoir stations. The error bar represents the 95th percentile around the mean. (Sources of Data: IEH Analytical (March 1 2016 – Sept 30 2016); GEI Consultants (Oct 1 2015 – Feb 28 2016))

An evaluation of seasonal mean TP concentrations (1992 – 2016) in the Reservoir indicates an increasing pattern in the last 30 years of 200% (Figure 33).

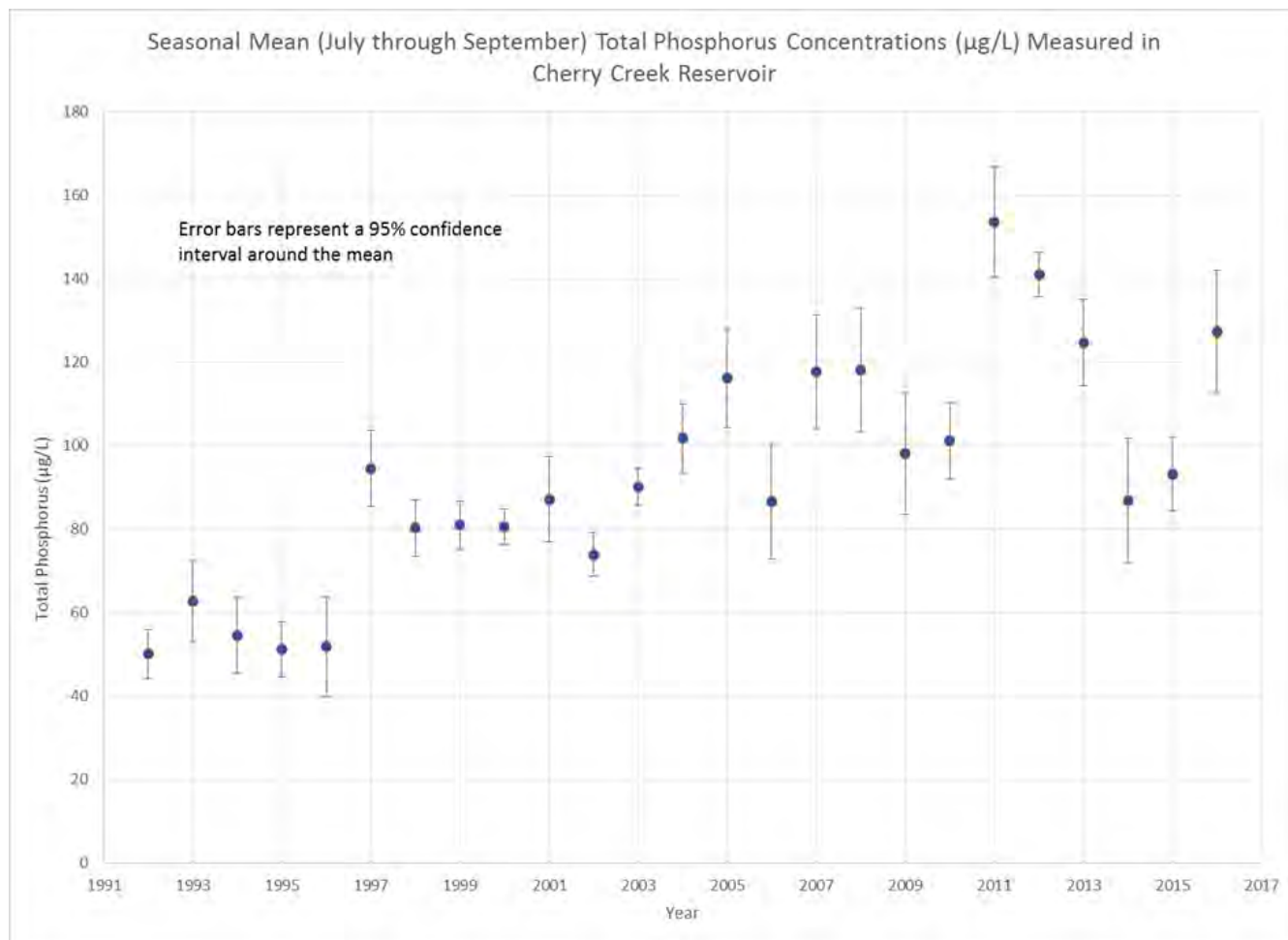


Figure 33. Seasonal Mean TP Concentrations in Cherry Creek Reservoir, 1992 – 2016. The error bar represents the 95th percentile around the mean. (Sources of Data: IEH Analytical (March 1 2016 – Sept 30 2016); GEI Consultants (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2005); University of Missouri (1992 – 1994).

TP profiles at Reservoir monitoring station CCR-2 at depths 1.5 meters to 7 meters are depicted in Figure 34. Internal TP loading was observed and more prevalent during June and August. As shown, the TP concentration at 7 m was measured up to 225 µg/L on June 14, 2016. The internal nutrient release of phosphorus from bottom sediments occurred when the bottom of the Reservoir becomes anoxic (very low DO concentrations) as discussed in Section 3.2.9. The sediment phosphorus load accumulates over time from external sources, including from the Reservoir, and is geochemically transformed and released when the sediment surface becomes anoxic (Nürnberg and LaZerte, 2008). This internal release of phosphorus facilitated the growth of all algae; increasing the seasonal mean chl-a concentrations and the production of cyanobacteria (blue green algae). Throughout June, DO concentrations at depths greater than 6 m were less than the upper threshold that facilitates internal loading (2 mg/L) and created an anoxic environment near the water/sediment boundary (see Figure 44) which resulted in elevated phosphorus concentrations at depth (Figure 34). Phosphorus can be released at rates as much as 1,000 times faster during anoxic conditions than during well oxygenated conditions (Horne and Goldman, 1994). Although the rate of exchange of nutrients (mainly phosphorus)

at the water/sediment interface remains unknown for the Reservoir, this internal nutrient loading component of the Reservoir has been estimated to account for approximately 25% of the cumulative TP load from 1992 to 2006 (Nürnberg and LaZerte, 2008).

However, it was not just the total amount of TP loading that was important in 2016. The timing of the load and bioavailability of TP was critical. Given Cherry Creek Reservoir is a polymictic reservoir¹ (Section 3.2.7) and the rapid influx of TP and SRP (Figures 34 and 35) during periods of robust biological activity shown by pH and DO changes (Sections 3.2.8 and 3.2.9), internal cycling of P within the Reservoir is one of the foremost drivers enabling excessive phytoplanktonic productivity. The WY2016 data illustrated in Figure 34 indicated that overall levels of phosphorus were very high, given the eutrophic-hypereutrophic boundary for TP is 100 µg/L and the eutrophic boundary starts at 25 µg/L (Nürnberg, 1996).

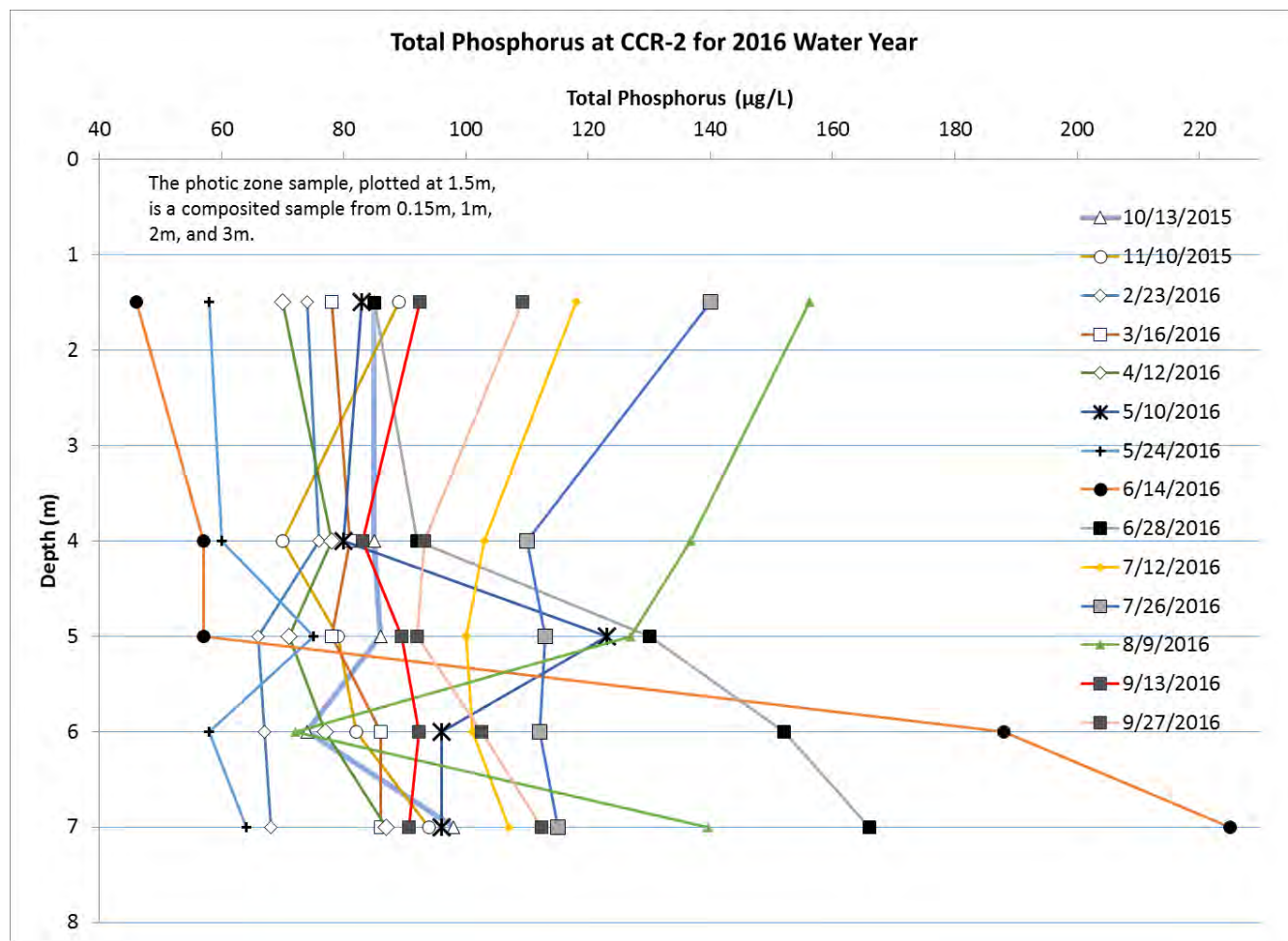


Figure 34. 2016 TP at Monitoring Station CCR-2 (1.5 – 7 meter depth profiles). Internal loading of TP observed at depths below 5 m in July, August, and September (Sources of Data: IEH Analytical (March 1 2016 – Sept 30 2016); GEI Consultants (Oct 1 2015 – Feb 28 2016))

¹ Polymictic reservoirs and lakes are too shallow to develop strong thermal stratification. Consequently, their waters tend to mix from top to bottom, many times through the ice-free period.

3.2.3 Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) represents the bioavailable form of this nutrient. Figure 35 depicts SRP data collected at Reservoir monitoring station CCR-2 during profile sampling in WY2106. As shown, the Reservoir was well-mixed in October 2015 through March 2016. During May 24th through July 12th, elevated bioavailable nutrients, up to 156 µg/L, were observed at depths below 5m, indicating an extended period of nutrient release from bottom sediments. The period of observed heightened nutrients at the Reservoir bottom suggest that even a few centimeters of anoxic water at the water/sediment interface, which the Sonde monitoring device may not have captured, is sufficient for creating a reducing environment and internal load release of nutrients (GEI, 2015). There may also be significant aerobic and anaerobic mineralization of organic-P to SRP with the decay of phytoplankton that has settled to the bottom. The elevated SRP at these depths show a rapid and dramatic spike in concentration of SRP at deeper reservoir depth, confirming soluble phosphorus was released from sediments during this time. This also indicates the P recycling within the reservoir is happening at a rapid rate and through multifaceted processes due to the history of nutrient retention within the Reservoir over the past several decades.

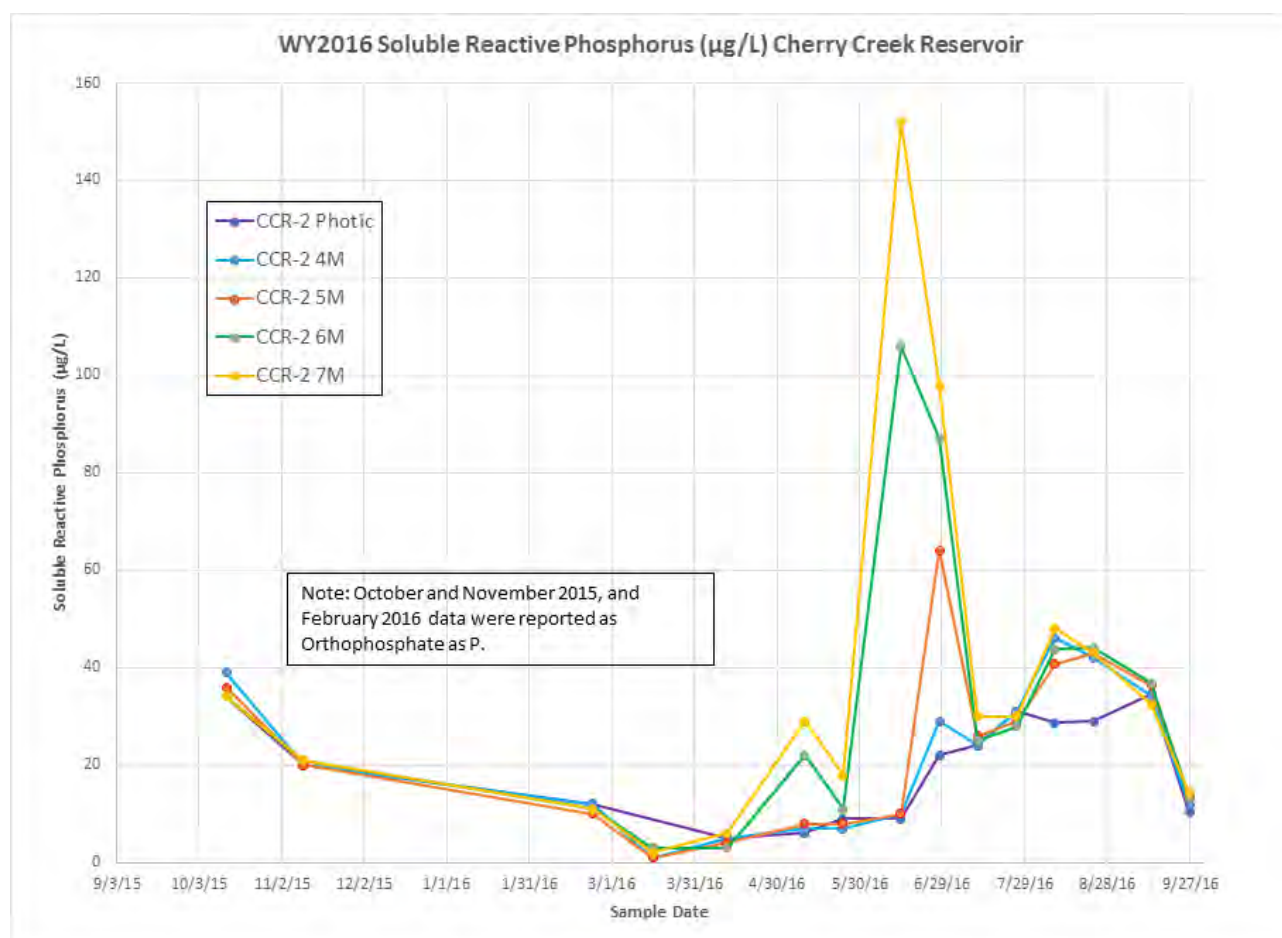


Figure 35. SRP Variability in Reservoir at CCR-2. Depth profile measurements confirm internal phosphorus loading at depths below 5 m during May 24th through July 12th. (Sources of Data: IEH Analytical (March 1 2016 – Sept 30 2016); GEI Consultants (October 1, 2015 – February 28, 2016)).

3.2.4 Total Nitrogen

The July – September seasonal mean TN in the Reservoir was 910 µg/L. The long term average from 1992 – 2016 is 938 µg/L and no discernible increasing or decreasing trend was identified with the TN data (Figure 36).

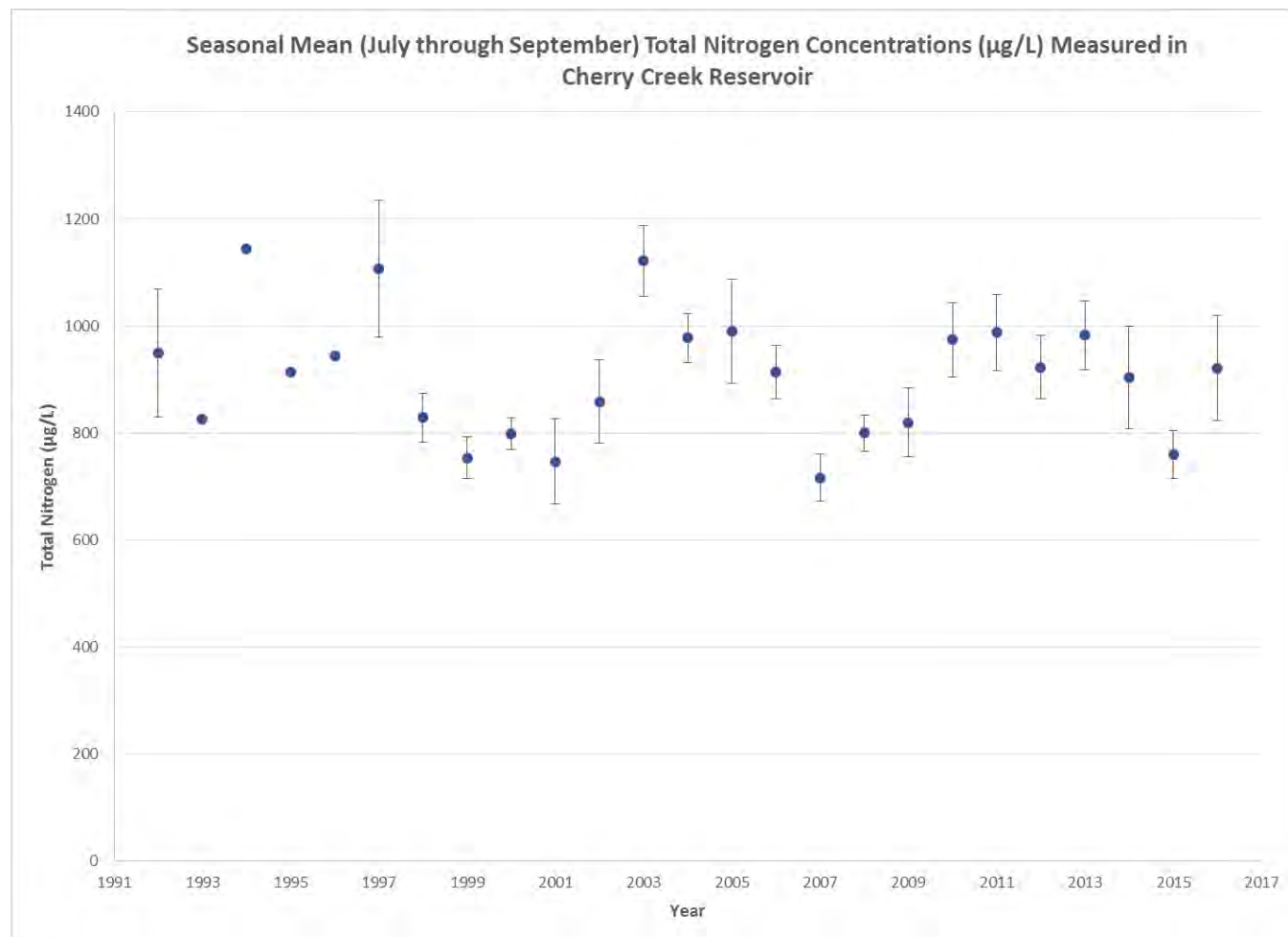


Figure 36. TN Measured in Cherry Creek Reservoir, 1992 – 2016. In 2016, TN concentration was 910 µg/L; the long term average is 938 µg/L. No long term trends, increasing or decreasing, are noted. (Sources of Data: IEH Analytical (March 1 2016 – Sept 30 2016); GEI Consultants (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).

3.2.5 Total Inorganic Nitrogen (TIN)

TIN is calculated as the sum of nitrate-nitrite as N and ammonia as N. Similar to SRP, TIN was elevated at depths of 6-7m, specifically during the June/July timeframe, suggesting the presence of internal nitrogen loading (Figure 37).

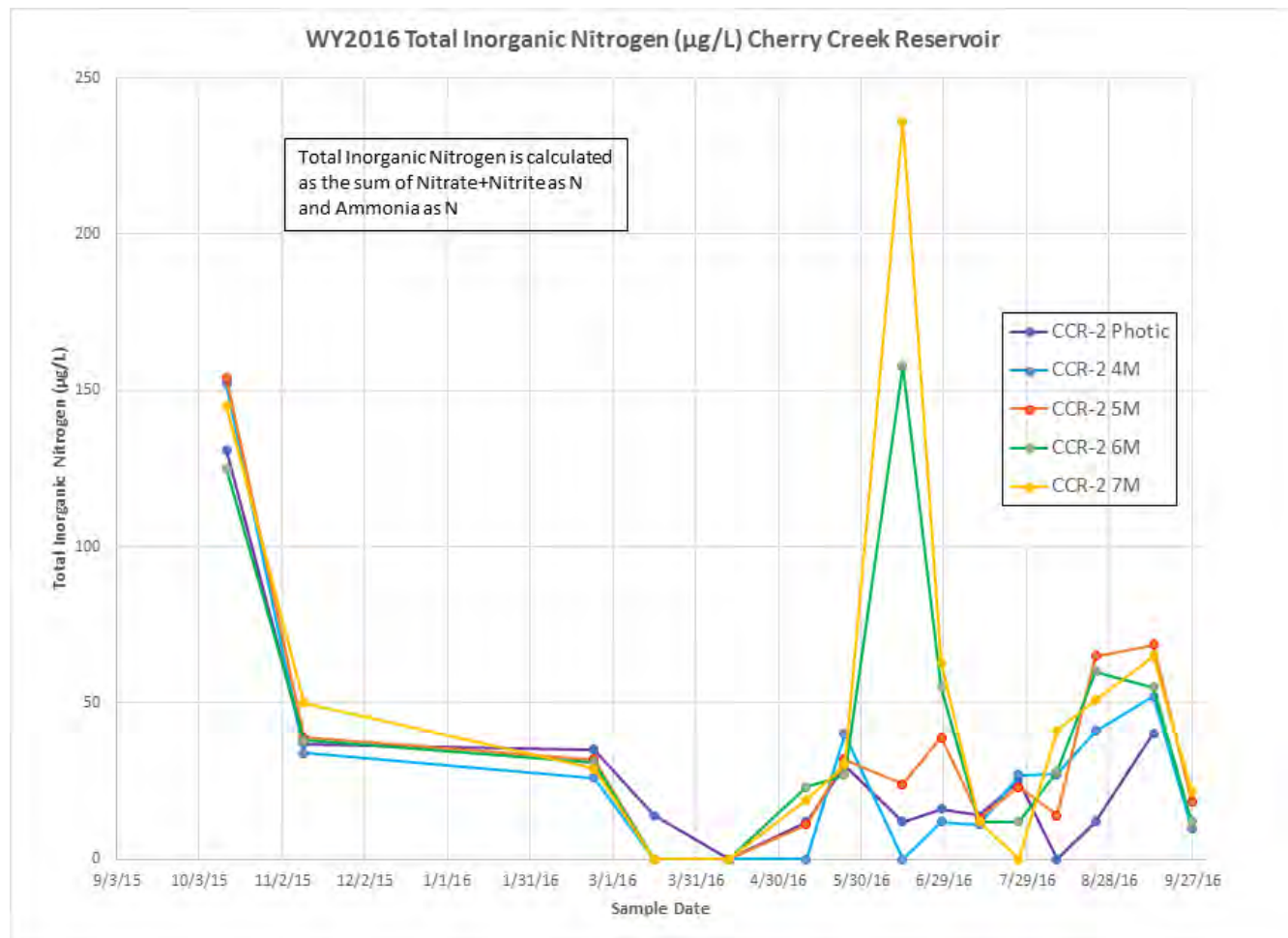


Figure 37. Total inorganic nitrogen (TIN) Concentrations at CCR-2, Photic Zone – 7 meters. Elevated data observed at depths of 6-7 meters in June/July suggest occurrence of internal nitrogen loading. (Sources of Data: IEH Analytical (March 1, 2016 – Sept 30, 2016); GEI Consultants (October 1, 2015 – February 28, 2016)).

Figure 38 depicts nitrate-N and ammonium-N separately in the Reservoir at 3-7 meters to determine whether it was decay of organics through aerobic or anaerobic processes that contributed to the N availability. This graphical analysis also serves to support our understanding of N utilization and the potential for N limitation for what algal group and, if so, the timing of this limitation. Of particular note is that cyanobacteria (blue-green algae) can use both ammonium and nitrate, while chlorophyta (green algae) and most diatoms require nitrate. Also, blue-greens can be a producer of ammonium. As shown, the highest ammonium concentration occurred at the middle of the lowest DO in the bottom water (7m) at CCR-2. This indicated sediment degradation with the release of ammonium that cyanobacteria could utilize.

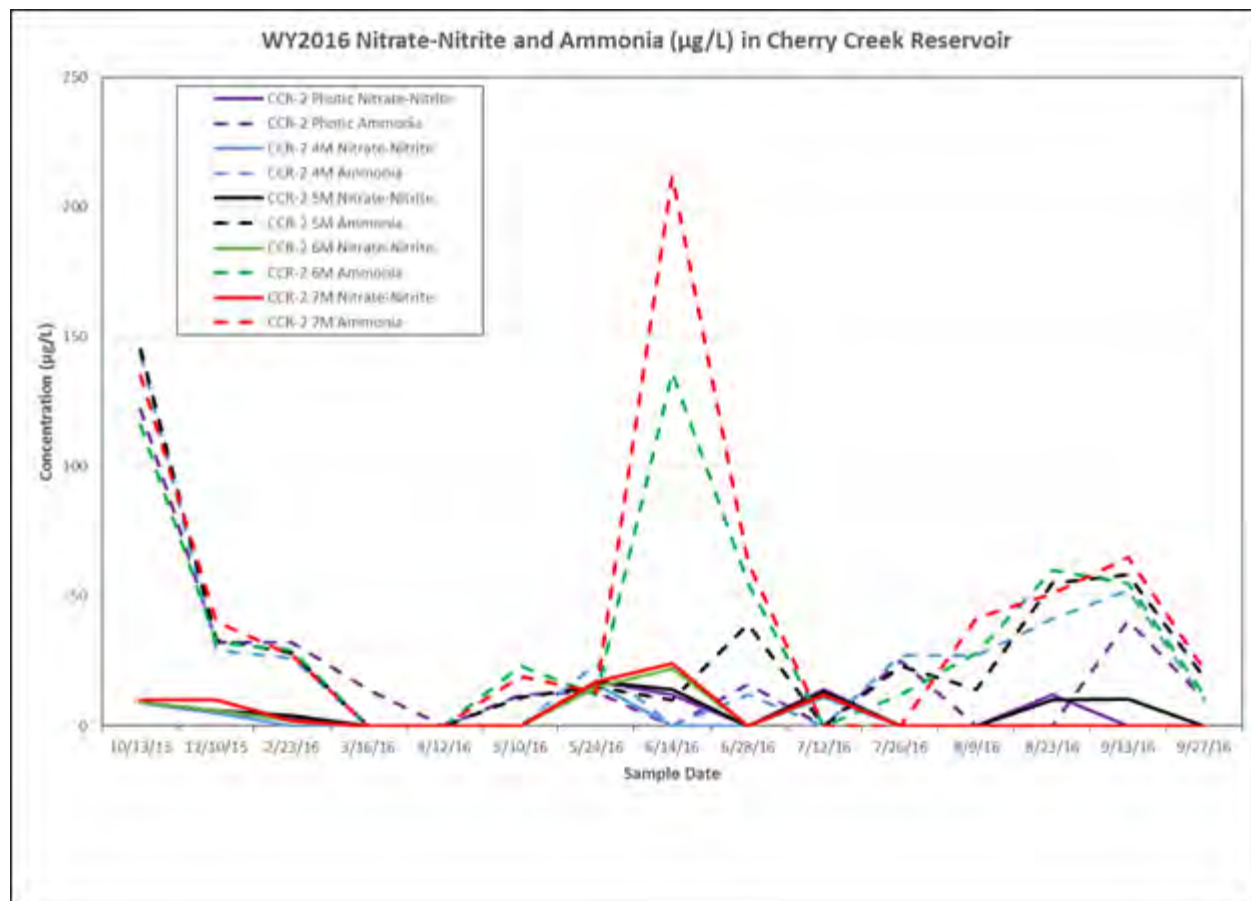


Figure 38. Nitrate-nitrite and ammonia concentrations at CCR-2, Photic Zone – 7 meters. Elevated ammonia observed at depths of 6-7 meters in June/July suggest occurrence of sediment degradation with the release of ammonia that could become available for cyanobacteria. (Sources of Data: IEH Analytical (March 1, 2016 – Sept 30 2016); GEI Consultants (October 1, 2015 – February 28, 2016))

3.2.6 Chl-a

The chl-a growing season (July through September) concentration was 23.6 µg/L, in exceedance of the 18 µg/L growing season average regulated for chl-a (Figure 39). The seasonal mean concentration is measured in the photic zone, with an allowable exceedance frequency of once in five years. The late July 12, 2016 sampling indicated a higher concentration and more variability in chl-a between the three reservoir stations. An algal bloom was observed at Station CCR-2 in July, affecting the chl-a concentration at this site (Figure 40). To add some perspective, Table 11 shows the past occurrences of chl-a concentrations above 50 µg/L. While the 59 µg/L is high, it is not unprecedented, nor is it unexpected given other parameters and the hypereutrophic condition (greater > 25 µg/L, Nürnberg, 1996) of the Reservoir during this time. Specifically, TP at this location was 190 µg/L and the chl:TP ratio was at the world average of 0.3 (from data used by Nürnberg, 1996 and presented in Welch and Jacoby, 2004), consistent with the chl-a measurement of 59 µg/L.

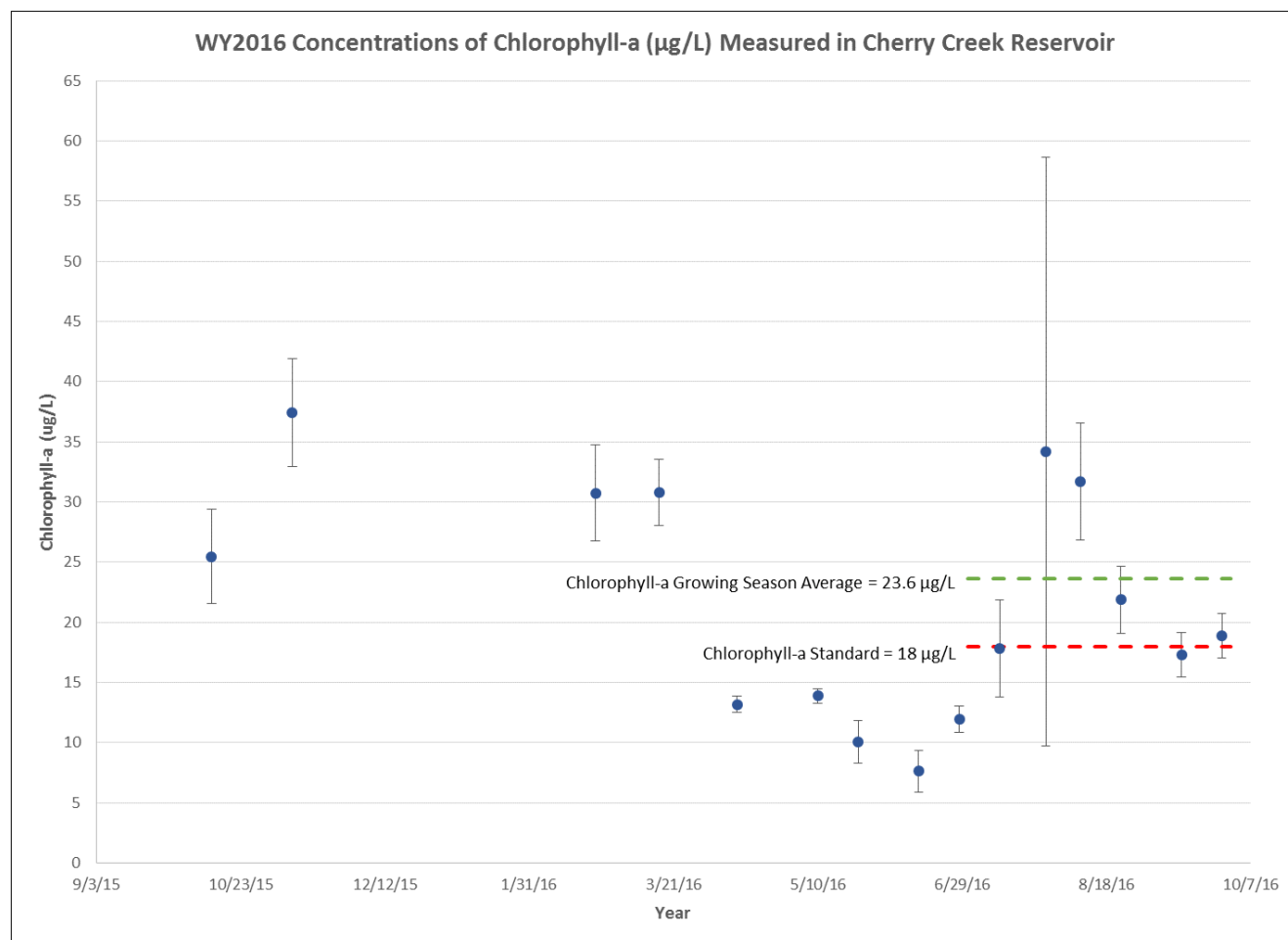


Figure 39. Chl-a, Growing Season Average, was 23.6 $\mu\text{g/L}$, in exceedance of the 18 $\mu\text{g/L}$ standard. The error bar represents the 95th percentile around the mean. (Sources of Data: IEH Analytical (March 1, 2016 – Sept 30, 2016); GEI Consultants, Inc. (October 1, 2015 – February 28, 2016)).

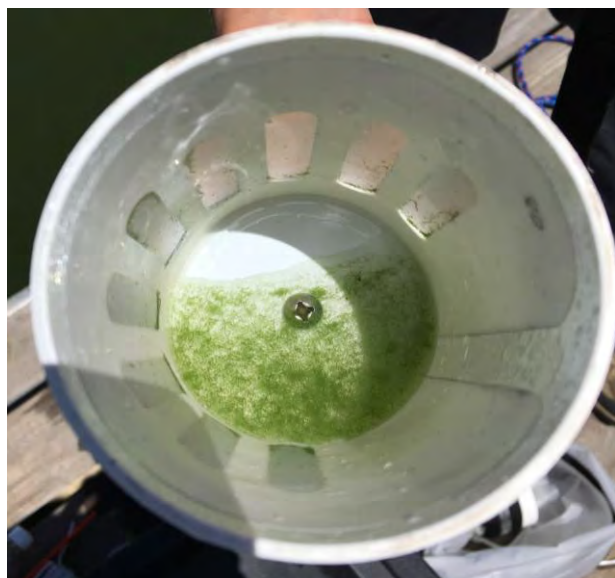


Figure 40. Algae in Zooplankton Net at CCR-2 (Photo taken July 12, 2016) The algal bloom, which appears as small grass clippings, was prolific at this site and supported the high, but not unprecedented, concentration of chl-a at 59 $\mu\text{g/L}$.

Table 11. Summary of Historic Chl-a Concentrations in Exceedance of 50 µg/L in the Reservoir. (1992 – 2016)

Date	Monitoring Location	Chlorophyll-a Concentration (µg/L)
8/27/1992	CCR1	65.1
8/4/1998	CCR1	60.75
7/27/1999	CCR3	54.85
8/17/1999	CCR1	53.65
1/17/2007	CCR3	53.7
1/17/2007	CCR2	56.8
2/23/2010	CCR3	52.8
8/10/2010	CCR2	56.6
10/14/2010	CCR2	51.3
11/16/2010	CCR2	52.5

The Reservoir has exceeded the chl-a standard in four of the last five years (Figure 41). The Reservoir is in a eutrophic-hypereutrophic state as defined by chl-a concentrations of >9 µg/L (eutrophic) and > 25 µg/L (hypereutrophic) and total phosphorus concentrations >25 µg/L (eutrophic) to >100 µg/L (hypereutrophic) (Nürnberg, 1996).

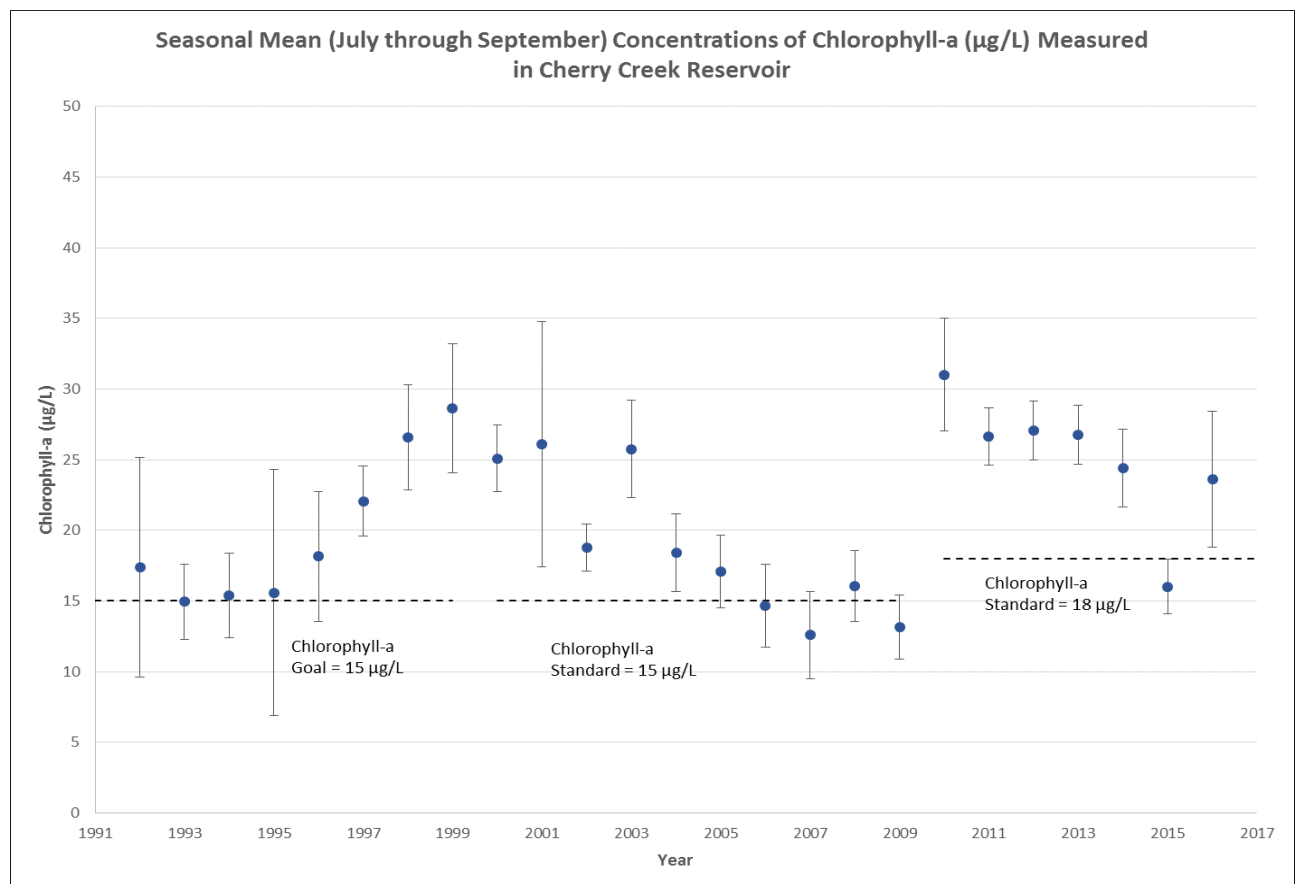


Figure 41. Seasonal Means of Chl-a in Reservoir, 1992 – 2016. The chl-a water quality standard is 18 µg/L, with a 1-in -5 year exceedance frequency. The Reservoir has exceeded the chl-a standard the last 4 out of 5 years. The error bar represents the 95th percentile around the mean. (Sources of Data: IEH Analytical (March 1, 2016 – Sept 30 2016); GEI Consultants (2006 – February 28, 2016); Chadwick Ecological Consultants (1995 – 2006); University of Missouri (1992 – 1994).

External P loading from the watershed, coupled with internal P loading in the Reservoir, were high enough to result in the generation of excess algal production and chl-a levels above the standard. The likely control factors for low versus high production summers appear to include internal mixing, flushing rate, and light limitation during the growing season. However, these factors are not really controllable or predictable and the Reservoir is getting more productive as time goes on due to the natural progression of man-made lakes, elevated nutrient concentrations observed within the watershed and recycled nutrients in the Reservoir sediments that are 2 -100 times that of the flushing rate under current conditions in the Reservoir. Reduction in external loading and management of internal P cycling are needed to meet the chl-a water quality standard in the Reservoir. Ongoing management of both external (in watershed) and internal (in-reservoir) nutrient loads will support lower productivity in the Reservoir to promote long term protection of beneficial uses.

3.2.7 Temperature

Figure 42 depicts the temperature variability (in degrees Celsius) at Reservoir station CCR-2. The Reservoir met the temperature standards established for the Reservoir, protective of the warm water fishery (WQCC Regulation No. 31, effective December 31, 2016) including the April – December temperature standards of 26.2 °C (chronic) and 29.3 °C (acute) and January – March temperature standards of 13.1 °C (chronic) and 24.1 °C (acute). As observed in polymictic lakes, the Reservoir was mixed relative to temperature, with very little vertical thermal stratification (thermal resistance to mixing).

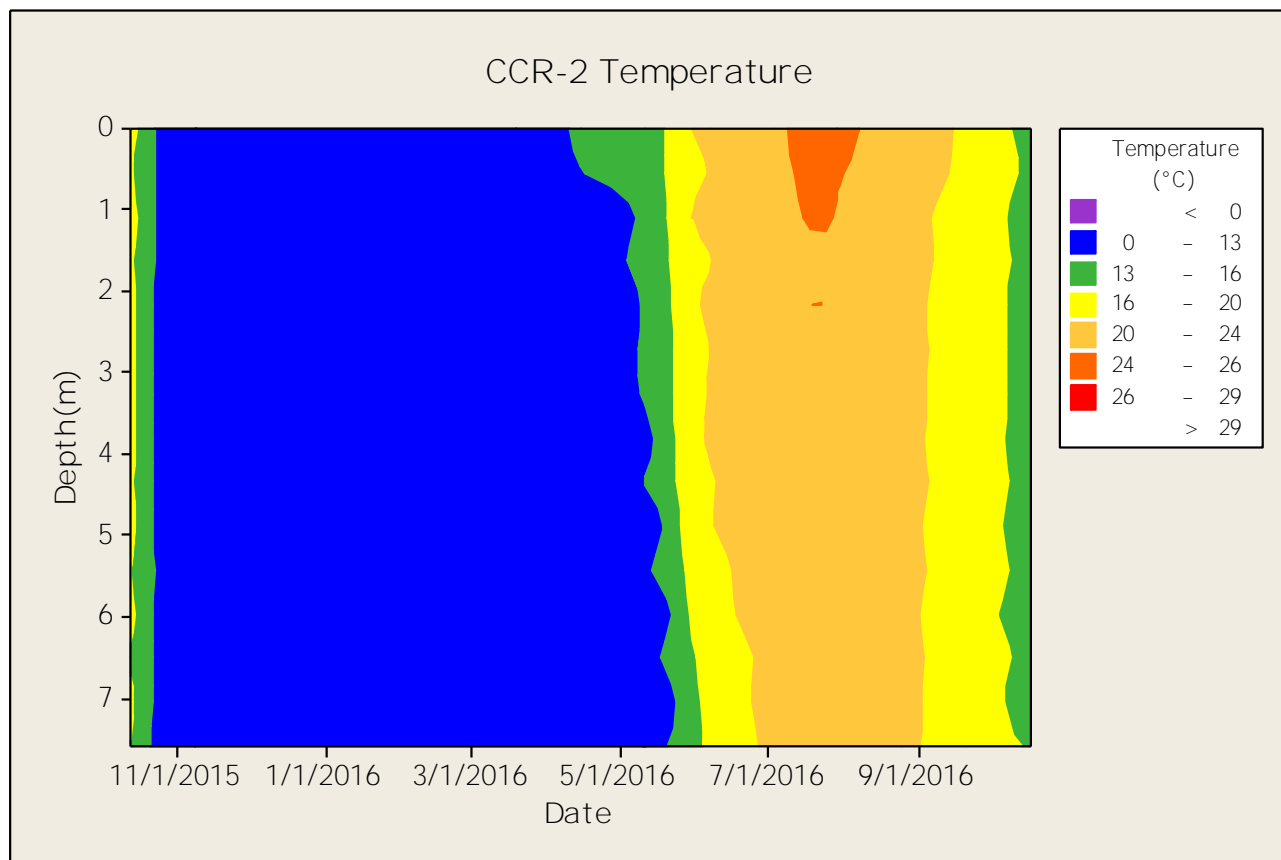


Figure 42. WY2016 Temperature Profile in Cherry Creek Reservoir, Station CCR-2. Data demonstrate the temperatures is protective of aquatic life. (Sources of Data: Tetra Tech, Inc. (March 1, 2016 – Sept 30 2016); GEI Consultants (October 1, 2015 – February 28, 2016)).

3.2.8 pH

The pH in the Reservoir ranged 7.4 to 8.6 (Figure 43). The higher pH observed during March through June and, to a slightly lesser extent, through the end of September was a direct result of photosynthetic production within the Reservoir. Given the historically higher reservoir releases during this period that flush some of the biomass, there was likely less chlorophyll buildup in the Reservoir than there was potential for, given the elevated nutrient levels.

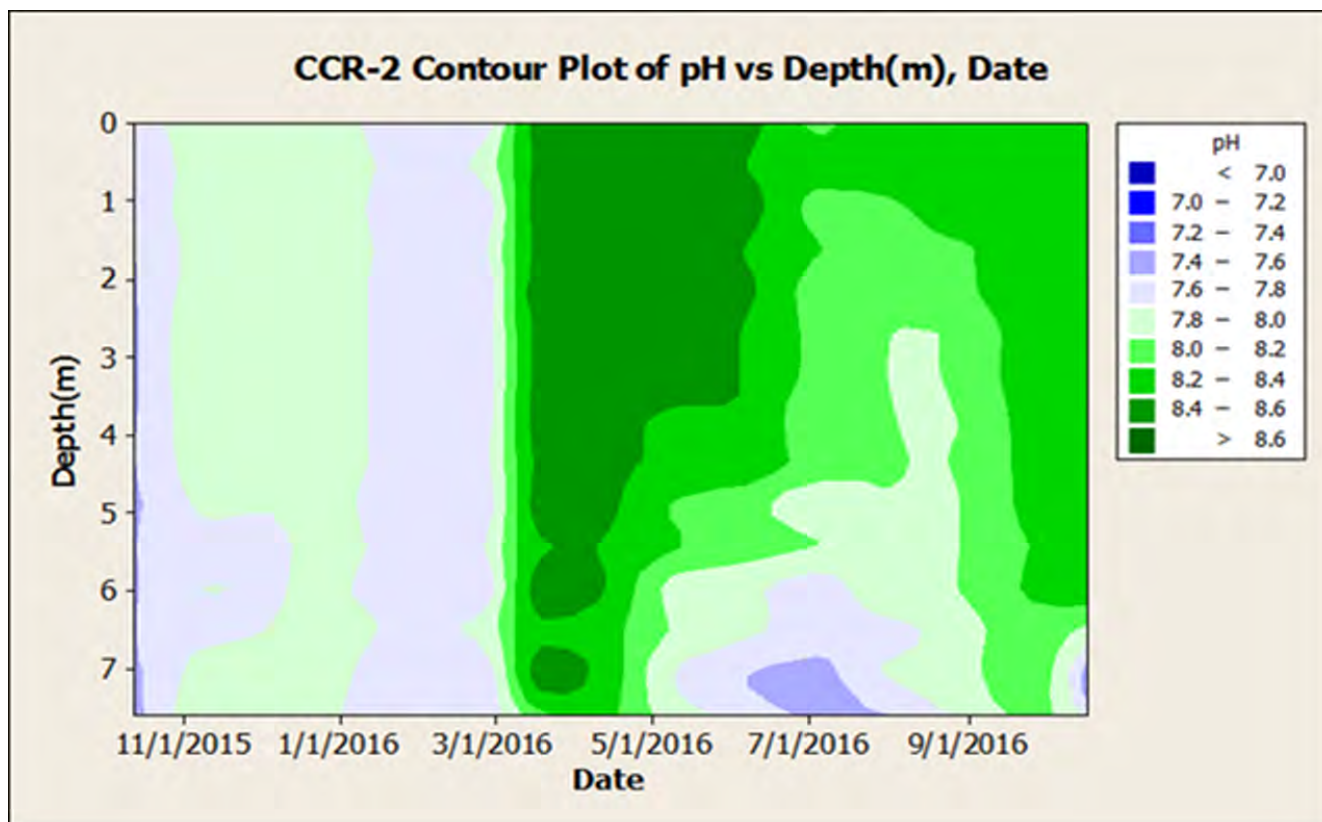


Figure 43. WY2016 pH Profile in Cherry Creek Reservoir, Station CCR-2 (October 1 2015 – September 30, 2016) – pH ranged 7.4 – 8.6. (Sources of Data: Tetra Tech, (March 1, 2016 -.September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016))

3.2.9 Dissolved Oxygen

The DO standard for Cherry Creek Reservoir is 5 mg/L near the surface. The DO may be less than 5 mg/L near the bottom as long as there is a refuge with DO levels greater than 5 mg/L available for aquatic life. Figure 44 depicts DO levels in the Reservoir at Station CCR-2. During June through September there were periods of low DO in the deeper waters; however, data demonstrated DO concentrations more than 5 mg/L throughout the majority of the Reservoir providing adequate habitat (refuge) for aquatic life. The lower DO levels, measured at depths near 7 meters, were a result of the sediment oxygen demand affecting DO. Based on review of the DO data, combined with the pH data, the Reservoir was chemo-stratified prior to the sampling on 13 September.

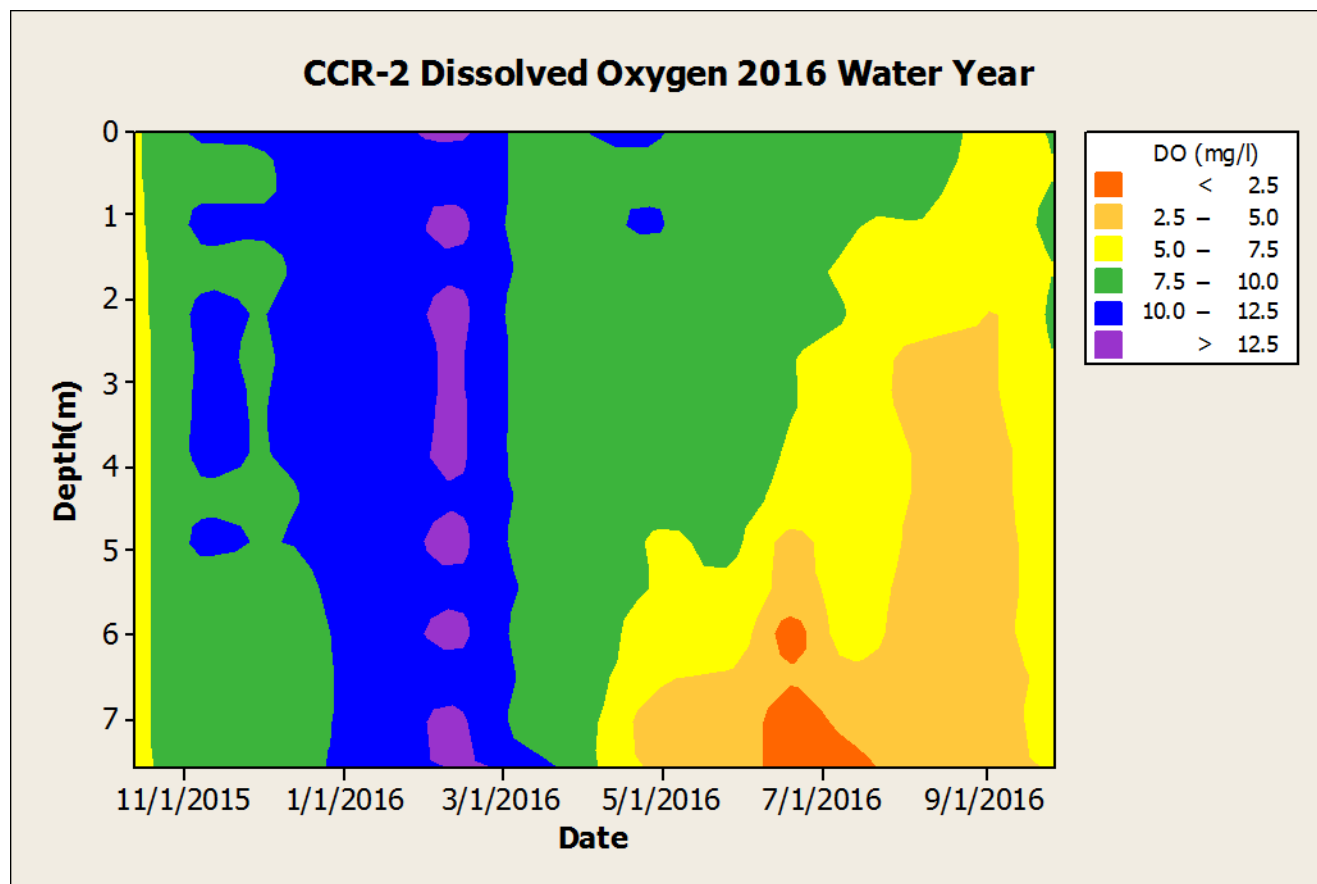


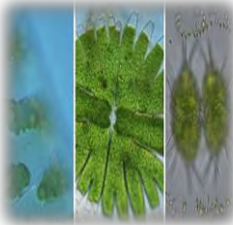
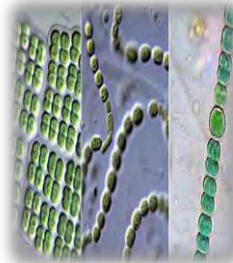

Figure 44. WY2016 DO Profile at Cherry Creek Reservoir Monitoring Station CCR-2 (2016) - DO was above 5 mg/L, providing refuge for the fishery. However, lower DO levels (less than 5 mg/L) were measured at depths near 5 to 7 meters in June through September, a result of the anoxic conditions in the sediment water interface. (Sources of Data: Tetra Tech, (March 1, 2016 -.September 30, 2016); GEI Consultants, Inc. (November 1, 2015 – February 28, 2016))

3.2.10 Reservoir Phycology

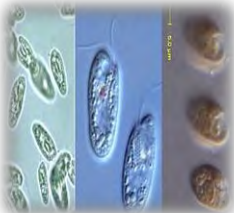


The primary plankton taxa observed in the Reservoir during WY2016 and their significance as an ecological stressor or benefit to the aquatic community is summarized in Table 12. The phytoplankton and zooplankton data indicates nutrient rich Reservoir conditions observed in WY2016. Cherry Creek Reservoir continues to exhibit characteristics of an over-productive, nutrient rich Reservoir.

Phytoplankton. The phytoplankton taxa included an abundance of Chlorophyta (green algae), Cyanophyta (cyanobacteria), and Bacillariophyta (diatoms, a great source of food for zooplankton) (Figure 45). The algal abundance (measured as cell counts/mL) for Cyanobacteria (photosynthetic bacteria, “blue green algae”) and Chlorophyta were all in excess of eutrophic levels, >1,000 algal cells/mL for each group. The green algae and diatoms community were dominated by species that are indicative of over-enriched conditions and some are not utilized as efficiently as other species as base of the food web. Also, the densities observed contributed to increased oxygen demand and other poor water quality conditions such as increasing phosphorus recycling and chlorophyll concentrations. Cyanobacteria do not directly contribute greatly to the food web and caused water quality issues such as turbidity, dissolve oxygen depletion, nutrient generation, elevated chl-a concentrations and potential periodic production of harmful algal blooms (HABs).

Table 12. Summary of Primary Plankton Taxa Observed, Ecological Benefits and Stressors

Phytoplankton or Zooplankton Taxonomic Division and Common Name	Picture (Photos courtesy of PhycoTech, Inc. and NOAA)	Period of Occurrence	Ecological Benefits for Reservoir	Ecological Stressors for Reservoir	Abundance (Yes/No)
Phytoplankton Chlorophyta "Green algae"		During periods of high nutrient concentrations; indicates both nitrogen and phosphorus are in excess supply. Higher ratio of desmids to other greens is indication of nitrogen abundance.	Small colonial and single celled greens are a good food source for zooplankton.	Sometimes filamentous green algae and large colonial forms (i.e. volvox) do not add to food web and create water quality problems. Also creates problems when it grows in "cotton candy" type clouds in the water.	Yes. When cell numbers exceed 3,000 to 5,000 cells/mL it is high and in excess of the eutrophic/beneficial use levels, >1,000 cells/mL; Reservoir typically measured over 10,000 cell/mL
Phytoplankton Cyanophyta "Cyanobacteria" - "Blue green algae" Note: Truly are bacteria so proper classification is Cyanobacteria.		During periods of over abundant enrichment <u>and</u> with very high nutrients, especially phosphorus. Their excess production will lead to water quality problems.	Do not contribute greatly to food web. Few people view cyanobacteria as beneficial organisms in a lake environment.	Blue-greens create water quality problems, i.e. oxygen depletion when their excessive growth produces algae blooms. Some species are toxic (cyanotoxins) and result in HABs.	Yes. Cyanophyta, were observed at nearly 75,000 cells/mL; this is too high for a balanced system, keeping the risk for cyanotoxins elevated.
Phytoplankton Bacillariophyta "Diatoms"		Typically, the first algae to bloom in early spring. When conditions in the upper mixed layer (nutrients and light) are favorable (spring), their competitive edge and rapid growth rate enables them to dominate phytoplankton communities	Important contributors to the primary production in aquatic ecosystems. Food resource for zooplankton and also produces atmospheric oxygen. Some diatoms can host nitrogen-fixing cyanobacterial symbionts that are high in protein, which may benefit the organisms grazing these diatoms.	Freshwater diatoms commonly observed in the reservoir are indicators of eutrophic (over enriched conditions) and their densities are greater than a balanced system would support. This contributes to environmental degradation through increased oxygen demand and phosphorus recycling.	Abundant in early June and early August, over 10,000 cells/mL. Predominant biovolume during same timeframe.

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Phytoplankton or Zooplankton Taxonomic Division and Common Name	Picture (Photos courtesy of PhycoTech, Inc. and NOAA)	Period of Occurrence	Ecological Benefits for Reservoir	Ecological Stressors for Reservoir	Abundance (Yes/No)
Phytoplankton Cryptophyta		Cryptophytes are abundant in the phytoplankton and can also live through the winter, under ice-cover and with little solar radiation for photosynthesis.	They are also an important food for zooplankton. Zooplankton, in turn, are food for fish and other organisms that are part of the aquatic food web.		Due to proliferation over the winter, Cryptophyta numbers were higher in May and June, tapering off later in the growing season.
Zooplankton Daphnids "Water flea", "Daphnia magna" and "Daphnia dubia"		Historically conditions are ideal for Daphnids around early June timeframe. These are the most effective phytoplankton harvesters and food source for fish.	Excellent zooplankton that play a significant role in the food web as major source of oils and proteins for fish. Large in size and preferred fish food (over 10 times the size of Bosminids).		Higher density in June reflects phytoplankton community structure, higher numbers with balance moderate production of phytoplankton.
Zooplankton Bosminid		High percentage of Bosminids indicates that the Cryptophytes and the single cells, chlorophytes, are the major algal food base.	Provides food base, but because of their small size, not a preferred food source.	Given Bosminids are smaller than the preferred Daphnids for fish food this indicates that most of the primary production is not being used by higher aquatic biota and hence contributes to over enrichment of the reservoir.	

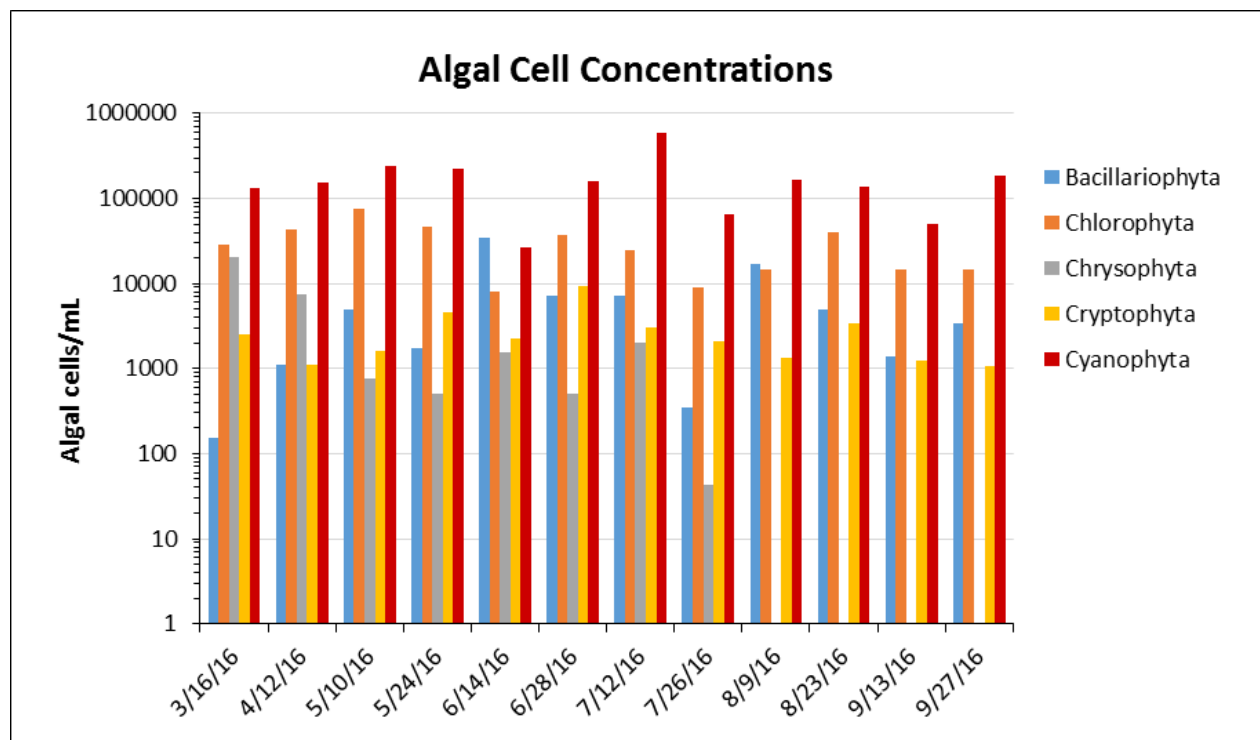


Figure 45. Algal Cell Concentrations Measured in Cherry Creek Reservoir in WY2016. The top 5 phytoplankton taxa observed in Cherry Creek Reservoir are depicted. The algal abundance (measured as cell counts/mL) for Cyanobacteria (photosynthetic bacteria, “blue green algae”) and Chlorophyta were all in excess of eutrophic levels, >1,000 algal cells/mL (Source of Data: PhycoTech, Inc.)

Chl-a accounted for the total phytoplankton community biomass and this biomass was dominated by Chlorophyta and Bacillariophyta (diatoms, a significant source of food for zooplankton, however not all of the diatoms species present fit into this function) during the growing season, as depicted in Figure 46. A significant amount of biomass energy from phytoplankton and bacteria was also stored in the sediments as organic carbon, which contributed to excess nutrient production during this timeframe.

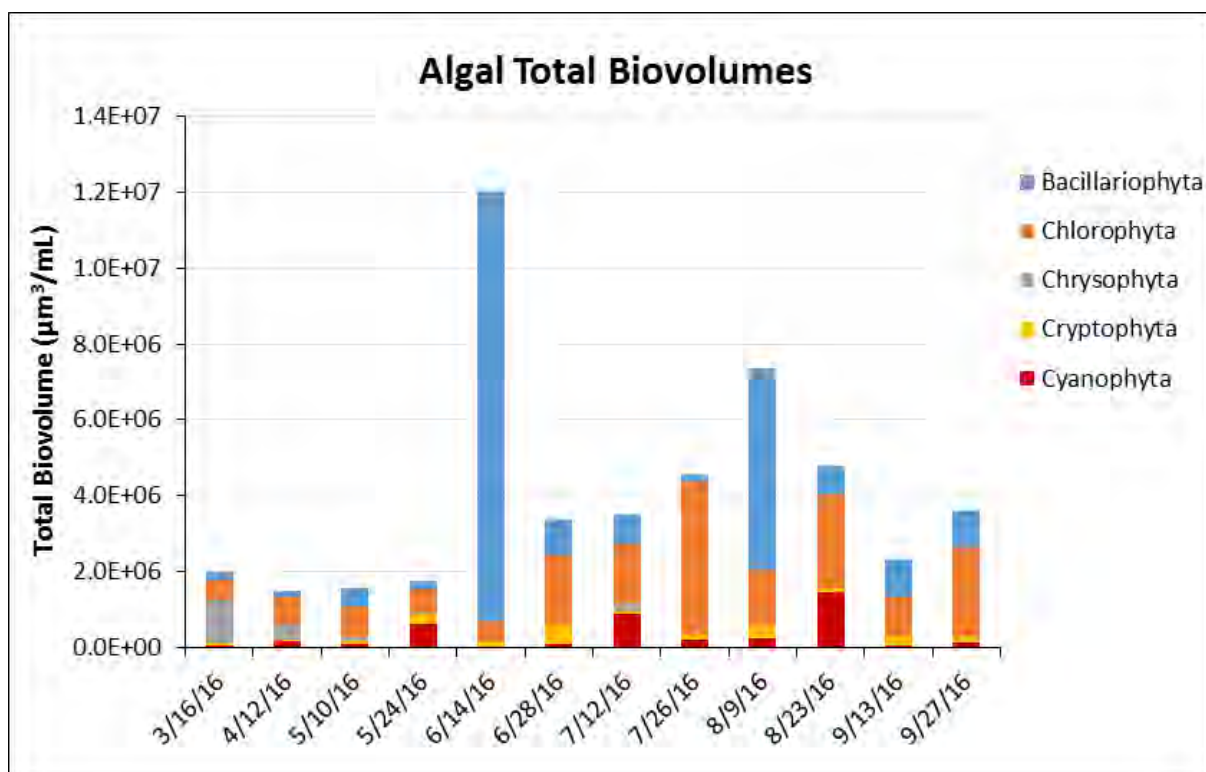


Figure 46. Algal Community Biomass - biomass was dominated by Chlorophyta (green algae) and Bacillariophyta (diatoms) during the growing season. (Source of Data: PhycoTech, Inc.)

Zooplankton. The 2016 zooplankton community structure was generally illustrative of a hypereutrophic system and not overly productive (biomass) relative to food base for fisheries (Figure 47). A generally higher Daphnid biomass was present in June and September, indicating this preferred fish food was available and abundant for the fishery. However, Bosminids, which are ten times smaller than the preferred Daphnids, were prevalent in July 2016. The dominance of Bosminids indicates that most of the primary production was not being used by higher aquatic biota during that period, which contributes to the over enrichment of the Reservoir.

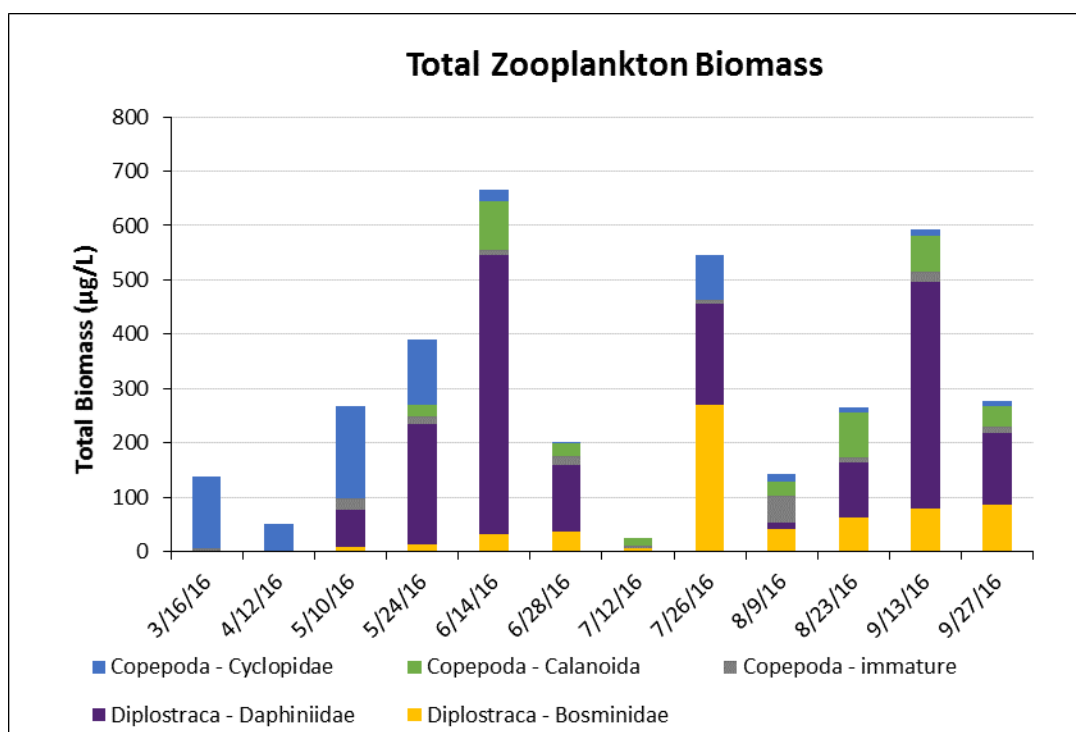


Figure 47. Zooplankton Biomass - A generally higher Daphnid biomass was present in June and September, indicating this preferred fish food was available and abundant for the fishery. However, Bosminids, which are ten times smaller than the preferred Daphnids, were prevalent in July 2016. (Source of Data: PhycoTech, Inc.)

3.2.11 Harmful Algal Blooms

A HAB was observed near Marina and Tower Loop from May 31 – June 9, 2016 (Figure 48). Due to the limited spatial distribution of the Microcystin concentrations above 10 µg/L, and the lower measurements at the swim beach (less than 0.3 µg/L and non-detect (ND) warning signage was posted. Low risk Microcystin thresholds for recreation are defined as concentrations less than 10 µg/L (US EPA, 2016; WHO, 2003). The HAB occurrence prompted a collaborative partnership between the Authority and CPW for future cyanotoxin sampling and analysis efforts if HABs are observed in the future. The partnership is a big step for the agencies that work to protect recreation uses, aquatic life, and public safety at Cherry Creek Reservoir.

The occurrence of HABs within the Reservoir are likely to continue to occur on the periodic and unpredictable level until phosphorus is reduced in both its external and internal loading dynamics. Fortunately, the dominant cyanobacteria observed in 2016 is not known as a significant toxin producer. However, when conditions are aligned to enable other cyanobacteria to grow that have a greater potential for toxin generation there will be a HAB occurrence. This is particularly true if nutrient and light conditions within the Reservoir are such that they promote nitrogen fixing cyanobacteria to have greater dominance than is currently occurring.

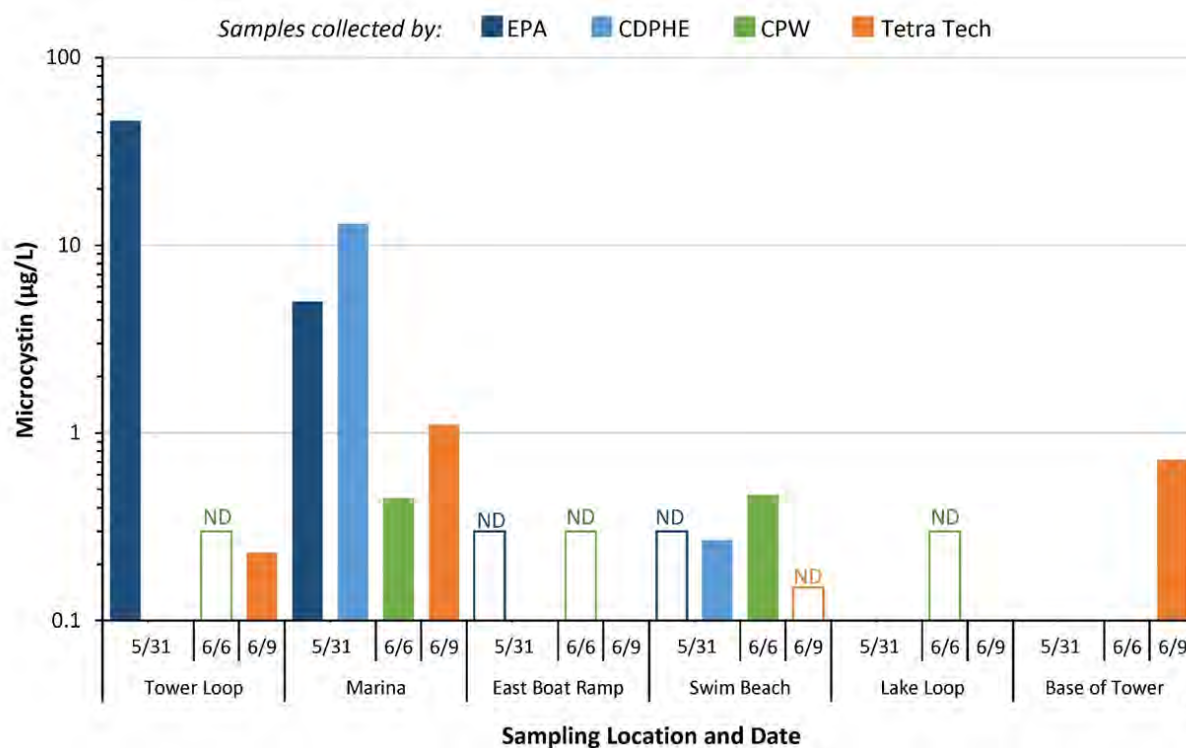


Figure 48. Microcystin concentrations in Cherry Creek Reservoir, May 31 - June 9, 2016. A harmful algal bloom was observed on May 31 by CPW staff. Microcystin concentrations had subsided by June 9, 2016 at all six sampling locations as less than 1 µg/L and non-detect (ND). Samples were taken by various staff during the period of the HAB and analyzed using different methods. (CPW staff used an Abraxis Dipstick field test for rapid turnaround of Microcystin concentrations. CDPHE lab used ELISA method. EPA lab used ELISA method confirmed by HPLC/MS. Tetra Tech samples were analyzed by GreenWater Lab, using ELISA method confirmed by LC-MS/MS.)

4.0 RESERVOIR NUTRIENT BALANCE

The calculated WY2016 water, phosphorus and nitrogen balances in the Cherry Creek Reservoir are presented in this section.

4.1 WATER BALANCE

The calculated WY2016 water balance for Cherry Creek Reservoir is presented in this section. The reservoir water balance can be calculated by the following equation:

$$\text{Ending Storage}_{9/30/2016} + \sum \text{Reservoir Inflows} - \sum \text{Reservoir Outflows} - \text{Starting Storage}_{10/1/2015} = \Delta \text{Storage}$$

The USACE's daily storage calculations (Appendix E), which are based on pool elevation, indicate a 26 ac-ft gain in storage (+ Δ Storage) from October 1, 2015 through September 30, 2016.

The reservoir inflows (gains) considered in the water balance include:

1. Precipitation (incident to the reservoir's surface).
2. Alluvial groundwater.
3. Cherry Creek surface water.
4. Cottonwood Creek surface water.
5. Ungaged inflows.

The reservoir outflows (losses) considered in the water balance include:

1. Evaporation.
2. Alluvial groundwater.
3. Reservoir releases.

The Authority measures surface water inflows (inflow item numbers 3 and 4), while precipitation (inflow item 1) can be estimated from the acreage of the reservoir and the amount of precipitation. Alluvial groundwater inflow (inflow item 2) is estimated at a constant 2,200 ac-ft/year based on evaluations conducted by Lewis, et al. (2005) and used by Hydros (2015) in the reservoir model. The USGS measures outflow item number 3 and the USACE provides an estimate of outflow item 1. The net influence of ungaged surface water inflows and alluvial groundwater losses (seepage) (inflow item 5 less outflow item 2) is calculated based on the difference between the measured and estimated inflows and outflows, and the USACE calculated WY2016 inflow of 25,014 ac-ft (Appendix E).

Surface water inflow from Cherry and Cottonwood Creeks are estimated from the continuous flow stations operated by the Authority at monitoring sites CC-10 (Cherry Creek) and CT-2 (Cottonwood Creek) (Figure 2). The estimated volumes of surface entering the Reservoir from these two surface water sources in WY2016 are:

- Cherry Creek: 16,002 ac-ft
- Cottonwood Creek: 3,854 ac-ft

Flow data from the Authority's gaging stations are provided in Appendix D.

Water is released from the Reservoir through the dam's outlet works. The USGS operates the Cherry Creek below Cherry Creek "Lake" gage approximately 2,300 feet downstream of the Reservoir. Other than releases from the Reservoir, there are no major surface water contributions to flow measured at this gage. The WY2016 flows at the gage totaled 22,532 ac-ft, with the

WY2016 mean daily discharge rate of 15.6 cfs exceeding the 57 year POR mean daily rate of 4.6 cfs (Figure 49).

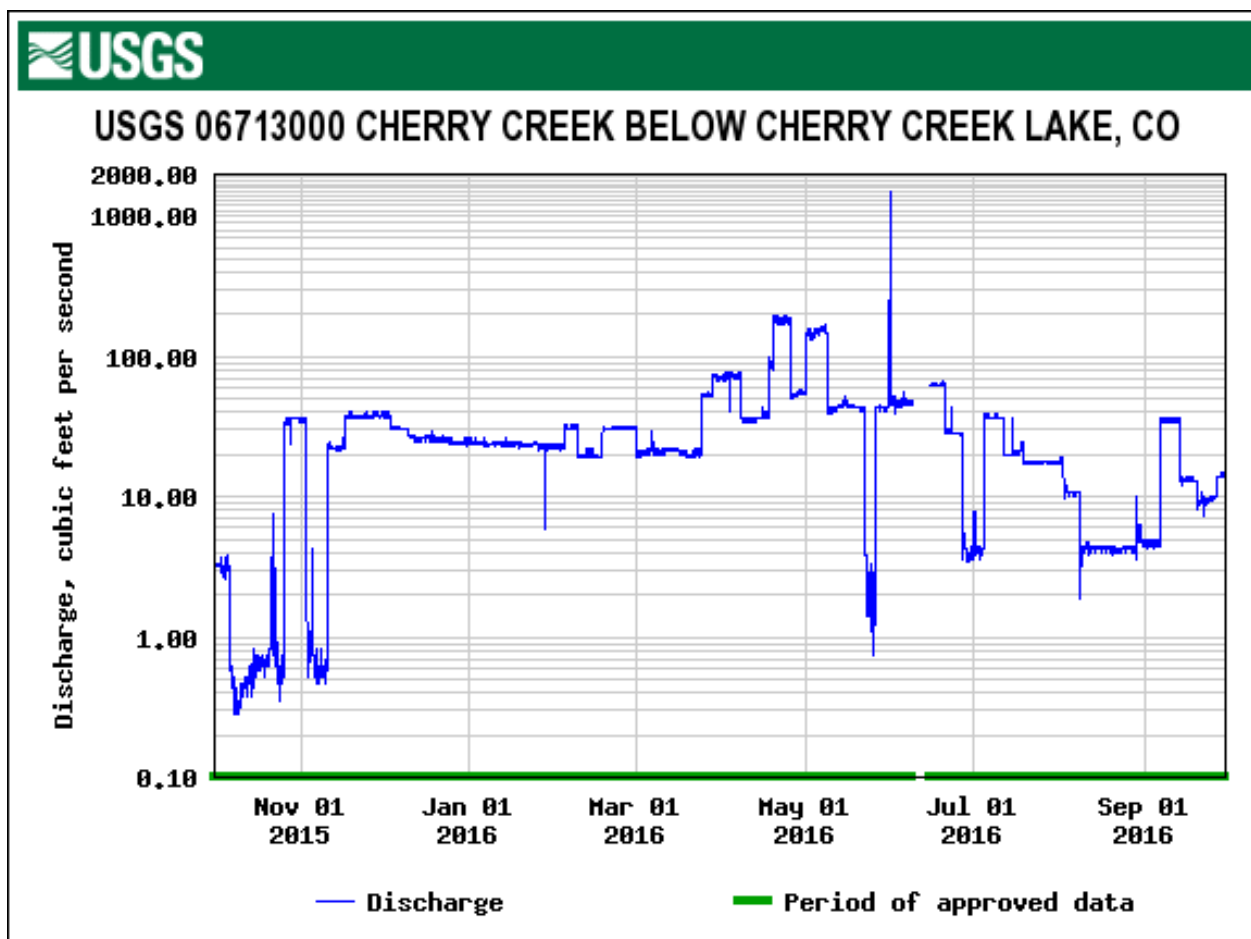


Figure 49. WY2016 Hydrograph and Historical Median Flows for USGS Gage Cherry Creek below Cherry Creek Lake (Source: <https://waterdata.usgs.gov/nwis/uv?06713000>)

During WY2016, the surface area of Cherry Creek Reservoir varied between 836 acres and 870 acres, with a median value of 849 acres². During WY2016, 15.26 inches (1.27 feet) of precipitation was recorded at the Denver-Centennial Airport weather station (KAPA). Assuming that 1.27 feet of water fell evenly over 849 acres results in an estimated 1,080 ac-ft of water contributed to the Reservoir by precipitation.

The USACE estimated evaporative losses from the reservoir in WY2016 at 2,996 ac-ft (Appendix E), or approximately 42.3 inches per acre assuming a median surface area of 849 acres.

The reservoir WY2016 water balance is summarized in Table 13.

² http://www.dwr.state.co.us/SurfaceWater/data/detail_graph.aspx?ID=CHRRESCO&MTYPE=STORAGE

Table 13. Cherry Creek Reservoir WY2016 Water Balance

Water Source	Water Volume (ac-ft)
Surface Water	
Cherry Creek (CC-10)	16,002
Cottonwood Creek (CT-2)	3,854
Reservoir Release (CC-Out)	-22,532
Alluvial Groundwater	
Inflow	2,200
Atmospheric	
Precipitation	1,080
Evaporation	-2,996
Net Ungaged Inflows/Outflows	
Calculation	2,418
WY2016 Change in Storage	26

The net ungaged inflows/outflows is calculated result in the Reservoir change in storage to equal the 26 ac-ft reported by the USACE (Appendix E). Components included in this calculated term are ungaged surface water inflows into the reservoir, groundwater seepage from the reservoir through the dam, and measurement uncertainties.

The relative contribution of the inflows to the reservoir in WY2016 are illustrated in Figure 50.

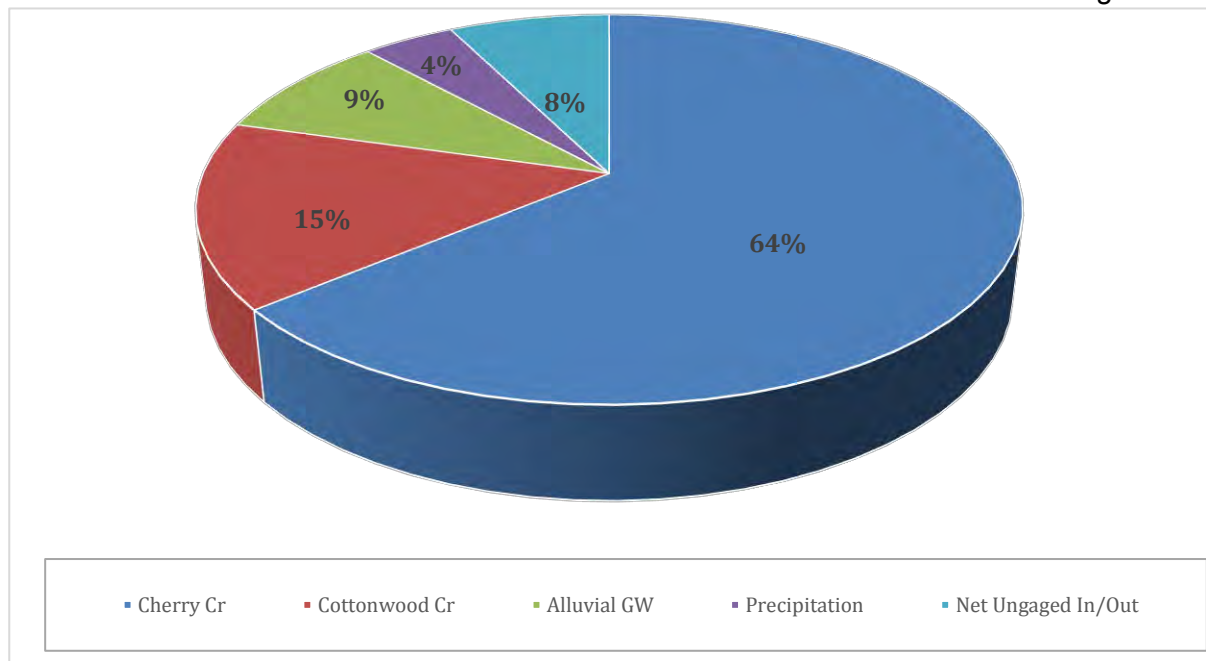


Figure 50. Relative Contribution of Cherry Creek Inflows to Reservoir Water Balance in WY2016

In keeping with prior year's nutrient loading calculations, the 2,418 ac-ft difference between the Authority's and the USACE's calculated inflows was apportioned to the two dominant surface water inflows (Cherry Creek and Cottonwood Creek) for purposes of calculating reservoir nutrient loads (Section 4.2). For WY2016 nutrient loading evaluation (Section 4.2), 81% of the 2,418 ac-ft (1,949 ac-ft) was allocated to the Cherry Creek inflow (CC-10) annual total while the remaining 19% of the 2,418 ac-ft (469 ac-ft) was allocated to the Cottonwood Creek inflow (CT-2).

4.2 NUTRIENT LOADS

The calculated WY2016 phosphorus and nitrogen balances in the Cherry Creek Reservoir are presented in this section. The reservoir nutrient loading was calculated using a mass-balance approach:

$$\sum \text{Reservoir Inflows}_{\text{Nutrient}} - \sum \text{Reservoir Releases}_{\text{Nutrients}} = \Delta \text{Storage}_{\text{Nutrients}}$$

A positive change in storage (+ $\Delta \text{Storage}_{\text{Nutrients}}$) indicates that inflows exceed releases and that nutrients are being retained (stored) within the Reservoir (both within the water and sediment). A negative change in storage (- $\Delta \text{Storage}_{\text{Nutrients}}$) indicates the opposite and would suggest that previously stored nutrients are being exported from the Reservoir.

The reservoir inflows (nutrient loads) considered in the WY2016 nutrient balance are:

- Precipitation (incident to the reservoir's surface).
- Alluvial groundwater.
- Cherry Creek surface water.
- Cottonwood Creek surface water.

The only physical release mechanism considered from the Reservoir in the WY2016 nutrient mass balance is surface water released through the dam's outlet works. Nutrient loss through evaporation is considered zero as the evaporating water is assumed to not contain any nutrients. The net ungagged inflow/outflow load was apportioned to the measured WY2016 Cherry Creek and Cottonwood Creek loads based on the flow adjustments described in Section 4.1. Internal loading (nutrient recycling) discussed in Section 3.2 is not included in the mass balance but contributes to the overall nutrients available to the phytoplankton that thrive in the Reservoir.

4.2.1 Surface Water Loads

The Authority collects water quality samples on a monthly basis at surface water monitoring stations CC-10, CT-2 and CC-Out (Table 4). The Authority also periodically collects storm event samples at CC-10 and CT-2 (Table 4). These samples are analyzed for the parameters indicated in Table 3, which includes total phosphorus and total nitrogen. The nutrient concentrations in samples collected at CC-10, CT-2 and CC-Out in WY2016 are summarized in Section 3.1. When combined with the WY2016 flows, the annual total phosphorus and total nitrogen loads can be calculated for the surface water inflows and outflows (releases) to/from the reservoir (Table 14). The Cherry Creek and Cottonwood Creek loads presented in Table 14 have been adjusted to apportion the ungagged inflows as discussed in Section 4.1.

Table 14. Cherry Creek Reservoir WY2016 Surface Water Nutrient Loads

Site	WY2016 Nutrient Load	
	Total Phosphorus (Pounds)	Total Nitrogen (Pounds)
Inflows		
Cherry Creek @ CC-10	12,182	49,400
Cottonwood Creek @ CT-2	1,030	23,748
Releases		
USGS Gage & CC-Out	- 9,156	- 60,627

4.2.2 Precipitation Loads

The WY2016 atmospheric nutrient loading through precipitation and dry deposition was seasonally monitored (April 2016 through June 2016) at the Authority's rain gage located immediately east of the reservoir (see "PRECIP" site on Figure 2). Seven precipitation samples were collected in WY2016 and analyzed for various forms of phosphorus and nitrogen, including total phosphorus and total nitrogen. The results are summarized below:

- WY2016 total phosphorus concentrations ranged from 14 µg/L to 1,907 µg/L, with a median value of 60 µg/L. The WY2016 median value is lower than the long-term median³ of 148 µg/L.
- WY2016 total nitrogen concentrations ranged from 444 µg/L to 12,074 µg/L, with a median value of 2,547 µg/L. The WY2016 median value is higher than the long-term median of 2,009 µg/L.

The long-term median total phosphorus and total nitrogen precipitation/dry fall concentrations were combined with the estimated 1,080 ac-ft of precipitation to calculate these nutrient loads from direct precipitation to the Reservoir:

- Total Phosphorus: 435 pounds
- Total Nitrogen: 5,898 pounds

4.2.3 Alluvial Groundwater Loads

Water quality samples collected from well MW-9 in WY2016 were analyzed for total phosphorus six times and for total nitrogen once. The results are summarized below:

- The WY2016 total phosphorus concentrations ranged from 189 µg/L to 239 µg/L, with a median value of 206 µg/L. The WY2016 median value is slightly higher than the long-term median of 190 µg/L (GEI, 2016).
- The one WY2016 total nitrogen result available from the May 2016 basin-wide event of 217 µg/L is approximately half the long-term median of 430 µg/L (GEI, 2016).

³ Available data in the Authority's database for location "Rain Gauge" from 2001, 2008-2010, and 2014-2016 were used to calculate long-term median total nitrogen and total phosphorus statistics.

The long-term median total phosphorus and total nitrogen concentrations reported in GEI (2016) were combined with the estimated 2,200 ac-ft of inflow to calculate these nutrient loads from the alluvial groundwater inflow to the Reservoir:

- Total Phosphorus: 1,136 pounds
- Total Nitrogen: 2,573 pounds

4.2.4 Nutrient Balances

The WY2016 total phosphorous and total nitrogen load balance calculations are presented in this section. . Internal loads are not included in the mass balances presented in this section.

4.2.4.1 Total Phosphorus Mass Balance

Based on the data presented in Sections 4.2.1 through 4.2.3, the WY2016 total phosphorous mass balance is summarized in Table 15.

**Table 15. Cherry Creek Reservoir WY2016 Total Phosphorus
Mass Balance**

Source	Mass (pounds)
Surface Water	
Cherry Creek (CC-10)	12,182
Cottonwood Creek (CT-2)	1,030
Reservoir Release (CC-Out)	-9,156
Alluvial Groundwater	
Inflow	1,136
Atmospheric	
Precipitation	435
Evaporation	0
WY2016 Change in Storage	5,627

The difference between the inflow and the outflow loads ($\Delta \text{Storage}_{\text{Nutrients}}$) indicates that a net 5,627 pounds (2.8 tons) of phosphorus were retained in the reservoir in WY2016. Some of this phosphorus was retained in the additional 26 ac-ft of water that was stored in the Reservoir in WY2016.

The relative contributions of the inflow sources to the Reservoir phosphorus load WY2016 are illustrated in Figure 51.

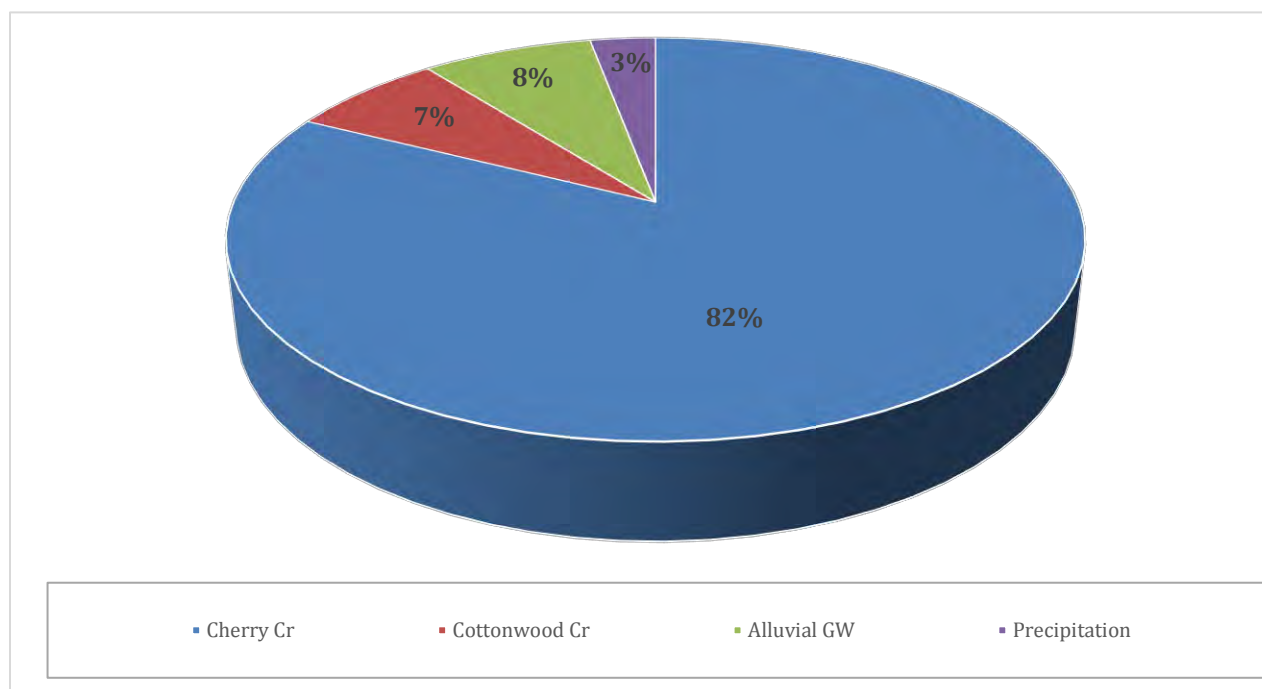


Figure 51. Relative Contribution of Cherry Creek Inflows to Reservoir Phosphorus Balance in WY2016

The WY2016 total phosphorus loading data are compared to prior year's loads in Table 16.

Table 16. Comparison of Cherry Creek Reservoir WY2016 Total Phosphorus Loading to Historic Loads

Period	Inflows (pounds)				Outflow (pounds)	Δ Storage (pounds)
	Surface Water	Alluvial Groundwater	Precipitation	Total		
Median (1993 – 2015)	7,868	1,033	379	9,301	-4,113	5,599
Median (2011 – 2015)	7,164	1,033	323	8,588	-4,114	5,187
WY 2015	15,141	1,033	526	16,701	-8,222	8,479
WY2016	13,212	1,136	435	14,783	-9,156	5,627

Note: Historic data modified from GEI (2016) Table 4-6.

The WY2016 total phosphorus inflow and outflow loads are similar to those in WY2015 and both are larger than those exhibited in long-term trends. However, the mass of phosphorus retained in the Reservoir in WY2016 is more consistent with the historic retention rates that that calculated in 2015.

4.2.4.2 Total Nitrogen Mass Balance

Based on the data presented in Sections 4.2.1 through 4.2.3, the WY2016 total nitrogen mass balance calculation is presented in Table 17.

Table 17. Cherry Creek Reservoir WY2016 Total Nitrogen Mass Balance

Source	Mass (pounds)
Surface Water	
Cherry Creek (CC-10)	49,400
Cottonwood Creek (CT-2)	23,748
Reservoir Release (CC-Out)	-60,627
Alluvial Groundwater	
Inflow	2,573
Atmospheric	
Precipitation	5,898
Evaporation	0
WY2016 Change in Storage	20,992

The difference between the inflow and the outflow loads ($\Delta \text{Storage}_{\text{Nutrients}}$) indicates that a net 20,992 pounds (10.5 tons) of nitrogen were retained in the Reservoir in WY2016. Some of this nitrogen was retained in the additional 26 ac-ft of water that was stored in the Reservoir in WY2016.

The relative contributions of the inflow sources to the reservoir nitrogen load WY2016 are illustrated in Figure 52.

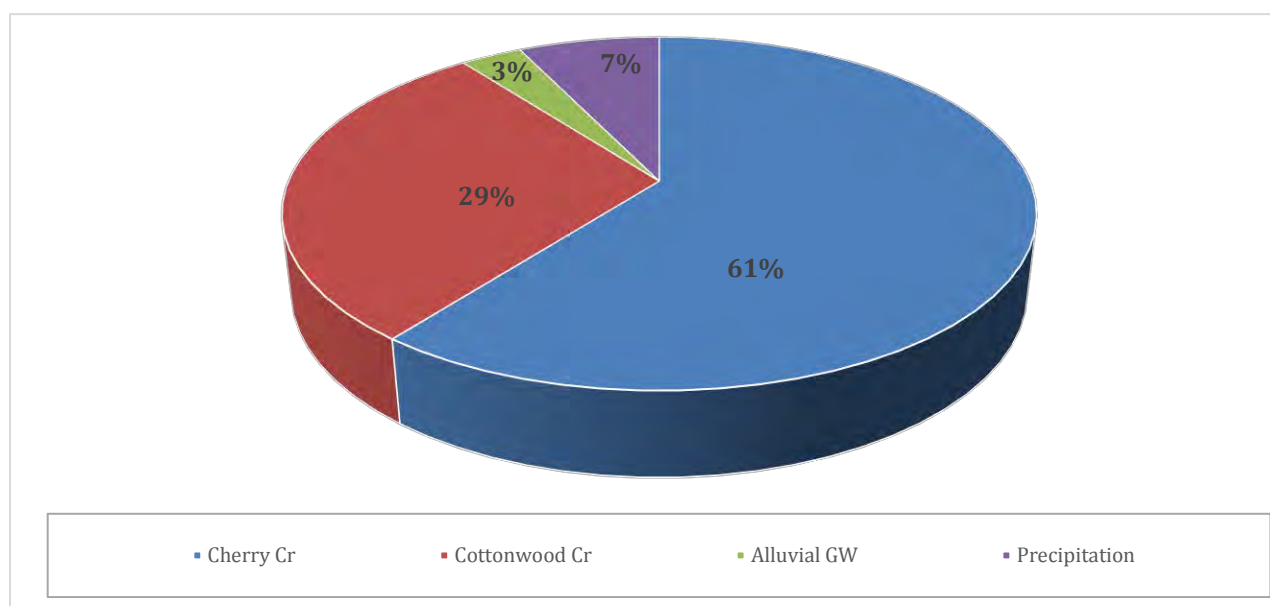


Figure 52. Relative Contribution of Cherry Creek Inflows to Reservoir Nitrogen Balance in WY2016

The WY2016 total nitrogen loading data are compared to prior year's loads in Table 18.

Table 18. Comparison of Cherry Creek Reservoir WY2016 Total Nitrogen Loading to Historic Loads

Period	Inflows (pounds)				Outflow (pounds)	Δ Storage (pounds)
	Surface Water	Alluvial Groundwater	Precipitation	Total		
Median (1999 – 2015)	59,573	2,337	6,578	68,592	-35,727	32,865
Median (2011 – 2015)	54,126	2,337	5,720	62,234	-32,120	21,434
WY 2015	68,630	2,339	8,546	79,515	-58,186	21,329
WY2016	73,148	2,573	5,898	81,619	-60,627	20,992

Note: Historic data modified from GEI (2016) Table 4-8.

The WY2016 total nitrogen inflow and outflow loads are similar to those in WY2015 and both are larger than those exhibited in the long-term trends. The mass of nitrogen retained in the Reservoir in WY2016 is similar to the recent (2011 – 2015) retention rate.

4.3 FLOW-WEIGHTED NUTRIENT CONCENTRATIONS

As summarized in Table 16, the phosphorus loading to the Reservoir from external sources in WY2016 totaled 14,783 pounds (7.4 tons) and was derived from these sources:

- Surface water: 13,212 pounds.
- Groundwater: 1,236 pounds.
- Precipitation: 435 pounds.

With respect to nitrogen, external sources resulted in 81,619 pounds (40.8 tons) of this nutrient being delivered to the Reservoir in WY2016 from these sources (Table 18):

- Surface water: 73,148 pounds.
- Groundwater: 2,573 pounds.
- Precipitation: 5,898 pounds.

The “surface water” loads of phosphorus and nitrogen include those from Cherry Creek and Cottonwood Creek and have been adjusted for ungaged runoff (Section 4.1).

The flow adjusted -weighted concentrations of total phosphorus and total nitrogen in WY2016 are summarized in Table 19.

Table 19. WY2016 Flow-Weighted TP and TN Concentrations

Nutrient	Inflows (µg/L)				
	Cherry Creek	Cottonwood Creek	Alluvial Groundwater	Precipitation	Total
Total Nitrogen	1,012	2,020	430	2,008	1,175
Total Phosphorus	250	88	190	148	213

The overall WY2016 flow-weighted TP inflow concentration of 213 µg/L is lower than the WY2015 value of 222 µg/L, but higher than the 2011-2015 median of 200 µg/L. In contrast, the overall WY2016 flow-weighted TN concentration of 1,175 µg/L is higher than the WY2015 value of 1,057 µg/L, but well below the 2011-2015 median of 1,344 µg/L.

5.0 2017 RECOMMENDATIONS AND NEXT STEPS

The following next steps are recommended in 2017 to support the monitoring program, data collection and water quality benefits.

- Wetland Harvesting – Commence wetland harvesting and monitoring at Shop Creek PRF (SC-1 and SC-2) to understand the nutrient reduction benefits of this maintenance program. Scheduling of harvesting program must be coordinated with State Parks Manager, Cherry Creek Stewardship Partners, and birding community. Similar vegetation harvesting is also recommended for the Cottonwood wetlands at CT-2 to promote additional pollutant reduction effectiveness.
- Split Sampling - Continue split sampling of nutrients and chl-a to support QAPP and parametric and nonparametric statistical evaluations to understand and quantify inter-lab variability.
- Replace Stream Gaging Equipment at Strategic Locations - Replace continuous monitoring hardware at CC-10 and CT-2.

6.0 REFERENCES

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7.0 APPENDICES

Appendices A through G are provided under separate cover.



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