City of Fort Collins Utilities

2013 HORSETOOTH RESERVOIR WATER QUALITY MONITORING PROGRAM REPORT

Prepared by:

Jared Heath, Watershed Technician

Jill Oropeza, Watershed Specialist

June 27, 2014

City of Fort Collins

Water Resources & Treatment Services

EXECUTIVE SUMMARY

The primary objectives of the City of Fort Collins Utilities (FCU) Horsetooth Reservoir Water Quality Monitoring Program are to provide water quality data and information to assist the FCU in meeting present and future drinking water treatment goals and to support the protection of the City's drinking water sources. The FCU 2014 Horsetooth Reservoir Water Quality Monitoring Program Report (2014 Report) documents data and information collected and assessed by FCU during the period of 2009 through 2013 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. The 2014 Report includes information and data on regulatory issues, special studies, and issues of concern; reservoir hydrology; Horsetooth Reservoir water quality; and Hansen Feeder Canal water quality and mass loads.

The FCU Horsetooth Reservoir Water Quality Monitoring Program includes routine sampling of Horsetooth Reservoir and influent flows from the Hansen Feeder Canal. FCU routine sampling of the Hansen Feeder Canal includes continuous monitoring with a multi-parameter YSI sonde and the collection of grab samples. Grab sampling is conducted weekly, although not all parameters are analyzed at this frequency. FCU routine sampling of Horsetooth Reservoir includes the collection of water quality profiles (with a multi-parameter YSI sonde) and grab samples at various depths at four locations (Inlet Bay Marina, Spring Canyon, Dixon Canyon, and Soldier Canyon). Monitoring of the reservoir in 2011 and 2012 included eight routine sampling events, and monitoring of the reservoir in 2013 included seven routine monitoring events.

Review of data for the 2014 Report indicates that the FCU Horsetooth Reservoir Water Quality Monitoring Program adequately captures the seasonal and annual patterns in water quality and provides a context for characterizing and assessing water quality. The 2011,2012, and 2013 temperature profiles show the typical development of thermal stratification beginning in the spring and progressing through the summer and early fall, with reservoir turnover occurring during the period of late October to early November. Also similar to previous years, the 2011, 2012, and 2013 dissolved oxygen (DO) profiles show depletion in both the metalimnion (middle depth of the reservoir) and hypolimnion (bottom depths) as the season progresses.

In addition to the routine monitoring, special studies are being conducted to address specific water quality issues in Horsetooth Reservoir and upstream components of the Colorado-Big Thompson (CBT) Project. FCU continues to collaborate with NW on determining the presence of contaminants of emerging concern (including pharmaceuticals and personal care products (PPCP)).

The Colorado Water Quality Control Commission adopted changes to Colorado's Section 303(d) List and Monitoring and Evaluation (M&E) List. Horsetooth Reservoir is on the 2012 M&E List for low DO in the metalimnion and for aquatic life chronic standard exceedances of copper and arsenic. Horsetooth Reservoir remains on the 303(d) List for Aquatic Life Use due to the presence of mercury in fish tissue. The Colorado Water Quality Control Division (WQCD) released interim nutrient standards (including total phosphorus (TP), total nitrogen (TN), and chlorophyll-a) that would apply to Horsetooth Reservoir. Horsetooth Reservoir exceeded the TN and chlorophyll-a nutrient standards in 2012 at all monitoring sites, except Solider Canyon Dam. Over the five year period, 2012 was the only year to exceed the proposed

nutrient standard and because the allowable exceedance frequency is 1-in-5-years Horsetooth Reservoir is considered to be in compliance with the standards for TN and chlorophyll-a.

Issues of concern related to Horsetooth Reservoir water quality continue to include:

- Low DO concentrations in the metalimnion and hypolimnion.
- Recurring episodes of the taste and odor (T&O) compound geosmin.
- Changes in total organic carbon (TOC) concentrations or characteristics that may increase the formation of disinfection by-products (DBP) during water treatment.
- Potential impacts from proposed water supply projects.
- Watershed impacts related climate change.

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LIST OF ABBREVIATIONS & ACRONYMS

#/100 mL	number per 100 milliliters
%	percent
CBT	Colorado-Big Thompson
CDPHE	Colorado Department of Public Health and Environment
CEC	Contaminant of Emerging Concern
cells/mL	cells per milliliter
cfs	cubic feet per second
CU	University of Colorado, Boulder
DO	Dissolved Oxygen
DBP	Disinfection By-Product
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
DUWS	Direct use water supply
FCU	Fort Collins Utilities
FCWQL	Fort Collins Water Quality Lab
FCWTF	Fort Collins Water Treatment Facility
HFCBBSCO	Charles Hansen Feeder Canal below Big Thompson Siphon
HFCLOVCO	Charles Hansen Feeder Canal Loveland Turnout
LC/TOF-MS	Liquid Chromatography/Time of Flight – Mass Spectrometry
ln	Natural logarithm
m	meter
M&E List	Colorado's Monitoring & Evaluation List
MDL	Method Detection Limit
mg/L	milligrams per liter
ng/L	nanograms per liter (equivalent to parts per trillion)
NH_4	Ammonia
NO_2	Nitrite
NO_3	Nitrate
NTU	Nephelometric Turbidity Units
NW	Northern Water
^{o}C	degrees Celsius

PPCP	Pharmaceuticals and Personal Care Products
PO_4	Ortho-Phosphate
ppt	parts per trillion
PQL	Practical Quantification Limit
T&O	Taste & Odor
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen (calculated from TKN + nitrate + nitrite)
TOC	Total Organic Carbon
TP	Total Phosphorus
TSI	Trophic State Index
µg/L	micrograms per liter
µS/cm	microSeimens per centimeter
USBR	United States Bureau of Reclamation
EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WQCD	Water Quality Control Division

1.0 BACKGROUND

1.1 Monitoring Program Goals and Scope of the 2014 Report

The 2014 Report summarizes Horsetooth Reservoir and Hansen Feeder Canal water quality data collected and assessed by the City of Fort Collins Utilities (FCU) in 2011, 2012, and 2013, and provides a comparison of water quality data collected over a five year period of 2009-2013. Hansen Feeder Canal flows were used with weekly measurements of total organic carbon (TOC) and nutrients to calculate constituent loading into Horsetooth Reservoir. Finally, this report provides a summary of special projects, regulatory issues, and issues of concern related to Horsetooth Reservoir water quality. The 2014 Report is the third report produced by the FCU and, together with the 2009 Report (Billica and Oropeza, 2010), 2010 Report (Billica and Oropeza, 2010) and the initial Horsetooth Reservoir Monitoring Program document (Billica and Oropeza, 2009), provide an in-depth review and assessment of the current water quality issues.

The details of the FCU Horsetooth Reservoir Water Quality Monitoring Program are documented in Billica and Oropeza (2009), including background information, the sampling and analysis protocols, data management, trend analysis, and a review of historic water quality data and issues. Horsetooth Reservoir serves as source water for the City of Fort Collins Water Treatment Facility (FCWTF). The Tri-Districts Soldier Canyon Filter Plant and the City of Greeley Bellvue Water Treatment Plant also treat water from Horsetooth Reservoir and cooperate in this monitoring program by providing staff to assist with field sampling.

The primary objectives of this monitoring program are to provide water quality data and information to assist the FCU in meeting present and future drinking water treatment goals, and to support the protection of the City's raw drinking water sources. The program provides data to support the following objectives:

- Determine long-term water quality changes that may increase costs associated with water treatment
- Support the design and optimization of water treatment plant processes
- Determine impacts of human activity and environmental perturbations on water quality

The data collected from the Horsetooth Reservoir Water Quality Monitoring Program provides for the following types of analysis:

- Calculate and assess the magnitude and statistical significance of temporal trends of selected variables
- Calculate and assess the statistical significance of spatial trends of selected variables
- Calculate and assess seasonal and annual mass loads to Horsetooth Reservoir of selected water quality variables
- Assess compliance with standards set by the Colorado Department of Public Health and Environment (CDPHE) for surface waters used as drinking water supplies
- Detect changes in water quality, evaluate implications for water treatment, and where possible, identify and mitigate contributing causes
- Assess the health (trophic state) of Horsetooth Reservoir on a seasonal and annual basis

Water quality issues in Horsetooth Reservoir that have directly impacted the FCU over the years include, low DO levels and associated high dissolved manganese concentrations at the bottom of the reservoir, increasing concentrations of TOC, and recurring episodes of geosmin, a taste and odor (T&O) compound. The FCU Horsetooth Reservoir Water Quality Monitoring Program has been designed to characterize and assess such issues, now and into the future.

Water quality monitoring of Horsetooth Reservoir is currently also being conducted by the Northern Water (NW). Fort Collins Utilities and NW are in the process of designing a future collaboration to monitor Horsetooth Reservoir water quality. This effort will be discussed further in Section 6.1 of this report. Water quality monitoring of the Big Thompson River and components of the Colorado-Big Thompson (CBT) Project upstream of Horsetooth Reservoir (including the Hansen Feeder Canal) is currently being conducted by the Big Thompson Watershed Forum, the United States Geological Survey (USGS), and NW (see http://www.btwatershed.org and http://www.ncwcd.org). This report only summarizes quality data collected by FCU.

1.2 Watershed Description

The following watershed description was adopted from Billica & Oropeza (2010). Horsetooth Reservoir is located directly west of the City of Fort Collins in Colorado. The reservoir was formed by the construction of Horsetooth, Soldier Canyon, Dixon Canyon, and Spring Canyon dams by the United States Bureau of Reclamation (USBR) and is a terminal reservoir of the USBR's CBT Project. Construction of the four Horsetooth Reservoir dams took place from 1946 to 1949. Water was first stored in Horsetooth Reservoir in January 1951. Horsetooth Reservoir and the other components of the CBT Project are operated by NW.

Horsetooth Reservoir water nearly all comes from the CBT Project. Because of this, the land areas that influence the water quality of Horsetooth Reservoir include watersheds both west and east of the Continental Divide (Figure 1.1). West of the Continental Divide, CBT Project and Windy Gap Project waters are mixed and transported together through the CBT system. Three main watersheds west of the Continental Divide provide the sources of these waters: Three Lakes Watershed, Willow Creek Watershed and Windy Gap Watershed. East of the Continental Divide, the CBT Project is situated within the Big Thompson River Watershed, which provides additional water supply. Water quality in Horsetooth Reservoir reflects the influence of these upstream watershed areas (1,093 square miles) in addition to the relatively small watershed area immediately surrounding Horsetooth Reservoir (17 square miles).

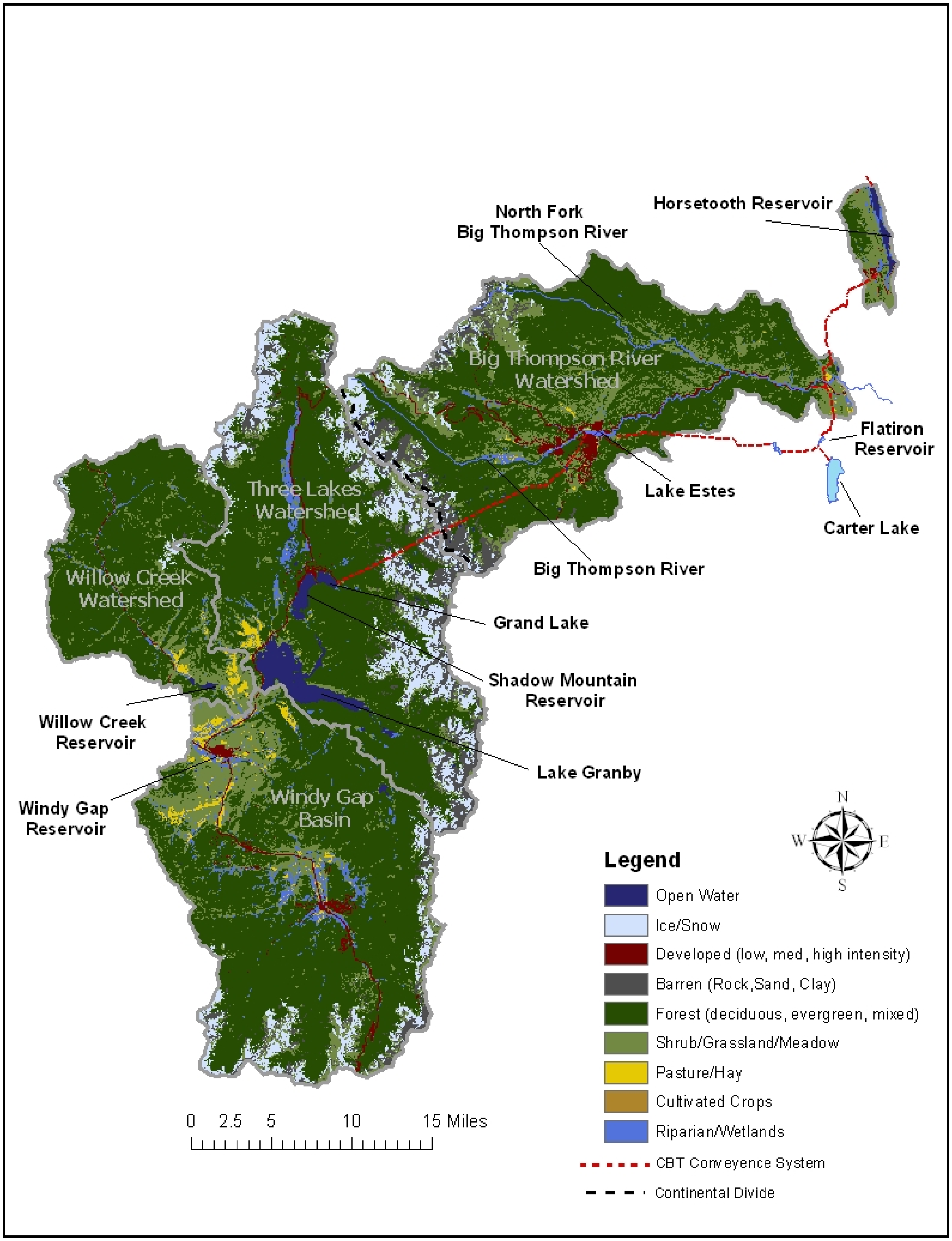


Figure 1.1 – Land use/land cover map for the combined watersheds of the CBT Project, Windy Gap Project, and Horsetooth Reservoir.

Big Thompson River Watershed above Dille Tunnel. Water is conveyed from Grand Lake to the eastern slope CBT system through the 13.1 mile long, 9.9 foot diameter Adams Tunnel. Water discharges from the east portal of the Adams Tunnel near Estes Park and flows to Lake Estes where it mixes with water from the Big Thompson River. Effluent from the Estes Park Sanitation District wastewater treatment plant discharges to the Big Thompson River just upstream of Lake Estes.

Water is conveyed downstream of Lake Estes via the Big Thompson River and the Olympus Tunnel, which transfers water to Flatiron Reservoir. From Flatiron Reservoir, CBT water travels 13 miles north to Horsetooth Reservoir through the Hansen Feeder Canal. The water that flows downstream of Lake Estes in the Big Thompson River can be diverted to the Hansen Feeder Canal (and on to Horsetooth Reservoir) through the Dille Tunnel. Big Thompson River water diverted at the Dille Tunnel is potentially impacted by upper and lower canyon residents and businesses, and by effluent from the Upper Thompson Sanitation District wastewater treatment plant (which discharges to the Big Thompson River just downstream of Lake Estes).

The watershed area of the Big Thompson River upstream of the Dille Tunnel (Figure 1.1) includes sub-drainages of the mainstem of the Big Thompson River (much of which is located within the boundaries of Rocky Mountain National Park) as well as the North Fork of the Big Thompson River. The total watershed area upstream of the Dille Tunnel is approximately 314 square miles of primarily mountainous terrain, of which 64% is forested. Shrub/grasslands are the second most dominant vegetation types, representing 20% of land cover, followed by rock, snow and ice, which combined represent 11% of the watershed area. The Town of Estes Park (approximate population of 6,300) as well as residential development in the Big Thompson Canyon comprises about 9 square miles, representing roughly 7% of the watershed area.

The Big Thompson Watershed Forum (http://www.btwatershed.org) was established in 1996 to "protect and improve water quality in the Big Thompson Watershed through collaborative monitoring, assessment, education and restoration projects." The FCU is a major financial contributor to the Forum, and a FCU representative serves on the Forum's Board of Directors.

Horsetooth Reservoir Local Watershed. Water from the Hansen Feeder Canal enters Horsetooth Reservoir at the south end of the reservoir, near the Inlet Bay Marina. The local watershed surrounding Horsetooth Reservoir is very small relative to the upstream watershed areas, and covers just 17 square miles of mixed forest, grassland, and residential land cover (Figure 1.1). The natural, local Horsetooth Reservoir watershed area includes several small, intermittent streams that flow into the west side of the Reservoir (including the named intermittent drainages Soldier Canyon, Well Gulch, Arthur's Rock Gulch, Mill Creek, and Spring Creek) during the spring snowmelt period and after significant rainfall events.

Although the local watershed surrounding Horsetooth Reservoir is small, there are certain types of disturbances that can potentially impact water quality, including wildfires and storm events that produce large amounts of runoff. Both Lory State Park and Larimer County Horsetooth Mountain Park are located in the hills west of the reservoir and within the boundaries of the Horsetooth Reservoir Watershed. In recent years, the respective management agencies have implemented forest fuel treatment plans to minimize the risk of wildfires within these areas. These types of watershed activities contribute to minimizing the risks to Horsetooth Reservoir water quality.

Water and land-based recreational activities at Horsetooth Reservoir can also potentially impact water quality. The recreational uses of Horsetooth Reservoir have been managed since 1954 by Larimer County (see http://www.larimer.org/naturalresources/horsetooth.htm). Campgrounds, trails, day use/picnic areas, boat ramps and associated facilities support boating, fishing, water skiing, camping, hiking, swimming, scuba diving, and rock climbing activities on and around the reservoir. Horsetooth Reservoir has approximately 25 miles of shoreline and Horsetooth Reservoir County Park lands completely surround the reservoir. Approximately 500,000 people visit the reservoir each year.

The potential sources of water quality pollutants associated with the recreational facilities and activities at Horsetooth Reservoir include:

- Runoff from construction areas, newly seeded areas, and other disturbed areas: sediments and nutrients (fertilizers)
- Runoff from parking areas and roadways: hydrocarbons and other fluids leaked from vehicles
- Boat fueling areas: hydrocarbons
- Shoreline erosion: sediments
- Swim beaches: microbiological contaminants
- Inadequate sanitary facilities (restrooms and/or sanitary sewer connections): microbiological contaminants and nutrients

1.3 Sampling Locations

Sampling locations for the FCU Horsetooth Reservoir Water Quality Monitoring Program (Figures 1.2 and 1.3) include the Hansen Feeder Canal just upstream of the reservoir (C50), and four sites within the reservoir: Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40). The reservoir sites include sampling at the depths outlined on Table 1.1. The concentrations of water quality parameters in Composition A and Composition B typically fall between concentrations observed from 1 meter below the surface (1M) and 1 meter from the reservoir bottom (Bottom +1M) and, follow similar seasonal patterns, respectively. In addition, Inlet Bay Narrows and Dixon Canyon Dam follow similar seasonal patterns as Spring Canyon Dam and Solider Canyon Dam. Therefore, this report focuses primarily on 1M and Bottom +1M results for Spring Canyon Dam and Solider Canyon Dam unless otherwise stated. Horsetooth Reservoir water is also sampled at the FCWTF raw water sample station, located at the FCWTF; sampling at this location represents water from the bottom of the reservoir at Soldier Canyon Dam.

Table 1.1 – Horsetooth Reservoir sampling depths.

	Inlet Bay Marina (R20)	Spring Canyon Dam (R21)	Dixon Canyon Dam (R30)	Soldier Canyon Dam (R40)
1 meter below surface	X	X	X	X
Composite A: 5 to 15 meters below surface		X		X
Composite B: 20 meters below surface to 5 meters above reservoir bottom		X		X
1 meter above reservoir bottom		X		X
Depth profiles, every 1 meter, from the surface to 1 meter above bottom	X	X	X	X

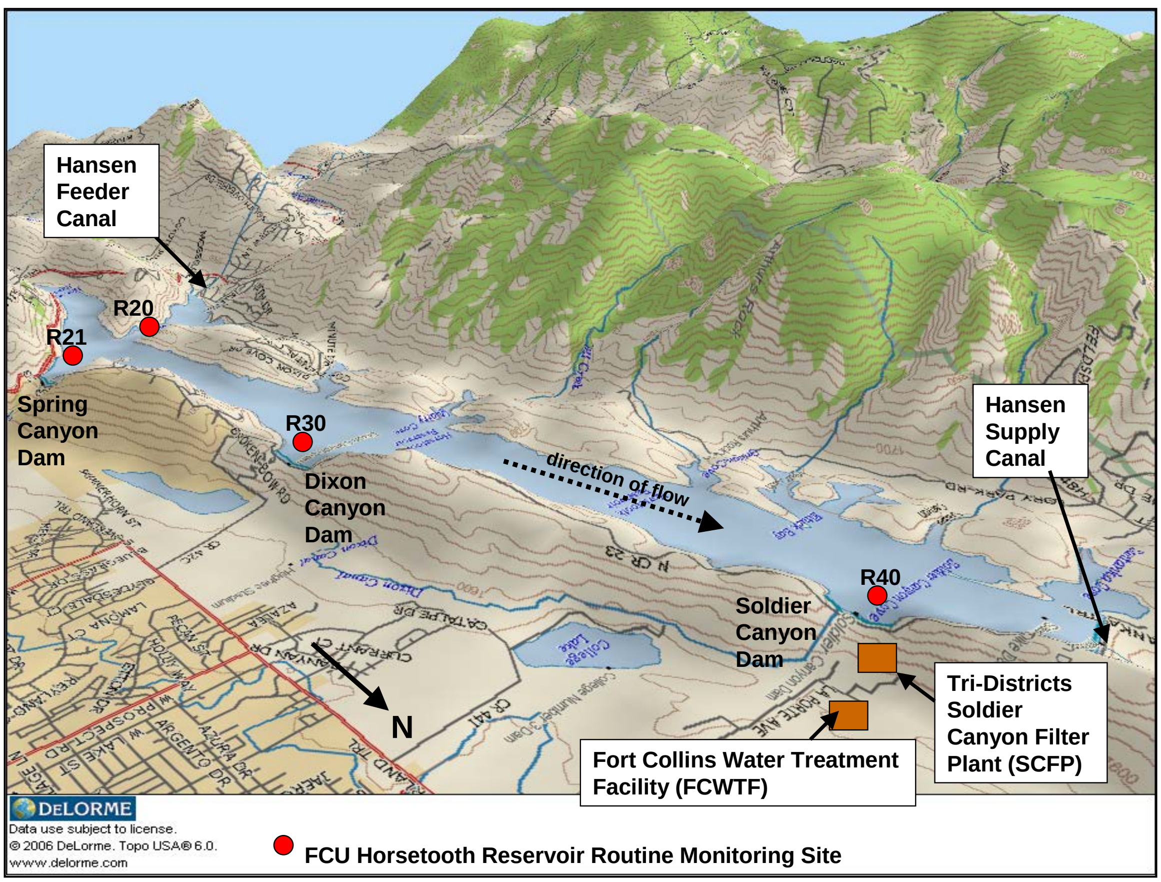


Figure 1.2 – FCU Horsetooth Reservoir routine water quality monitoring sites.

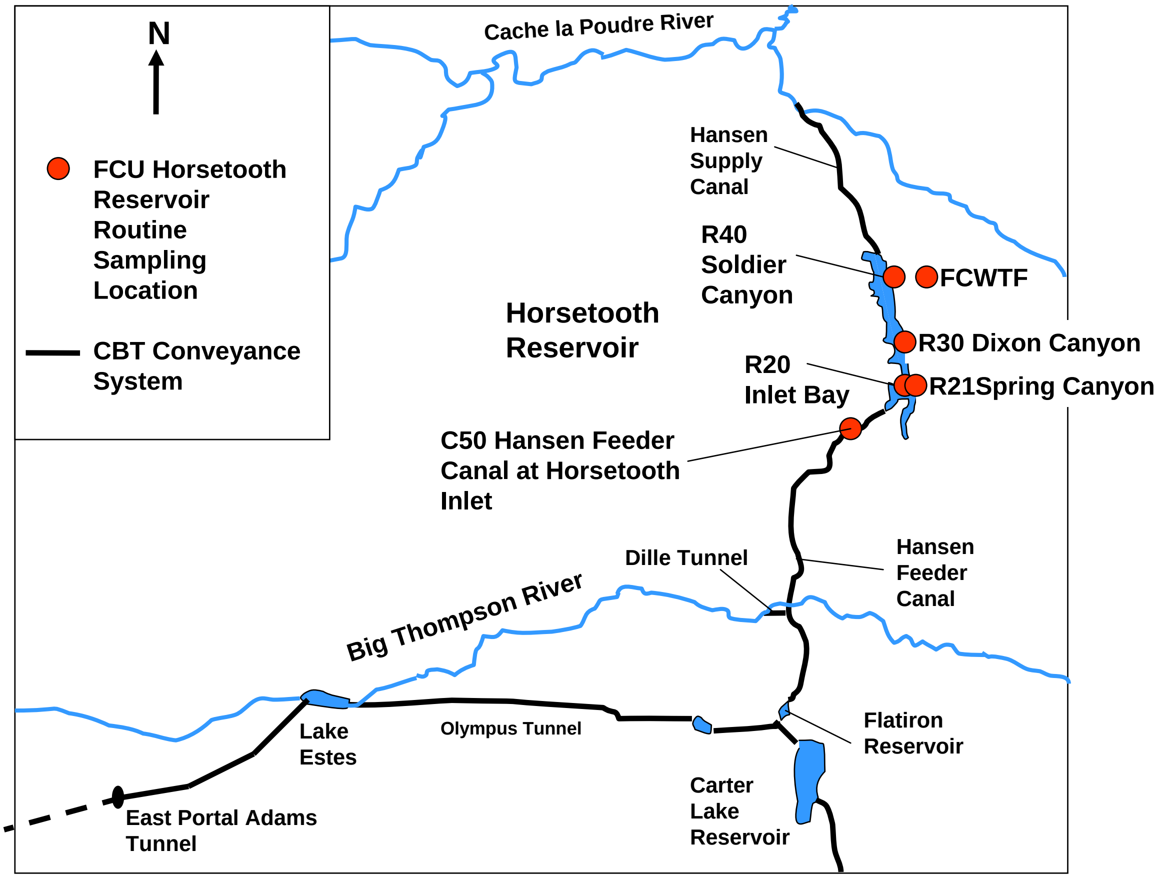


Figure 1.3 – Overview map of FCU Horsetooth Reservoir routine water quality monitoring sites and the CBT project's eastern slope distribution system.

1.4 Sampling Frequency and Parameters

Water quality monitoring of Horsetooth Reservoir is conducted from April through November. In 2011 and 2012 there were eight routine Horsetooth Reservoir monitoring events, and in 2013 there were seven routine monitoring events. Table 1.2 outlines the exact monitoring dates for 2011-2013.

FCU sampling of the Hansen Feeder Canal includes continuous monitoring with a multi-parameter YSI sonde and the routine collection of grab samples. Grab sampling is conducted weekly, although not all parameters are analyzed at this frequency.

The monitoring parameters measured in 2011, 2012, and 2013 for the Hansen Feeder Canal and Horsetooth Reservoir sites are located in Table 1.3. The

Table 1.2 – Horsetooth Reservoir routine water quality monitoring dates for the 2011, 2012, and 2013 monitoring seasons.

HORSETOOTH MONITORING EVENTS			
MONTH	2011	2012	2013
	DAY		
April	18	16	-
May	16	14	13
June	13	27	10
July	18	9	8
August	15	7	5
September	12	4	9
October	10	8	7
November	7	5	19

frequency of analysis for the various parameters is indicated on this table. Those parameters shown with an "x" were analyzed during every routine monitoring event. All analyses were conducted by the City of Fort Collins Water Quality Laboratory (FCWQL) except for phytoplankton identification and enumeration which was conducted by Mr. Richard Dufford (private consultant). Analytical methods, reporting limits, sample preservation, and sample holding times are located in Appendix A.

Note that for the FCWQL, the "Reporting Limit" is functionally the same as the Practical Quantitation Limit (PQL). PQL is defined as the lowest concentration of an analyte that can be reliably measured within specified limits of precision and accuracy during routine laboratory operating conditions. The Method Detection Limit (MDL) is the lowest concentration that an analytical instrument can reliably *detect* and is a statistical value based on the reproducibility of the instrument signal at a low analyte concentration. The PQL is estimated at 5 x MDL or higher, with the exact value determined empirically. All concentrations above the MDL are reported by the FCWQL. Although confidence in the exact concentration of results between the MDL and PQL is uncertain, such values do represent detected analytes. In this report, graphical and statistical analysis includes all data reported by the FCWQL. The data sets for some parameters (nutrients) include many values below their respective Reporting Limits, as can been seen in the various time series plots presented in this report. The reporting limit for each constituent is represented by a dashed black line on most figures discuss in this report.

Table 1.3 – Horsetooth Reservoir Routine Monitoring Parameters.

	Hansen Feeder Canal	Inlet Bay	Spring Canyon (R21)				Dixon Canyon	Soldier Canyon (R-40)			
			1Meter	Comp A	Comp B	Bottom+1M		1 Meter	Comp A	Comp B	Bottom+1 M
	C50	R20	R21-1M	R21-A	R21-B	R21-B+1	R30	R40-1M	R40-A	R40-B	R40-B+1 M
Field Parameters											
Secchi Depth		x	x				x	x			
Temperature	continuous	every meter	every 1 meter				every 1 meter	every 1 meter			
Dissolved Oxygen	continuous	every meter	every 1 meter				every 1 meter	every 1 meter			
pH	continuous	every meter	every 1 meter				every 1 meter	every 1 meter			
Specific Conductance	continuous	every meter	every 1 meter				every 1 meter	every 1 meter			
General & Misc Parameters											
Alkalinity	1/wk	x	x	x	x	x		x	x	x	x
Color	1/wk										
Geosmin (fall)	1/mo	x	x	x	x	x	x	x	x	x	x
Hardness	1/wk	x	x	x	x	x		x	x	x	x
pH	1/wk										
Spec Cond	1/wk										
TDS	1/mo							x	x	x	
TOC	1/wk	x	x	x	x	x		x	x	x	x
Turbidity	1/wk	x	x	x	x	x		x	x	x	x
VOC (BTEX)	1/mo	x	x					x			
Nutrients & Phytoplankton											
Ammonia	1/wk	x	x	x	x	x		x	x	x	x
Chlorophyll-a	1/wk	x	x				x	x			
Nitrate	1/wk	x	x	x	x	x		x	x	x	x
Nitrite	1/wk	x	x	x	x	x		x	x	x	x
O-Phosphate	1/wk	x	x	x	x	x		x	x	x	x
Phos. - Total	1/wk	x	x	x	x	x		x	x	x	x
Phyto-plankton	1/mo	x	x				x	x			
TKN	1/mo	x	x	x	x	x		x	x	x	x
Major Ions											
Calcium	1/mo		x	x	x	x		x	x	x	x
Chloride	1/mo										
Fluoride	1/wk										
Magnesium	1/mo		x	x	x	x		x	x	x	x
Potassium	1/mo							x	x	x	x
Silica	1/mo										
Sodium	1/mo							x	x	x	x
Sulfate	1/mo	x	x	x	x	x		x	x	x	x
Microbiological Constituents											
E. Coli	1/wk										
Fecal Strep	1/wk										
Heterotrophic Plate Count	1/wk										
Total Coliform	1/wk										

Table 1.3 – Horsetooth Reservoir Routine Monitoring Parameters (continued).

			Spring Canyon (R21)					Soldier Canyon (R-40)			
	Hansen Feeder Canal	Inlet Bay	1Meter	Comp A	Comp B	Bottom+1M	Dixon Canyon	1 Meter	Comp A	Comp B	Bottom+1 M
	C50	R20	R21-1M	R21-A	R21-B	R21-B+1	R30	R40-1M	R40-A	R40-B	R40-B+1 M
Metals (all metals total unless otherwise specified; D= dissolved)											
Aluminum	1/mo							x	x	x	x
Aluminum - D								x	x	x	x
Antimony	3/yr										
Arsenic	3/yr							1/yr	1/yr	1/yr	1/yr
Barium	3/yr										
Beryllium	3/yr										
Cadmium	3/yr										
Chromium	3/yr										
Copper	1/wk										
Copper - D	1/wk										
Iron	1/mo	x	x	x	x	x		x	x	x	x
Iron – D		x	x	x	x	x		x	x	x	x
Lead	1/mo							1/yr	1/yr	1/yr	1/yr
Manganese	1/mo	x	x	x	x	x		x	x	x	x
Manganese -D	1/mo	x	x	x	x	x		x	x	x	x
Mercury	3/yr										
Molybdenum	3/yr										
Nickel	3/yr										
Selenium	3/yr										
Silver	3/yr							1/yr	1/yr	1/yr	1/yr
Thallium	3/yr										
Zinc	3/yr										

2.0 REGULATORY ACTIVITIES, SPECIAL STUDIES, and ISSUES OF CONCERN

This section provides an overview of ongoing watershed issues of concern, an update of water quality regulations that directly impact Horsetooth Reservoir, and a status report of activities. Special studies are designed to address specific long-term issues or new concerns that are outside of the scope of the routine monitoring program.

2.1 Colorado's 2012 Section 303(d) and Monitoring and Evaluation (M&E) Lists

Colorado's Section 303(d) List and Monitoring and Evaluation (M&E) List (Regulation #93) for the 2012 listing cycle were adopted on February 13, 2012 and became effective on March 30, 2012. When water quality standard exceedances are suspected, but uncertainty exists regarding one or more factors (such as the representative nature of the data used in the evaluation), a water body or segment is placed on the M&E List. Horsetooth Reservoir (COSPCP14) is listed for the following parameters:

- Copper & Arsenic - 303(d): Horsetooth Reservoir was on the M&E List in 2010 for copper and arsenic (aquatic life standards), but moved to the 303(d) list in 2012 for further data collection.

- Fish Mercury - 303(d) List: Horsetooth Reservoir remains on the 303(d) List for mercury for Aquatic Life Use. Fish consumption advisory was issued in January 2007 due to the presence of mercury in the tissue of fish in Horsetooth Reservoir.

In previous years, Horsetooth Reservoir was listed on the Section 303(d) List and the M&E List for low DO (D.O in the metalimnion. In 2012, new 303(d) listing methodology for DO was developed and, resulted in Horsetooth Reservoir being delisted from the M&E List for DO The Colorado Water Quality Control Division (WQCD) used 79 temperature and DO profiles collected by the USGS and NW from 2003 to 2008 to make this determination.

2.2 Colorado Nutrient Standards

The WQCD is currently in the process of developing numeric nutrient criteria for different categories of state surface waters. The intent is to develop numerical criteria for phosphorus, nitrogen, and chlorophyll-a that would be included in the Basic Standards and Methodologies for Surface Water (Regulation #31). The numerical criteria are being developed to protect designated uses of lakes and reservoirs, and rivers and streams from nutrient pollution.

The Basic Standards and Methodologies (Regulation #31) became effective on January 31, 2013. Interim numeric standards have been proposed for total phosphorus (TP) and total nitrogen (TN) (section 31.17 of Regulation #31) for lakes and reservoirs. For cold water lakes and reservoirs greater than 25 acres (including Horsetooth Reservoir), the proposed interim TP standard is 25 µg/L while the proposed interim TN standard is 426 µg/L. A chlorophyll-a standard of 8 µg/L has also been proposed for cold water lakes and reservoirs greater than 25 acres. In all cases, the proposal includes assessment of the criteria using summer averages (July, August and September data) or summer medians of the mixed layers with an allowable exceedance frequency of 1-in-5 years. The data presented in this report for nutrient standards utilized the summer average values of the 1M and Composite A samples because these depths represent the mixed layers of the water column during the summer months.

The WQCD has proposed a lower chlorophyll-a standard to support Direct Use Water Supply (DUWS) Lakes and Reservoirs of the existing Water Supply use classification. The intent of this chlorophyll-a standard is to help maintain or reduce the disinfection by-product (DBP) formation potential of lakes and reservoirs that supply raw water directly to water treatment plants (such as Horsetooth Reservoir). Controlling nutrients and algal growth may also result in other benefits for drinking water utilities, including reduced coagulant dosages and/or reduced usage of activated carbon for T&O control. The proposed interim numeric chlorophyll-a value is 5 μg/L (summer average chlorophyll-a in the mixed layers or median of multiple depths) with a 1-in-5 year exceedance frequency.

Horsetooth Reservoir exceeded the TN and chlorophyll-a nutrient standards in 2012 at all monitoring sites, except Spring Canyon Dam (Figure 2.1). The TN standard was exceeded at Solider Canyon Dam; however, the average chlorophyll-a concentration was slightly below the numeric standard. Total nitrogen average concentrations ranged from a minimum 400 μg/L at Spring Canyon Dam to a maximum 536 μg/L at Inlet Bay Marina. Chlorophyll-a average concentrations ranged from 4.67 μg/L at Solider Canyon Dam to 6.81 μg/L at Inlet Bay Narrows. Over the five year period, 2012 was the only year to exceed the proposed nutrient standard and because the allowable exceedance frequency is 1-in-5-years, Horsetooth Reservoir is in compliance with the standards for TN and chlorophyll-a. Total phosphorus median concentrations were below the proposed 25 μg/L standard over the entire five year period (Figure 2.1). Make note that his report is a not a water quality compliance report, but may utilize designated water quality standards to evaluate the health of Horsetooth Reservoir.

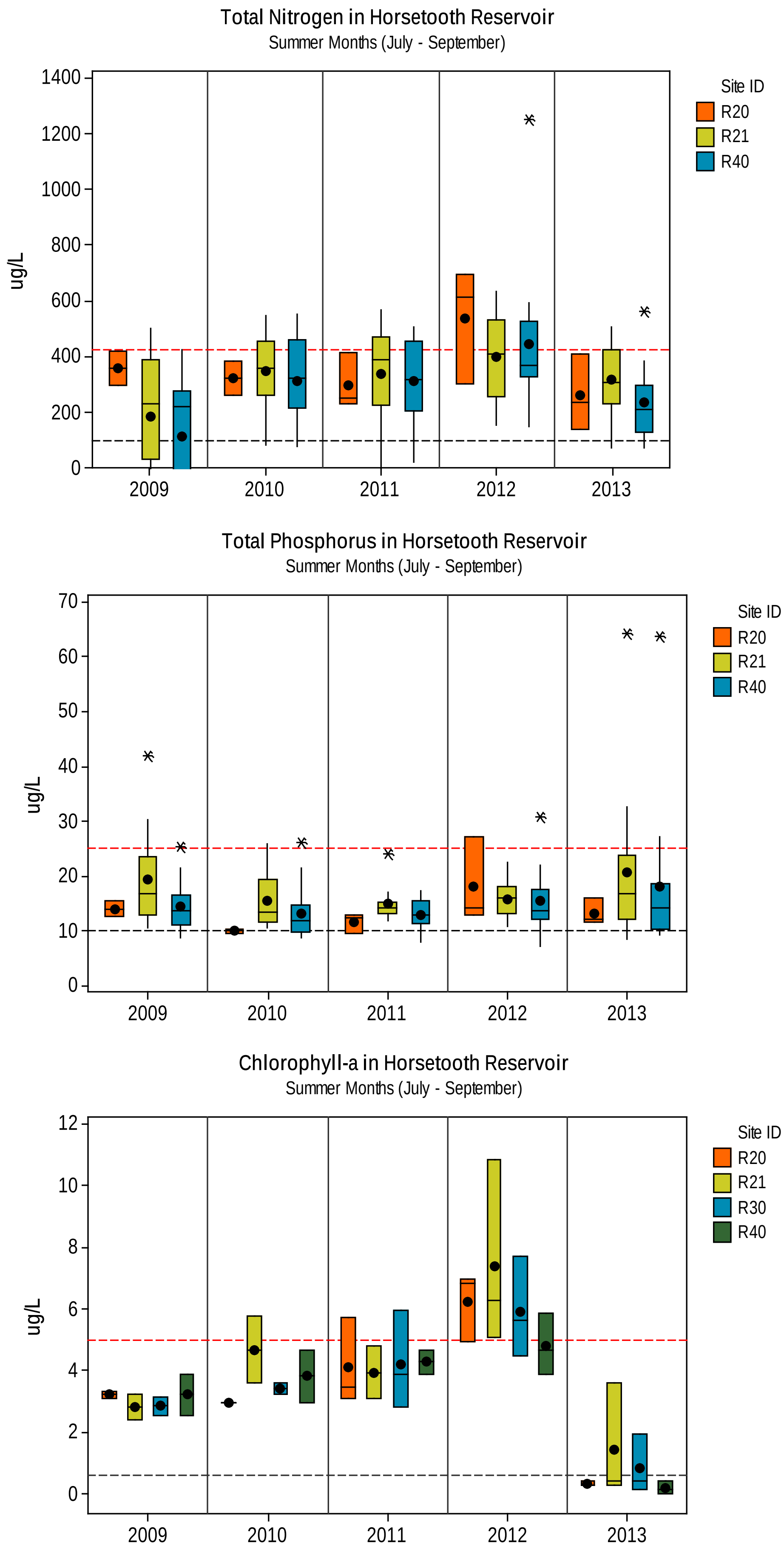


Figure 2.1 – Total nitrogen, phosphorus, and chlorophyll-a concentrations measured during the summer months (July through September) at Horsetooth Monitoring sites. Average concentrations (depicted by the black dot in the box plot) were calculated using data from mixed layers (1-meter below the surface and Comp A). Nutrient and chlorophyll-a drinking water supply standards are represented by the dashed red line.

2.3 Geosmin Monitoring in Horsetooth Reservoir and CBT Project delivery system

Geosmin is a naturally occurring organic compound produced by some species of cyanobacteria (blue-green algae) and actinomycetes (filamentous bacteria). Geosmin imparts an earthy odor to the water and can be detected by the most sensitive noses at extremely low concentrations (<5 nanograms per liter (ng/L) or 5 parts per trillion (ppt) by some FCU customers). It has been detected in both raw Poudre River water and raw Horsetooth Reservoir water and is very difficult to remove.

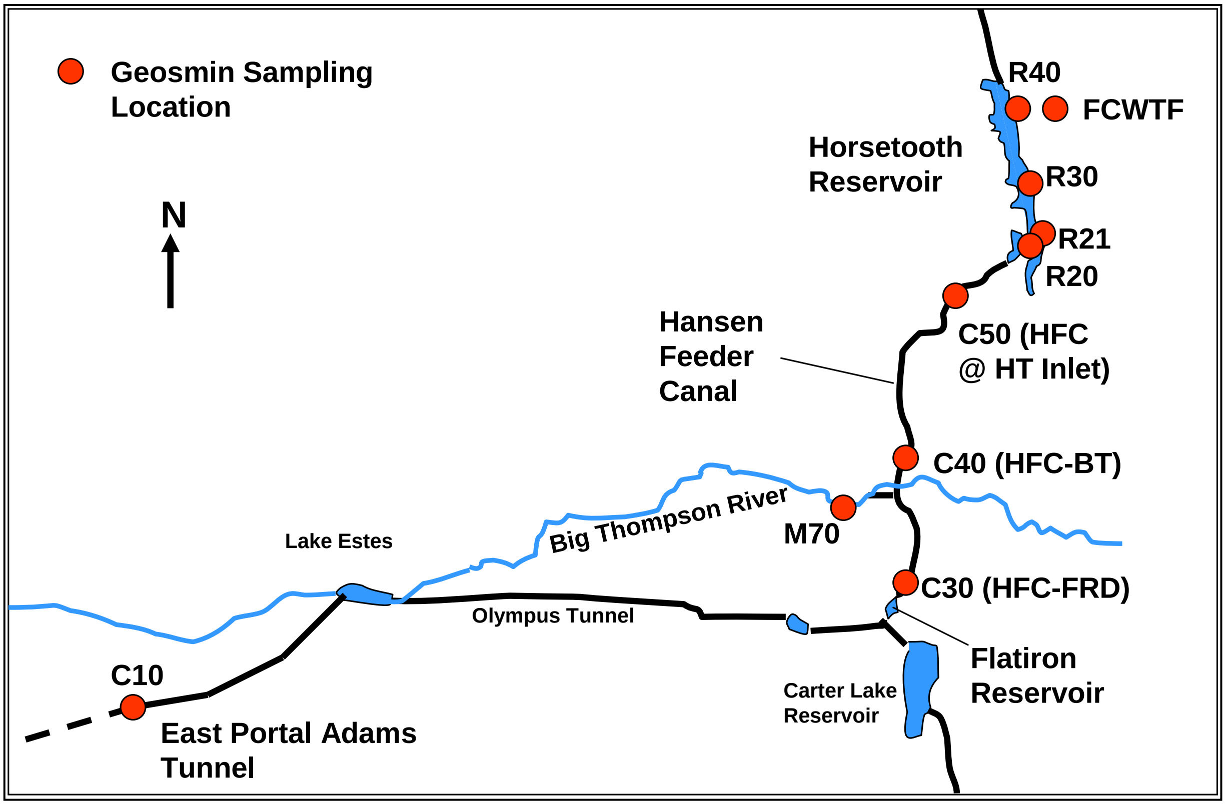


Figure 2.2 – FCU geosmin sampling locations on the CBT project delivery system and Horsetooth Reservoir.

Fort Collins Utilities staff has conducted watershed monitoring for geosmin since 2008 to help determine geosmin occurrence and production sites in Horsetooth Reservoir and upstream components of the CBT system (Figure 2.2). Beginning in 2009, watershed monitoring was also designed to provide for a geosmin "early warning" system for the treatment plant. Since 2008, watershed geosmin sampling has included the Horsetooth Reservoir routine sampling sites and beginning in 2009, the Hansen Feeder Canal sites, Big Thompson River above the Dille Tunnel, and the east Portal Adams Tunnel were also sampled on a monthly basis starting from August to November. The results of the 2008 and 2009 sampling efforts are presented and assessed in Billica, Oropeza, and Elmund (2010).

Geosmin concentrations in Horsetooth Reservoir generally follow seasonal patterns. Concentrations increase throughout the monitoring season and peak in the late summer and early fall before decreasing during and following fall turnover. Geosmin in the CBT system decreases moving downstream from Adams Tunnel before entering Horsetooth Reservoir via the Hansen Feeder Canal. Previous work suggests that geosmin in Horsetooth Reservoir originates from upstream sites on the Hansen Feeder Canal as well as from in-reservoir production (Oropeza, Billica, and Elmund, 2010). Geosmin is subject to both volatilization and biodegradation that impact its fate in aquatic systems. These are the likely mechanisms that resulted in a reduction in geosmin concentrations as the Adams Tunnel water was transported downstream through the east slope CBT system.

Horsetooth Reservoir geosmin data from 2011, 2012, and 2013 are presented in Figure 2.3 and corresponding CBT geosmin data are present in Figure 2.4. The following bullets summarize geosmin detected in Horsetooth Reservoir and the CBT system during the 2011, 2012, and 2013 monitoring seasons:

- 2011 HT and CBT Geosmin Summary: Geosmin concentrations at all Horsetooth Reservoir monitoring sites were below 4 ng/L. The highest concentration was 3.55 ng/L in the Dixon Canyon Dam hypolimnion on October 10th. Geosmin in the CBT system exceeded 4 ng/L on one occurrence. The highest geosmin concentration was 12.64 ng/L at Adams Tunnel on October 4th.

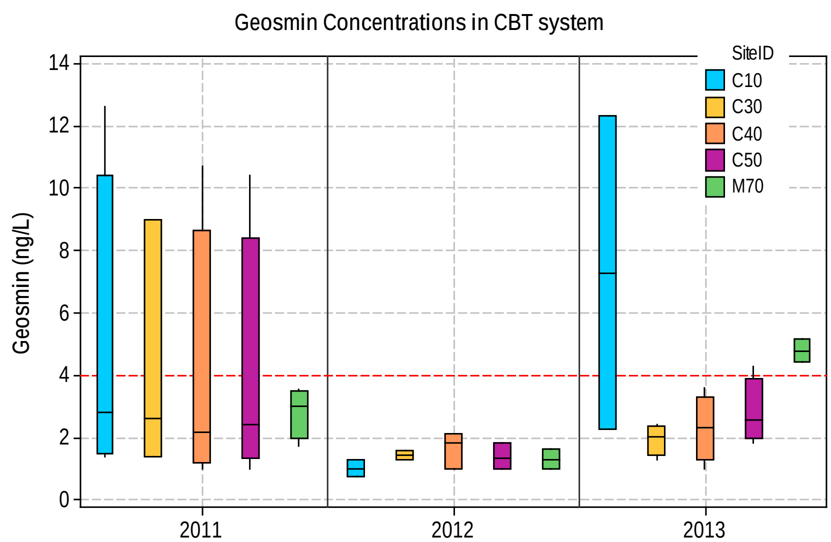


Figure 2.3 – Box plots of gesomin concentrations monitored in the CBT system during the 2011, 2012, and 2013 monitoring season.

- 2012 HT and CBT Geosmin Summary Summary: Geosmin concentrations in the hypolimnion of Horsetooth Reservoir exceeded the 4 ng/L threshold at all locations except the Inlet Bay Narrows in 2012. The highest concentration was 8.44 ng/L in the Dixon Canyon Dam hypolimnion on September 4th. Epilimnetic and metalimnetic geosmin concentrations were below 4 ng/L at all Horsetooth Reservoir monitoring sites throughout the entire season. Geosmin concentrations in the CBT system were below 4 ng/L on all monitoring dates.

- **2013 HT and CBT Geosmin Summary Summary**: Geosmin concentrations in Horsetooth Reservoir exceeded the 4 ng/L threshold at all locations in 2013, but only on one occurrence. The highest concentration was 6.72 ng/L in the Spring Canyon Dam epilimnion on September 9th. Geosmin concentrations in the CBT system exceeded 4 ng/L on one monitoring date at C10, C50, and M70. The highest concentration was 12.3 ng/L on August 7th at the Adams Tunnel.

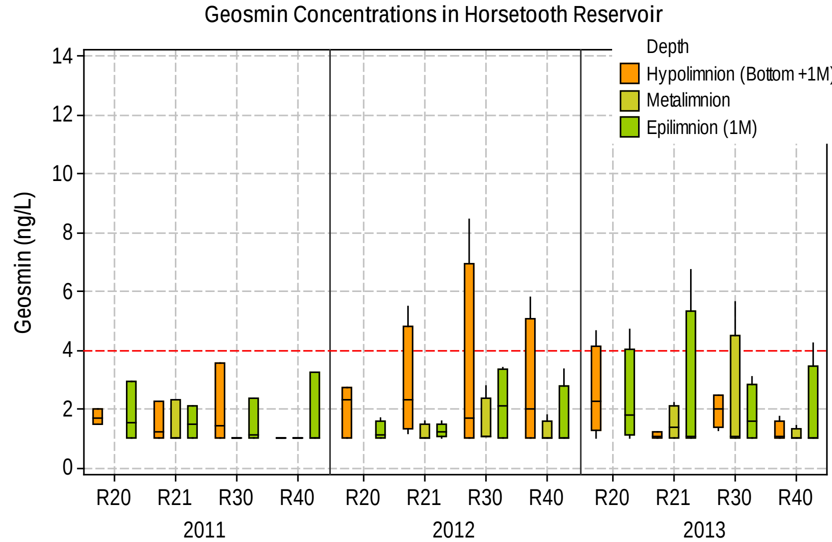


Figure 2.4 – Box plots of geosmin concentrations monitored in Horsetooth Reservoir during the 2011, 2012, and 2013 monitoring seasons. The red dashed line indicates the T&O threshold 4 ng/L.

It should be noted, that despite detections greater than 4 ng/L geosmin in the Reservoir, concentrations did not result in detectable concentrations in treated drinking water. Geosmin was removed in the treatment processes due to the ability of FCWTF to blend raw Horsetooth water with raw Poudre River water.

2.4 Northern Water Collaborative Emerging Contaminant Study

Contaminants of emerging concern (CEC) and their presence in water have recently received national attention. CEC are trace concentrations (at the nanogram/L or part per trillion level, or less) of the following types of chemicals:

- Pharmaceuticals: prescription and non-prescription human drugs (including pain medications, antibiotics, β-blockers, anti-convulsants, etc) and veterinary medications
- Personal care products: fragrances, sunscreens, insect repellants, detergents, household chemicals
- Endocrine disrupting chemicals: chemicals that interfere with the functioning of natural hormones in humans and other animals; includes steroid hormones (estrogens, testosterone, and progesterone), alkylphenols, and phthalates
- Pesticides and herbicides

In 2008, NW initiated a collaborative emerging contaminant study to determine the presence of these compounds in waters of the CBT system including Horsetooth Reservoir (Figure 2.5). Sampling of Horsetooth Reservoir initially included only a 1 meter sample at Soldier Canyon Dam (Nov 2008 and June

2009 samples), but has since expanded to include middle and bottom samples at Soldier Canyon Dam plus surface, middle, and bottom samples at Spring Canyon Dam (June 2010 and August 2010 samples).

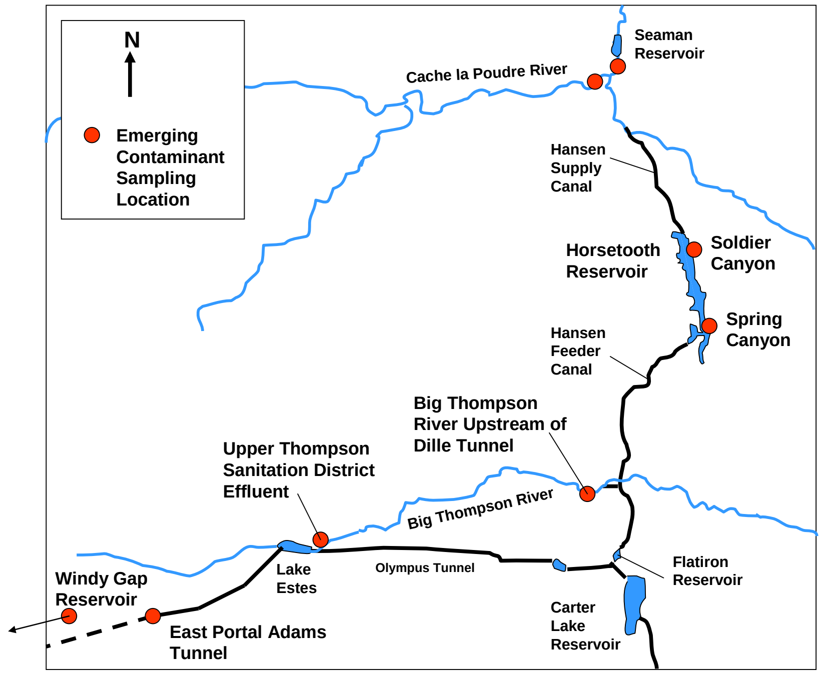


Figure 2.5 – Northern Water Collaborative Emerging Contaminant Study sampling sites located on the CBT Project delivery system and Horsetooth Reservoir.

Samples were submitted to the Center for Environmental Mass Spectrometry Laboratory at the University of Colorado at Boulder (CU) for analysis of 51 pharmaceuticals and 103 pesticides by Liquid Chromatography – Time of Flight – Mass Spectrometry (LC/TOF-MS). Beginning with the June 2009 sampling event, samples were also submitted to Underwriters Laboratories, Inc. for analysis of estrogens and other hormones (9 compounds, UL Method L211), and phenolic endocrine disrupting chemicals (8 compounds including bisphenol A, UL Method L200). Beginning in 2010, the CU laboratory also began conducting low-level analysis by liquid chromatography with tandem mass spectrometry for a subset of 22 different pharmaceuticals and personal care products (PPCP), in addition to the analysis of 51 pharmaceuticals and 103 pesticides by LC/TOF-MS.

The wastewater treatment plant effluent from Estes Park Wastewater Treatment Plant is the primary source of many PPCP to Horsetooth Reservoir via the Hansen Feeder Canal. Many of these compounds do not appear to be persistent in the aquatic environment since they do not consistently occur in downstream water samples. The Big Thompson River above the Dille Tunnel site is the closest downstream site to the Upper Thompson Sanitation District discharge site and has the highest number of detected pharmaceuticals. The effect of wastewater treatment plant effluent on Windy Gap and East Portal Adams Tunnel waters appears to be very low or non-existent. The following bullets summarize findings from NW's Emerging Contaminants Program: Summary Report 2008-2011 and Emerging Contaminants Program: 2013 Annual Report for emerging contaminants detected in Horsetooth Reservoir during the 2011, 2012, and 2013 monitoring seasons.

Emerging Contaminants Summary (2011-2013):

- *Pharmaceuticals and Personal Care Products (PPCP)* detected in Horsetooth Reservoir were consistent with those detected in the Hansen Feeder Canal. The most commonly detected PPCP in the Hansen Feeder Canal and Horsetooth Reservoir include cotinine, gemfibrozil, lamotrigine, metoprolol, and venlafaxine. PPCP in Horsetooth Reservoir were generally low in 2011 with concentrations less than 10 ng/L. Metoprolol and sucralose were detected at every monitoring event. Sucralose was the most common compound detected in Horsetooth Reservoir with concentrations ranging between 46 ng/L and 243 ng/L. Metoprolol (a beta blocker) appears to be a stable, persistent pharmaceutical. Low levels of metoprolol were measured in Horsetooth.
- *Endocrine disruptors* were not detected in the Hansen Feeder Canal or Horsetooth Reservoir.
- *Herbicide and insecticide* concentrations were generally low in Horsetooth Reservoir (<20 ng/L). The only detected herbicide in Horsetooth Reservoir in 2011 was 2,4-D. The two herbicides, 2,4-D and diuron, are used to control weeds in agricultural applications as well as along fences and highways and may be used around the canals and reservoirs. Although it has a short half-life in soil and aquatic systems, 2,4-D was consistently observed throughout Horsetooth Reservoir. A maximum contaminant level of 0.07 mg/L (70,000 ppt) has been set for 2,4-D by the U.S.E.P.A. for finished drinking water. Diuron is mobile and more persistent in the environment than 2,4-D. Microbial degradation is the primary process by which it is removed from aquatic environments. Diuron is on the U.S.E.P.A.'s Contaminant Candidate List 3 (CCL3) currently being considered for regulation under the Safe Drinking Water Act based on its potential to occur in public water systems. NW is actively evaluating best practices and researching alternative algaecides and herbicides for managing aquatic weeds in the Hansen Feeder Canal.
- *Recreational contaminants*, DEET, caffeine, sucralose, and triclosan, were all detected in Horsetooth Reservoir. DEET concentrations were the highest in August. Caffeine can indicate the presence of domestic wastewater (treatment plant effluents and septic systems) in a water supply system. In addition, the large amount of caffeine that is consumed and discarded (i.e., pouring out unused caffeinated beverages) in our watersheds can also contribute to continuous loading of caffeine to the aquatic environment. Sources of caffeine in Horsetooth Reservoir likely originate from both upstream wastewater discharges and direct inputs.

2.5 Climate Change

Climate change is one of the most critical issues impacting watersheds and water supplies in Colorado (Ray et al., 2008). Warming temperatures can result in changes to the water cycle, impacting the health of watersheds that collect, store, and deliver clean water for consumptive and non-consumptive uses. The most serious consequences of climate change on Colorado watersheds, affecting both quantity and quality, are:

- Changes in precipitation patterns
- Shifts in timing and intensity of runoff and streamflow
- Increases in severity and frequency of droughts and wildfires

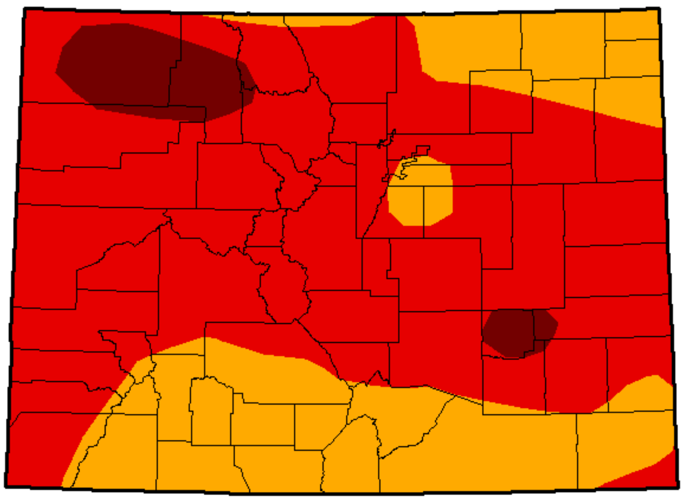
U.S. Drought Monitor

Colorado

July 3, 2012

(Released Thursday, Jul. 5, 2012)

Valid 7 a.m. EST



Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.00	100.00	100.00	100.00	70.69	5.52
Last Week 6/26/2012	0.00	100.00	100.00	97.72	45.83	0.00
3 Months Ago 4/3/2012	0.00	100.00	55.48	18.50	0.15	0.00
Start of Calendar Year 1/3/2012	65.37	34.63	24.98	10.60	0.04	0.00
Start of Water Year 9/27/2011	60.62	39.38	27.69	19.99	7.88	0.56
One Year Ago 7/5/2011	49.31	50.69	34.84	29.02	16.64	1.57

Intensity:

- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

Author:
Richard Tinker
CPC/NOAA/NWS/NCEP

http://droughtmonitor.unl.edu/

Figure 2.6 – Colorado drought conditions in July 3, 2012. Map obtained from the U.S. Drought Monitor (http://droughtmonitor.unl.edu/).

Colorado's water resources are already limited, making the state vulnerable to increasing extremes due to climate change. Many consequences of a changing climate directly impact drinking water supplies. Precipitation patterns in Colorado vary over space and time and changes in these patterns, timing, and type (rain vs. snow) can result in extended drought, as well as intense precipitation events leading to unprecedented flooding. This increased variability from year to year makes it difficult for municipalities to predict water supply, and the influence of extreme climate patterns on water quality.

In addition, shifts in the timing and intensity of runoff and streamflow add further challenges to managing water supplies. The onset of streamflow from melting snow is projected to shift to earlier in the spring, resulting in reduced runoff in the late summer months when demand for water is highest for all beneficial uses. These climate-driven changes to the water cycle make it difficult to estimate the quantity of water available to meet current and future demand.

In combination with changes to water quantity, changes to water quality can also occur as a result of a changing climate. The increase in the severity, frequency, and intensity of droughts and wildfires are resulting in dramatic changes to the land cover of Colorado's watersheds, directly impacting water quality. Droughts are the leading cause of wildfires and therefore, with the occurrence of more prolonged droughts, an increased frequency in wildfires can be expected. Wildfires impact watershed hydrology by altering vegetation and soils, resulting in increased likelihood of sediment erosion and debris runoff into rivers and streams. Sediment loading into water bodies can lead to increases in turbidity, nutrients, and organic carbon, making careful management essential to providing clean water to the public.

Over the three year monitoring period from 2011 through 2013, extreme weather events impacted watersheds in the CBT system. In 2011, Colorado experienced one of the wettest winters on record. Snow water equivalent in the Big Thompson Watershed was 166% of average and 152% of average in the Upper Colorado River Basin (NRCS Snowpack Reports for Colorado, http://www.wcc.nrcs.usda.gov/cgibin/snow_rpt.pl?state=colorado). Due to the record breaking snowpack in 2011, drought and fire were suppressed. In contrast to 2011, drought conditions amplified following abnormally low snowpack levels in 2012 in both the Big Thompson and Upper Colorado Watersheds (Figure 2.6). The largest fire in the history of the Poudre River Watershed located north of Horsetooth Reservoir began in June of 2012. The High Park Fire burned nearly 88,000-acres. Horsetooth Reservoir water supply was not directly impacted, but the proximity of the fire to the FCU Poudre River water intake structure forced FCU to rely solely on Horsetooth Reservoir water supply for approximately 102 days. The Fern Lake Fire followed and ignited on October 9, 2012 and burned approximately 3,500-acres near the headwaters of the Big Thompson Watershed in Rocky Mountain National Park. Snowpack conditions in 2013 were near average, but did little to suppress drought conditions. The Galena Fire began in March 2013 west of Horsetooth Reservoir in Lory State Park and burned approximately 1,350-acres. The Big Meadows Fire followed and was initiated by lightning on June 10, 2013 and burned approximately 600-acres in the Three Lakes Watershed.

Dry conditions unexpectedly were followed by an extreme precipitation event in September of 2013 resulting in historic flooding through Northern Colorado's Front Range. The Big Thompson Watershed was especially hit hard with many areas receiving rainfall amounts over the seven day event (September 9-16) exceeding annual precipitation totals (Figure 2.7). The extreme moisture led to unprecedented flooding resulting in severe damage to water supply infrastructure and compromised water quality throughout the watershed.

The extreme weather events observed over the three year monitoring period provide examples of the future challenges faced by water resources managers in Colorado. Climate change introduces high variability and uncertainty from year to year, but long-term monitoring of these resources can provide a valuable tool to better understand changes driven by climate and extreme events, and how to best respond now and into the future.

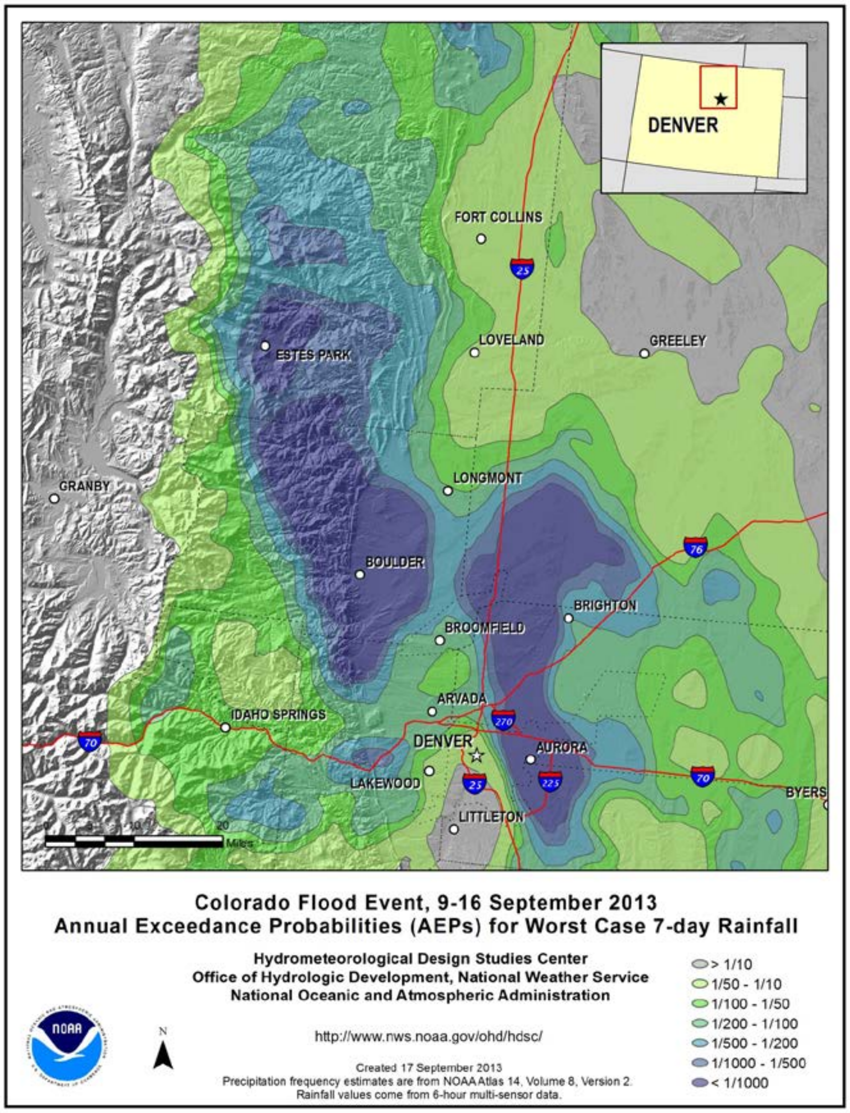


Figure 2.7 – Annual exceedance probabilities map for the worst case 7-day rainfall following the September 2013 flood event in Northern Colorado.

3.0 HORSETOOTH RESERVOIR HYDROLOGY

3.1 Reservoir Inflows and Outflows

The primary inflow to Horsetooth Reservoir is the CBT Project Charles Hansen Feeder Canal (also referred to as Hansen Feeder Canal). Hansen Feeder Canal flows to Horsetooth Reservoir are measured at Station HFCBBSCO (Charles Hansen Feeder Canal below Big Thompson Siphon. However, there are approximately twenty diversions out of the canal between HFCBBSCO and the reservoir that must be subtracted from the measured HFCBBSCO flow in order to compute the net inflow to Horsetooth Reservoir. One of these diversions is the City of Loveland turnout, measured at Station HFCLOVCO (Charles Hansen Feeder Canal Loveland Turnout). Flow data for the remaining diversions are not readily available and are assumed to be minor. Accordingly, the net Hansen Feeder Canal inflow to Horsetooth Reservoir is *estimated* here as:

Hansen Feeder Canal Inflow to Horsetooth (cfs) = HFCBBSCO – HFCLOVCO

HFCBBSCO and HFCLOVCO data are available on the Colorado Division of Water Resources website for flow gaging stations in the South Platte River Basin (http://www.dwr.state.co.us/). HFCLOVCO data are also available on NW's website (http://www.ncwcd.org).

Daily inflows from the Hansen Feeder Canal are illustrated in Figure 3.1 from January 1, 2011 through December 31, 2013. During the three year period, inflow to Horsetooth Reservoir was nearly continuous except during short periods each fall when the canal was shut down for annual maintenance. In 2011, inflow to Horsetooth Reservoir was increased from January through August corresponding to a historic snowpack in the mountains. Conversely, flows in 2012 during the runoff season were variable and short lived due to a historically low snowpack in the mountains. In flows in 2012 were increased in September through November.

The Horsetooth Reservoir local watershed includes several small, intermittent drainages that flow into the west side of the Reservoir (including Solider Canyon, Well Gulch, Arthur's Rock Gulch, Mill Creek, and Spring Creek) during the spring snowmelt period and after significant rainfall events. These drainages are not gaged and are considered insignificant (at least on an annual basis) compared to the Hansen Feeder Canal inflow. Flows into the Hansen Feeder Canal are controlled and largely influenced by mountain snowpack conditions.

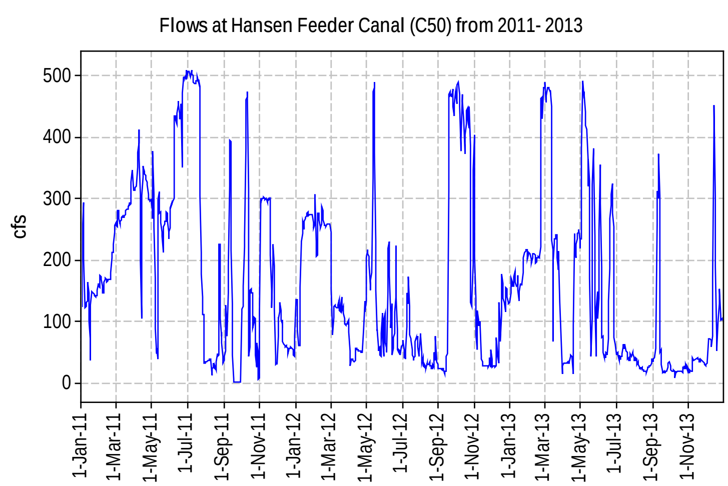


Figure 3.1 – Hansen Feeder Canal Inflow estimates to Horsetooth Reservoir from 2011 to 2013.

4.0 HORSETOOTH RESERVOIR WATER QUALITY

4.1 Profile Data (2011-2013)

The data presented below outlines summary statistics and significant findings from Horsetooth Reservoir profile data over the reservoir monitoring period of 2011 through 2013. Depth profiles were obtained monthly at all reservoir monitoring sites beginning in April and ending in November. Table 1.2 outlines the routine monitoring event dates which occurred over the 2011-2013 monitoring period. Measurements of temperature, DO, specific conductivity, and pH were obtained at 1-meter intervals from the water surface to the reservoir bottom using a YSI 6600 multiparameter water quality sonde to obtain profiles for each parameter. Profile data are used to help identify seasonal water quality characteristics within Horsetooth Reservoir to monitor reservoir stratification and help facilitate the management of the FCU water treatment processes and operations.

4.1.1 Temperature

Horsetooth Reservoir temperature profiles show similar seasonal patterns of most deep temperate lakes and reservoirs. The coldest temperatures occur during the winter months. The reservoir begins to warm in the late spring and early summer with the warmest temperatures typically occurring from late July through August. As the days grow longer and air temperature becomes warmer in the spring and early summer, the surface waters of the reservoir warm and thermal stratification begins to develop creating three distinct vertical zones located through the water column. The upper warmer water zone is called the *epilimnion*; the middle zone is called the *metalimnion (*or *thermocline)*; and the bottom coldest zone is called the *hypolimnion* (Figure 4.1).

The development of these temperature zones throughout the water column is strongly related to water density with the warmer, well mixed, and less dense water resting on top of the colder, denser water of the hypolimnion. These two layers are separated by a layer of rapidly changing water density (metalimnion/thermocline). Typical development of thermal stratification in Horsetooth Reservoir begins in the early to late spring and continues to develop through the summer and early fall (Figure 4.1b). Spatial and temporal trends in thermal stratification are observed at Horsetooth Reservoir. The onset of thermal stratification typically occurs earlier at Inlet Bay Narrows and Spring Canyon Dam compared to Dixon Canyon and Solider Canyon Dams. Earlier thermal stratification at Inlet Bay Narrows and Spring Canyon Dam is largely influenced by the cooler inflowing water from the Hansen Feeder Canal.

In the fall when air temperatures begin to decrease, heat loss from the epilimnion occurs more rapidly. Physical disturbance caused by fall wind events can further weaken the thermocline, eventually resulting in full mixing of upper and lower water column. This is referred to as fall turnover and results in uniform water temperatures throughout the water column. Fall turnover in Horsetooth Reservoir typically begins in late October and compete mixing of the water column is attained by November depending on seasonal weather patterns (Figure 4.1). Spatial and temporal trends in fall turnover are observed at Horsetooth Reservoir. Complete mixing of the water column occurs earlier at Soldier Canyon Dam (R40) than Spring Canyon

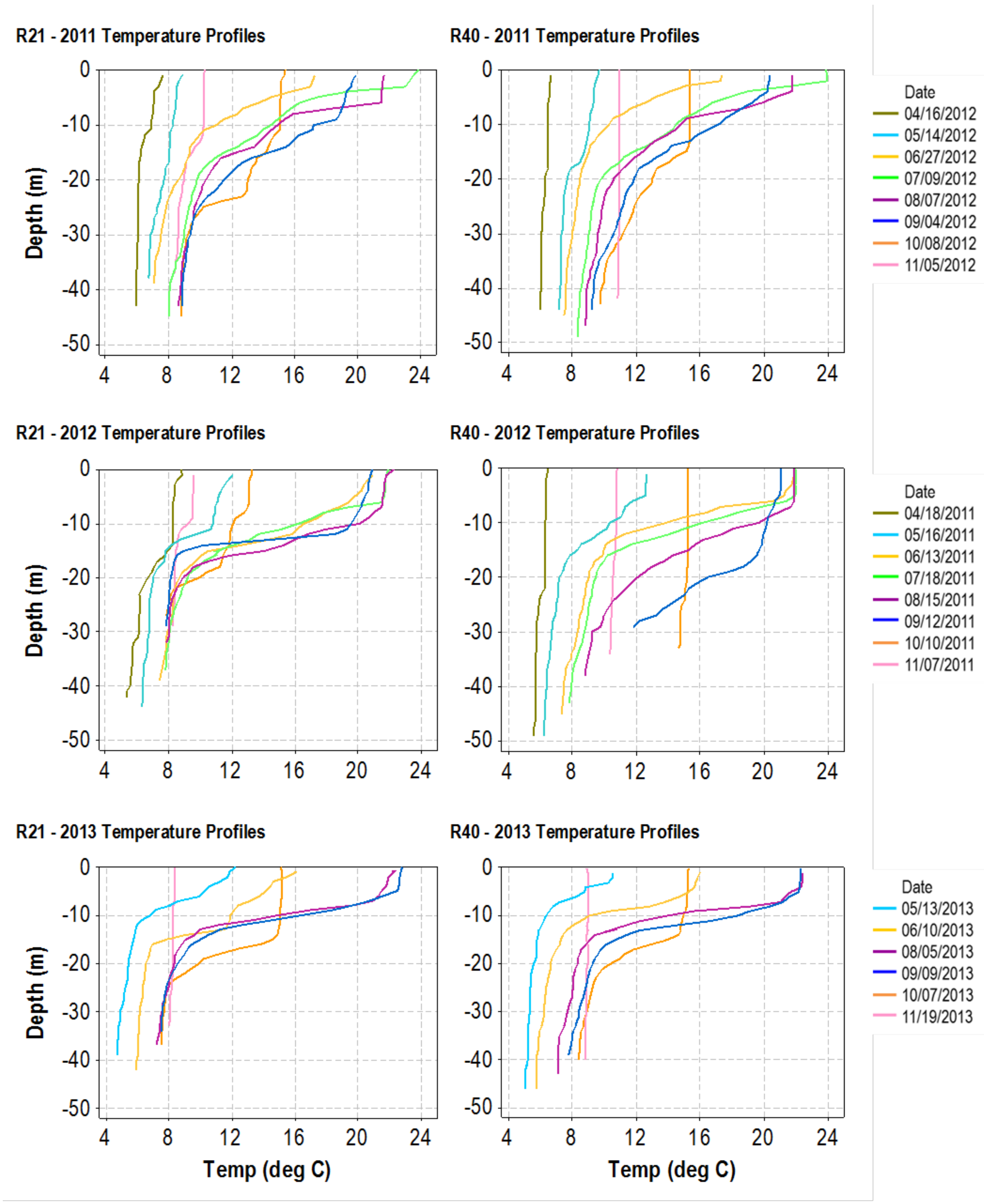


Figure 4.1 – Temperature profiles measured at Spring Canyon Dam (R21) and Soldier Canyon Dam (R40) during the 2011, 2012, and 2013 monitoring seasons showing the typical seasonal dynamics of temperature in Horsetooth Reservoir.

(R21) and Dixon Canyon Dams (R30). Earlier turnover at Solider Canyon Dam is largely influenced by the withdrawal of hypolimnetic waters from the Solider Canyon Outlet.

Reservoir monitoring is not conducted during the winter months. However, Horsetooth Reservoir rarely freezes completely over during the winter season and cold winter winds continue to aid in reservoir water mixing preventing winter thermal stratification.

Table 4.1 provides summary statistics for temperature profile data measured during the 2011, 2012, and 2013 monitoring season. The following bullet points provide key findings over the three year monitoring period:

Table 4.1 – Horsetooth Reservoir temperature profile summary statistics for Inlet Bay (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Solider Canyon Dam (R40).

	R20			R21			R30			R40		
	mean	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*
2011	12.0	23.7	6.1	10.3	23.9	5.9	10.4	23.7	6.1	10.6	23.9	6.1
2012	12.6	22.2	6.1	10.8	22.3	5.4	10.5	22.0	6.1	11.4	22.0	5.6
2013	12.0	23.0	5.2	9.8	22.7	4.8	9.6	22.5	5.0	9.6	22.4	5.1

- Thermal stratification was delayed in 2011 likely as a result of a cooler than average spring, historic snowpack, and longer than normal runoff season.
- In 2012, thermal stratification began earlier likely as a result of an abnormally dry and warm spring and summer.
- The start of fall turnover was observed in September and October, and complete turnover was observed by November at all monitoring locations in all years (Figure 4.1).
- Maximum surface water temperatures were commonly observed in July (Figure 4a). The warmest surface water temperatures were observed in 2011 with a peak maximum temperature of 23.9^{o}C at Soldier Canyon Dam (Table 4.1).
- The 22.8^{o}C aquatic life chronic standard in the 0.5 to 2.0 meter depth interval was exceeded at all sites in July of 2011 (Figure 4.2a).
- Water temperatures measured near the bottom of the reservoir progressively increase throughout the monitoring season, but less so than the water surface because of the decreased influence of solar radiation as water depth increases (Figure 4.2b).
- Spring Canyon Dam characteristically experienced the coldest water temperatures as influenced by inflowing colder water from the Hansen Feeder Canal.

4.1.2 Dissolved Oxygen

Dissolved oxygen (DO) is an important water quality parameter monitored in Horsetooth Reservoir. Its occurrence allows for certain chemical and biological reactions to take place through various reservoir processes. A balance between the consumption and production of DO is desired to maintain a healthy aquatic ecosystem. Changes in DO concentrations, specifically depletion of DO, can result in undesirable water quality changes both for aquatic organisms and to the City of Fort Collins' water supply. Monitoring DO profiles in Horsetooth Reservoir provides valuable information on reservoir processes that may pose treatment challenges for the FCWTF.

Temperature is the most important factor regulating DO concentrations. Dissolved oxygen is inversely proportional to water temperature meaning that as temperature decreases DO increases because oxygen is more soluble in cold water than warm water. In thermally stratified reservoirs like Horsetooth Reservoir, DO is influenced by seasonal stratification. Therefore, it is important to consider how DO is produced and consumed to appreciate DO dynamics in thermally stratified reservoir systems.

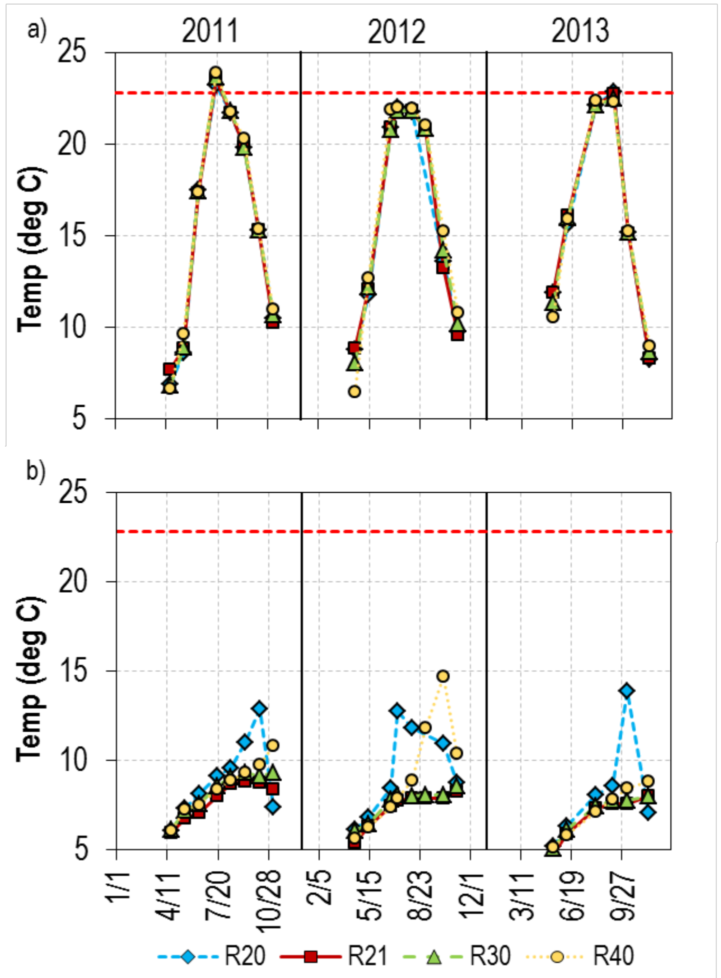


Figure 4.2 – Horsetooth Reservoir water temperature monitored at Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40) at a) 1 meter below the water surface and b) 1 meter above the reservoir bottom. The dashed red line indicates the temperature standard for aquatic life.

Oxygen in Horsetooth Reservoir is produced from atmospheric oxygen and photosynthesis (Figure 4.3). The atmosphere contains a greater concentration of oxygen than water, which results in diffusion of oxygen from the atmosphere into the reservoir. This process is accelerated by wind rapidly mixing atmospheric oxygen into the reservoir epilimnion. Photosynthesis is a process utilized by plants to convert sunlight, water, and carbon dioxide into energy. Oxygen and organic matter are released from aquatic plants (algae) as byproducts of photosynthesis and produced only when sufficient light and nutrients are available. Therefore, photosynthetic oxygen is limited to the upper sunlit waters of the reservoir (or photic zone). Both processes of oxygen production result in high concentrations of oxygen in the epilimnion.

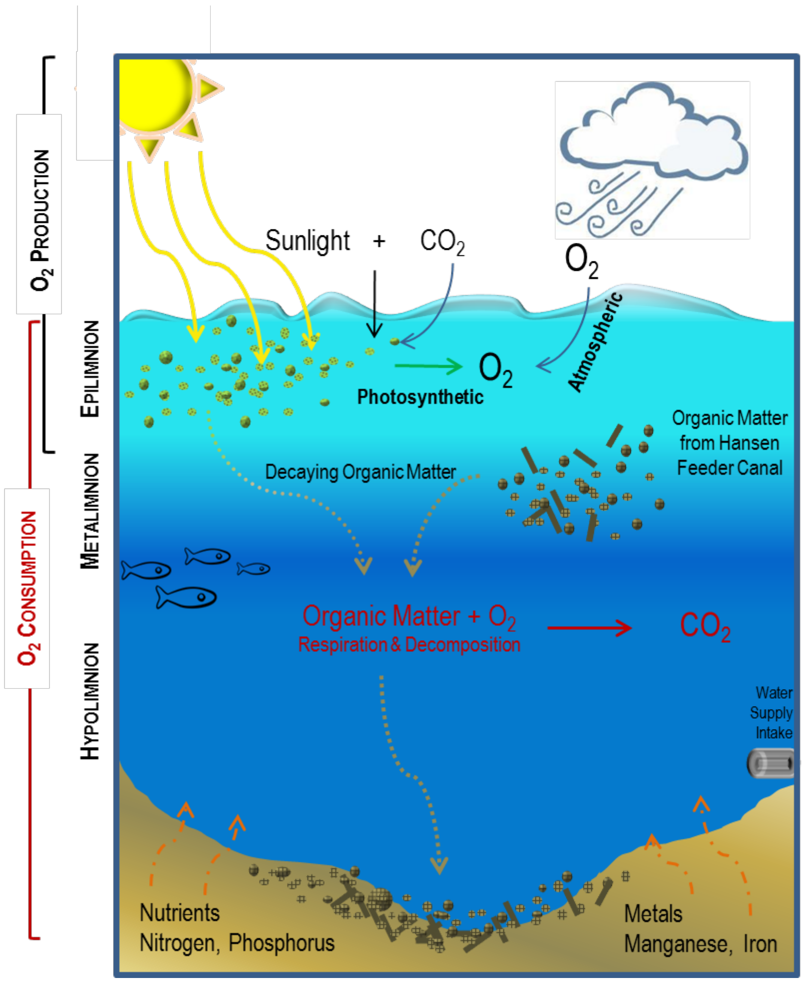


Figure 4.3 – Conceptual model of dissolved oxygen dynamics in Horsetooth Reservoir.

Oxygen in Horsetooth Reservoir is consumed through aquatic respiration and decomposition, and to a lesser extent, via certain chemical reactions in the sediments. Aquatic respiration is the process by which aquatic organisms consume organic matter and oxygen to create energy. In contrast to oxygen production, depletion can occur at all reservoir depths during all times of the day. As dead and decaying material sink from the epilimnion to the bottom of the reservoir it is decomposed by a variety of aquatic organisms that consume oxygen in the process. As a result, the lowest DO concentrations occur during the night when photosynthesis has ended and at the bottom of the reservoir where organic matter that settles on the reservoir bottom is decomposed by bacteria. When oxygen levels decrease to concentrations near-zero (hypoxic) or zero (anoxic), specialized anaerobic microbes facilitate the release of metals, particularly manganese and iron, and nutrients from bottom sediments. Sufficiently high concentrations of dissolved metals can result in discoloration or even impart off-odor or taste to drinking water, Furthermore, the release of nutrients can stimulate algal blooms, which not only affect the T&O of the water, but also serve as precursors to DBP formation in the water treatment process.

Horsetooth Reservoir exhibits seasonal characteristics in DO profiles (Figure 4.4). The highest DO concentrations in Horsetooth Reservoir are usually observed in April and May when water temperatures are the coldest and the water column is completely mixed. Dissolved oxygen begins to deplete in both the metalimnion and the hypolimnion as the reservoir becomes thermally stratified through the summer season when oxygen consumption is greater than production. Horsetooth Reservoir experiences a *negative heterograde oxygen curve*, which is evident by low oxygen concentrations in the metalimnion. It is suspected the high consumption (low concentrations) of oxygen in the metalimnion is a result of additional decaying organic matter contributions from the Hansen Feeder Canal. As is observed in differences in specific conductivity values (described in section 4.1.3), Hansen Feeder Canal inflow is apparent in the

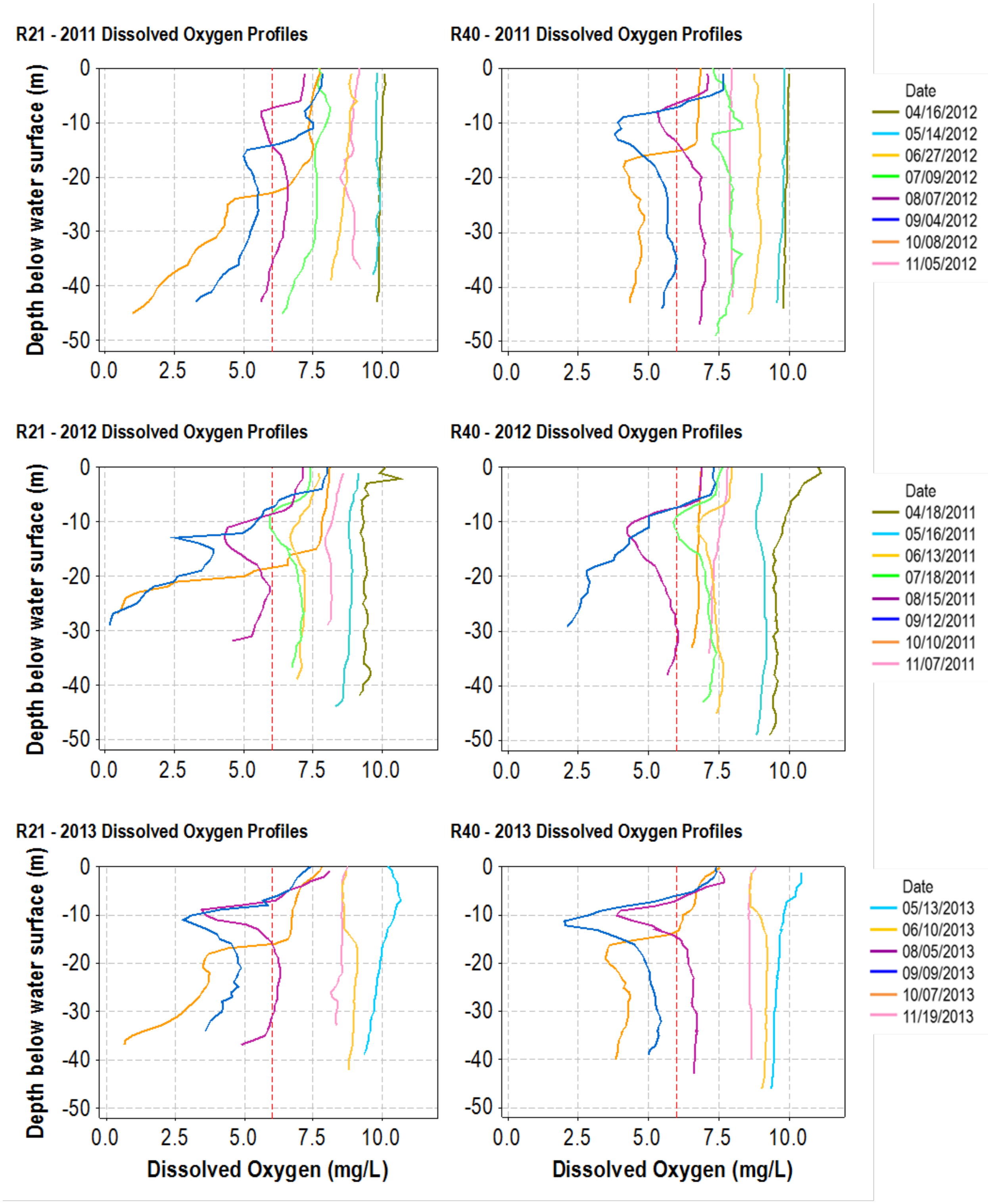


Figure 4.4 – Dissolved oxygen profiles measured at Spring Canyon Dam (R21) and Soldier Canyon Dam (R40) during the 2011, 2012, and 2013 monitoring season showing the typical seasonal dynamics of dissolved oxygen concentrations in Horsetooth Reservoir. The dashed red line indicates the aquatic life standard of 6.0 mg/L dissolved oxygen.

metalimnion of Horsetooth Reservoir. Oxygen depletion in the metalimnion and hypolimnion continues through the summer season and into the fall when oxygen poor bottom waters are mixed with the well-oxygenated surface waters.

The timing of stratification and turnover differ by location and are influenced by site specific conditions because the reservoir monitoring sites represent the three distinct pools (connected by a narrow channel). Typically, Spring Canyon and Dixon Canyon sites experience the earliest and most prolonged periods of seasonal low oxygen, and are the last to turnover in the fall. Soldier Canyon also experiences low oxygen conditions late in the summer and in early fall, although turnover typically occurs earlier at this site due to the disruptive influence of water being pulled from the water supply outlet and the Hansen Supply Canal outlet (Figure 4.4).

It is important for the FCU to monitor the seasonality of DO in order to be alert to hypoxic or anoxic conditions that favor the release of manganese and iron from the bottom sediments of the reservoir to the water column near the FCWTF intake. Identifying these issues early through monitoring allows for efficient management of water treatment processes. After turnover, the solubility of these metals decreases due to increased DO concentrations, thus posing less of a concern to the City of Fort Collins water supply.

Table 4.2 provides summary statistics for temperature profile data measured during the 2011, 2012, and 2013 monitoring season. The following bullet points provide key findings over the three year monitoring period:

Table 4.2 – Horsetooth Reservoir DO profile summary statistics for Inlet Bay (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Solider Canyon Dam (R40).

Horsetooth Reservoir D.O. Profile Summary Statstics (in mg/L)												
	R20			R21			R30			R40		
	mean	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*
2011	8.2	10.2	4.4	7.7	10.1	1.0	7.7	9.9	2.3	7.7	10.0	0.8
2012	7.9	10.3	3.0	7.2	10.6	0.2	7.2	10.7	0.5	7.5	11.2	2.1
2013	7.6	10.3	2.6	7.2	10.7	0.7	7.2	10.7	2.1	7.4	10.5	2.0

- The expected seasonal trends in DO concentrations were observed at all monitoring sites in all years. Dissolved oxygen was well mixed throughout the water column at the beginning of the monitoring season with the depletion of oxygen in the metalimnion and hypolimnion during the summer months. The water column was re-oxygenated during and following fall turnover (Figure 4.4)
- A similar spatial trend was seen across monitoring sites in both DO depletion and timing of reservoir turnover of DO, with both processes beginning first at the Inlet Bay Narrows followed by Spring Canyon and Solider Canyon Dams, and then finally at Dixon Canyon Dam. DO depletion and stratification persisted longer at both Spring Canyon Dam and Dixon Canyon Dam.
- The lowest DO concentrations were observed at Spring Canyon Dam.

- Epilimnetic DO concentrations were greater than 6 mg/L for all years throughout the monitoring season. Eplimnetic DO concentrations decreased throughout the monitoring season with the lowest concentrations in September and October. Seasonal minimum epilimentic DO concentrations occurred later in 2013 compared to 2011 and 2012. Epilimnetic concentrations increased following seasonal lows and fall turnover (Figure 4.5a).
- Metalimnetic DO concentrations decreased throughout the monitoring season to below 6 mg/L by July. The lowest concentrations ranged from 2.0 – 4.0 mg/L in August and September, and then began to steadily increase following the onset of fall turnover in October. The lowest metalimnetic DO concentration of 2.04 mg/L was monitored at Solider Canyon Dam in 2013 (Figure 4.5b).
- Hypolimnetic DO concentrations progressively decreased throughout the early and late summer. Concentrations dropped below 6 mg/L in August in all years. Minimum hypolimnetic DO concentrations approached 0 mg/L in October in 2011 and 2013. Hypolimnetic minima in 2012 occurred a month earlier and were the lowest observed over the three year monitoring period (Figure 4.5c).

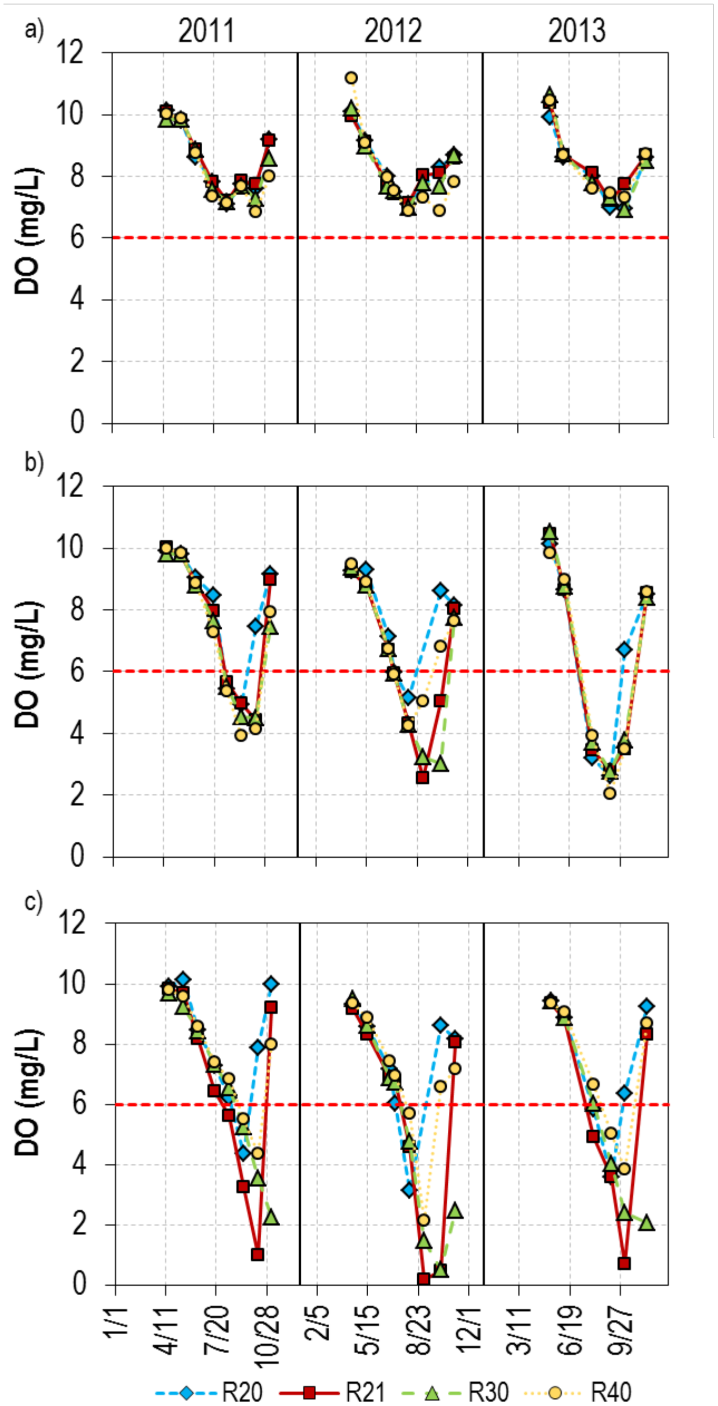


Figure 4.5 – Horsetooth Reservoir dissolved oxygen monitored at Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40) in the a) epilimnion, b) metalimnion, and c) hypolimnion.

4.1.3 Specific Conductivity

Conductivity is a simple measurement used to monitor for potential variations or changes in water quality in Horsetooth Reservoir. Conductivity is a measure of the ability for water to convey an electrical current, typically reported in micro Siemens per centimeter (µS/cm) or micromhos per centimeter (µmhos/cm). The presence of certain positive and negative charged ions (cations and anions, respectively) dissolved in water influence conductivity. Major cations that contribute to electrical current in natural waters include sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}). Certain metals such as iron (Fe) and aluminum (Al) can also contribute positive charge to natural waters. Major anions include inorganic compounds such as chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}) and phosphate (PO_4^{3-}). The presence of these ions in Horsetooth Reservoir and other water bodies is primarily controlled by watershed characteristics, specifically the geology of the watershed. Minerals in rock and soils are dissolved in water leading to varying concentrations of anions and cations. It is the concentration, mobility, and oxidation state of these ions, and the water temperature that determines the specific conductivity of Horsetooth Reservoir. Certain land use practices may also influence changes to conductivity, such as agricultural and storm water runoff, and leaking septic systems. Due to the simplicity in measuring conductivity, it is useful

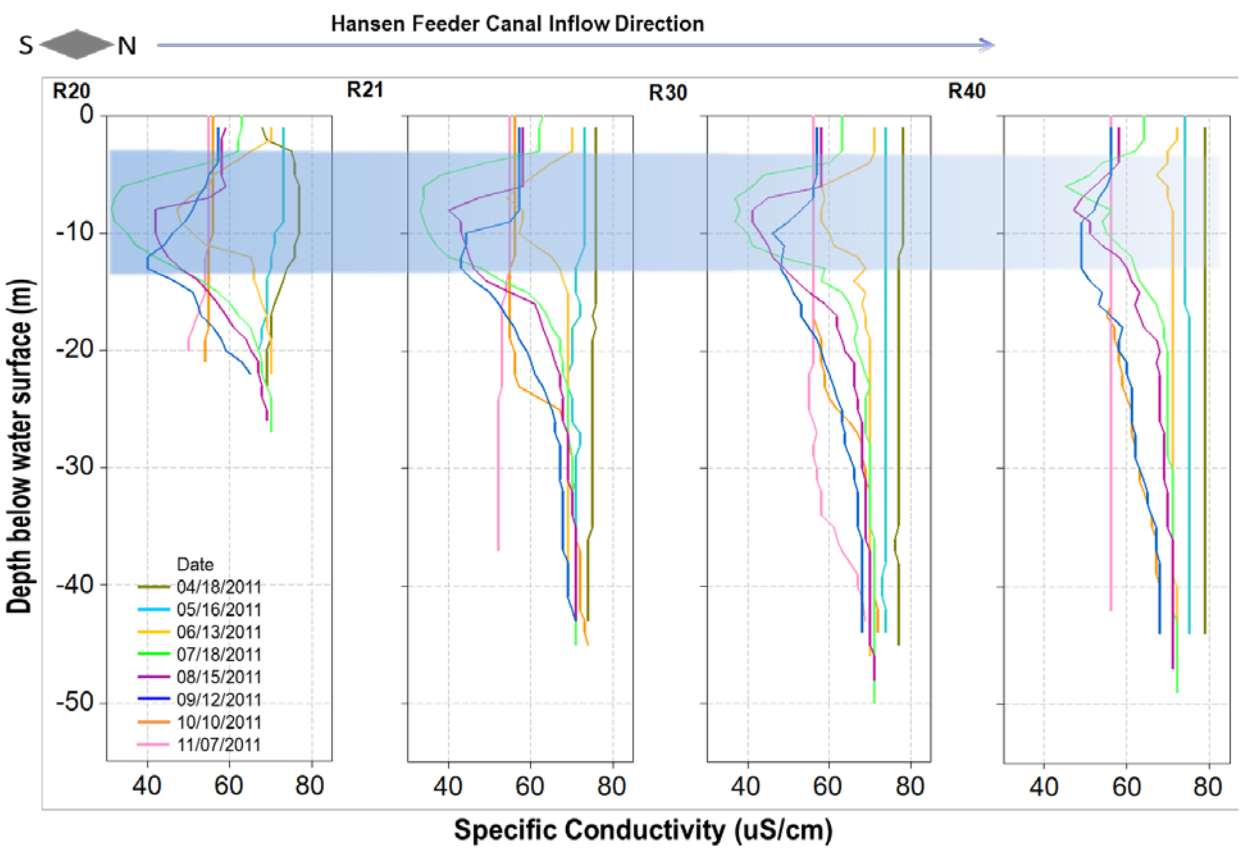


Figure 4.6 – Specific conductivity profiles measured at Inlet Bay Marina (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40) during the 2011 monitoring season showing the typical seasonal dynamics of specific conductivity and the influence of Hansen Feeder Canal inflows in Horsetooth Reservoir.

for Horsetooth Reservoir monitoring to identify abrupt changes in water quality because conductivity varies with water source (i.e. ground water, snowmelt water, precipitation, agricultural water, and wastewater).

Monitoring of specific conductance has been of particular importance for understanding flow dynamics in Horsetooth Reservoir. Hansen Feeder Canal inflow moves through the reservoir as an interflow. The occurrence of a minimum in specific conductance and temperature differences in the metalimnion provides evidence for the occurrence of interflow (Figure 4.6). The specific conductance of Hansen Feeder Canal water is less than the ambient Horsetooth Reservoir water during the summer, and therefore, can be used as a tracer for reservoir flow dynamics. On average, specific conductance in ambient Horsetooth Reservoir water ranges between 60 µS/cm to 80 µS/cm. Interflow specific conductance values in recent years have been measured as low as 30 µS/cm. The specific conductance profiles collected at Inlet Bay Narrows, Spring Canyon Dam, Dixon Canyon Dam, and Soldier Canyon Dam can be compared to evaluate the degree to which the Hansen Feeder Canal interflow is maintained or dissipated along the length of the reservoir. The influence of Hansen Feeder Canal inflow generally dissipates from the Inlet Bay Narrows to Solider Canyon Dam (Figure 4.6). Table 4.3 provides summary statistics for specific conductance profile data measured during the 2011, 2012, and 2013 monitoring season. The following bullet points provide key findings over the three year monitoring period:

- Specific conductance values ranged from a minimum 31 µS/cm to a maximum 84 µS/cm over the three year monitoring period (Table 4.3).
- The effect of Hansen Feeder Canal inflow dissipated moving down reservoir in all years.
- Seasonal minimum metalimnetic specific conductance values in 2011 were the lowest observed over the three year monitoring period (Figure 4.7).
- The anomalies in specific conductivity observed in the metalimnion in 2011 compared to 2012 and 2013 illustrate the influence of varying water sources on Horsetooth Reservoir water quality. In 2011, historic snowpack levels may have led to early higher volumes of snowmelt water from the Big Thompson River to Horsetooth Reservoir. Snowmelt water generally has a low specific conductance. In normal years, water is delivered from western slope storage reservoirs via the CBT Project after snowmelt has subsided.
- In 2012, a decrease in metalimnetic specific conductance was not observed at Solider Canyon Dam likely because of drought conditions that occurred in 2012, and limited snowmelt water supply from the CBT system.
- Less variability in specific conductance was observed in 2013, and there was less of an effect of Hansen Feeder Canal inflow water on the metalimnion compared to 2011.

Table 4.3 – Horsetooth Reservoir specific conductance profile summary statistics for Inlet Bay (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Solider Canyon Dam (R40).

Horsetooth Reservoir Specific Conductance (uS/cm) Profile Summary Statstics												
	R20			R21			R30			R40		
	mean	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*
2011	60.0	77.0	31.0	64.1	76.0	33.0	65.8	78.0	37.0	66.5	79.0	45.0
2012	55.8	66.0	42.0	57.5	76.0	51.0	57.6	70.0	50.0	58.1	67.0	51.0
2013	65.0	84.0	53.0	64.7	78.0	55.0	63.8	72.0	59.0	63.6	72.0	59.0

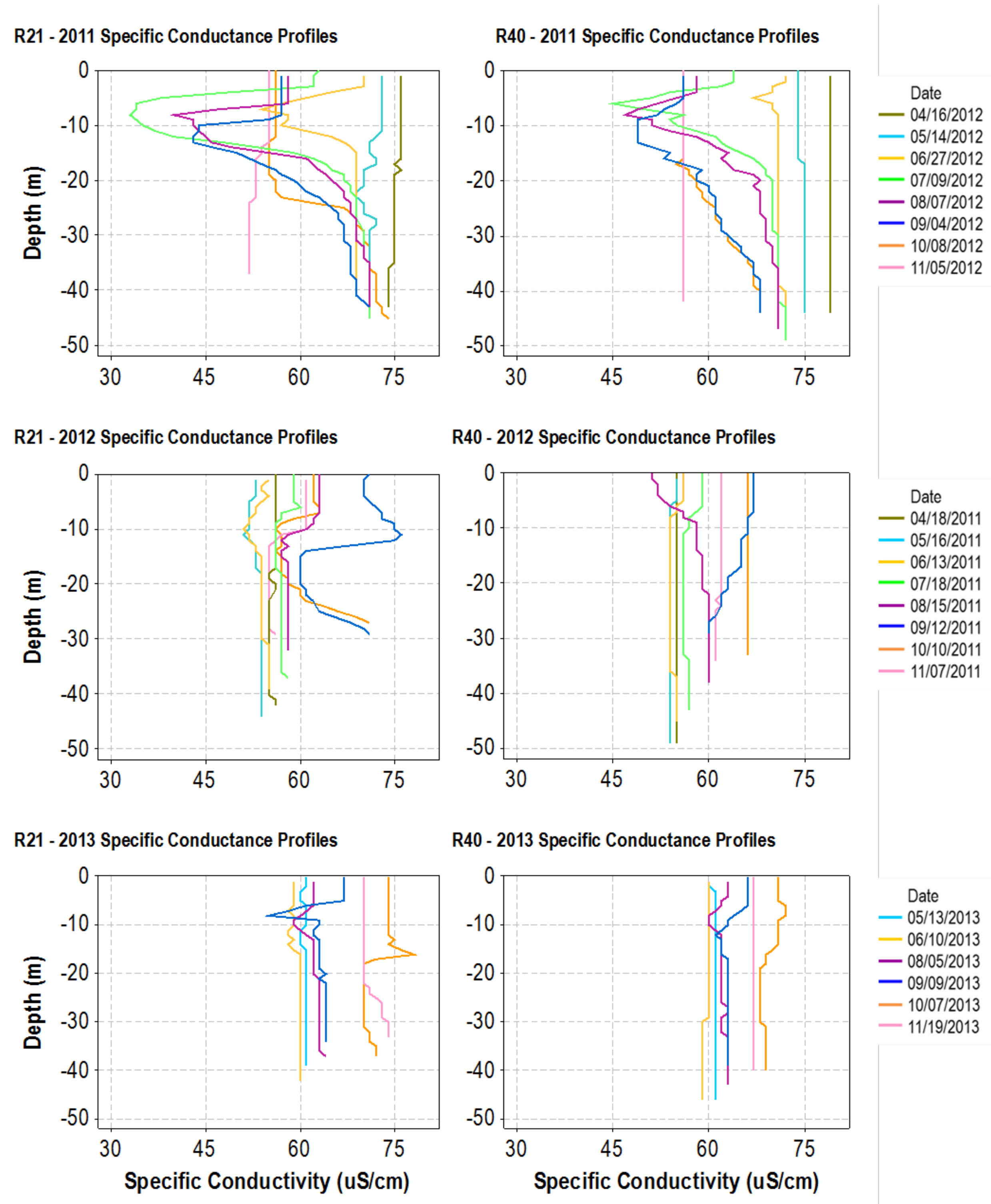


Figure 4.7 – Specific conductance profiles measured at Spring Canyon Dam (R21) and Soldier Canyon Dam (R40) during the 2011, 2012, and 2013 monitoring season showing the typical seasonal dynamics of specific conductivity levels in Horsetooth Reservoir.

4.1.4 pH

pH is a measure of the amount of free hydrogen (H^+) and hydroxide (OH^-) ions in water. pH is measured on a logarithmic scale ranging from 0 to 14 and a one unit change is representative of a 10-fold change in the acidity or basicity of the water source. A water of neutral pH (*pH = 7*) contains equal amounts of hydrogen and hydroxide ions, while an acidic water (*pH < 7*) contains more hydrogen ions and a basic water (*pH > 7*) contains more hydroxide ions, and is termed alkaline (Figure 4.8).

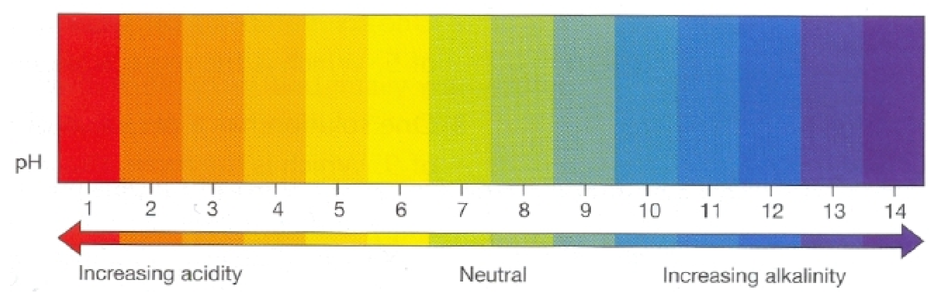


Figure 4.8 – pH is measured on a logarithmic scale ranging from 0 to 14. The water quality standard to sustain aquatic life is a pH between 6.5 and 9.0.

pH is an important water quality parameter to monitored because it influences the solubility and biological availability of chemical constituents, including nutrients and heavy metals. Under acidic conditions, toxic heavy metals become mobile and nutrients become more available for uptake by aquatic plants and animals, which can indirectly lead to undesirable water quality conditions. The Colorado Water Quality Control Commission has established a numeric standard for pH in natural waters to be at a minimum of 6.5 and maximum of 9.0 to avoid undesirable water quality conditions and protect aquatic habitat.

On average, pH in Horsetooth Reservoir water ranges between 6.5 and 8.5. On rare occasions, hypolimnetic pH decreased below the numeric standard. Typically, the pH of Horsetooth Reservoir water is uniform throughout the water column at the start of the monitoring season in late spring and early summer when the reservoir is well mixed. As the season progresses and thermal stratification evolves, reservoir pH changes with temperature and potentially from changes in DO as a result of algal activity in the epilimnion. Seasonal trends in pH are inversely proportional to temperature meaning pH tends to decrease as water temperature increases through the summer. During thermal stratification, Horsetooth Reservoir pH is higher in the epilimnion and progressively decreases through the metalimnion and hypolimnion (Figure 4.9). Reservoir pH becomes uniform through the water column following fall turnover in October and November. Table 4.3 provides summary statistics for pH profile data measured during the 2011, 2012, and 2013 monitoring season. The following bullet points provide key findings over the three year monitoring period:

Table 4.4 – Horsetooth Reservoir pH profile summary statistics for Inlet Bay (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Solider Canyon Dam (R40).

Horsetooth Reservoir pH Profile Summary Statstics												
	R20			R21			R30			R40		
	mean	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*	*mean*	*max*	*min*
2011	7.6	7.9	7.1	7.5	7.9	6.9	7.5	8.0	7.0	7.5	8.2	7.0
2012	7.7	8.2	6.9	7.4	8.2	6.5	7.4	8.2	6.6	7.5	8.6	6.6
2013	7.6	7.9	7.0	7.5	8.1	6.9	7.4	7.9	6.8	7.5	8.2	6.9

- pH values were consistent across all monitoring sites during all years and showed little to no spatial trend.
- pH values ranged from a minimum 6.5 to a maximum 8.6 over the three year monitoring period, while mean pH values ranged from 7.4 to 7.6 (Table 4.4).
- pH was higher in the epilimnion and progressively decreased through the metalimnion and hypolimnion at all monitoring sites in all years.
- pH values steadily decreased throughout the duration of the monitoring season in all years. The lowest pH values were observed between July and October in the hypolimnion when the reservoir was strongly stratified, and the highest pH values were observed in spring and fall following turnover (Figure 4.9).
- Seasonal maximum values were highest in 2012, and seasonal minimums in 2012 were the lowest over the three year monitoring period with hypolimnetic pH falling below 6.5 in September (Figure 4.9).

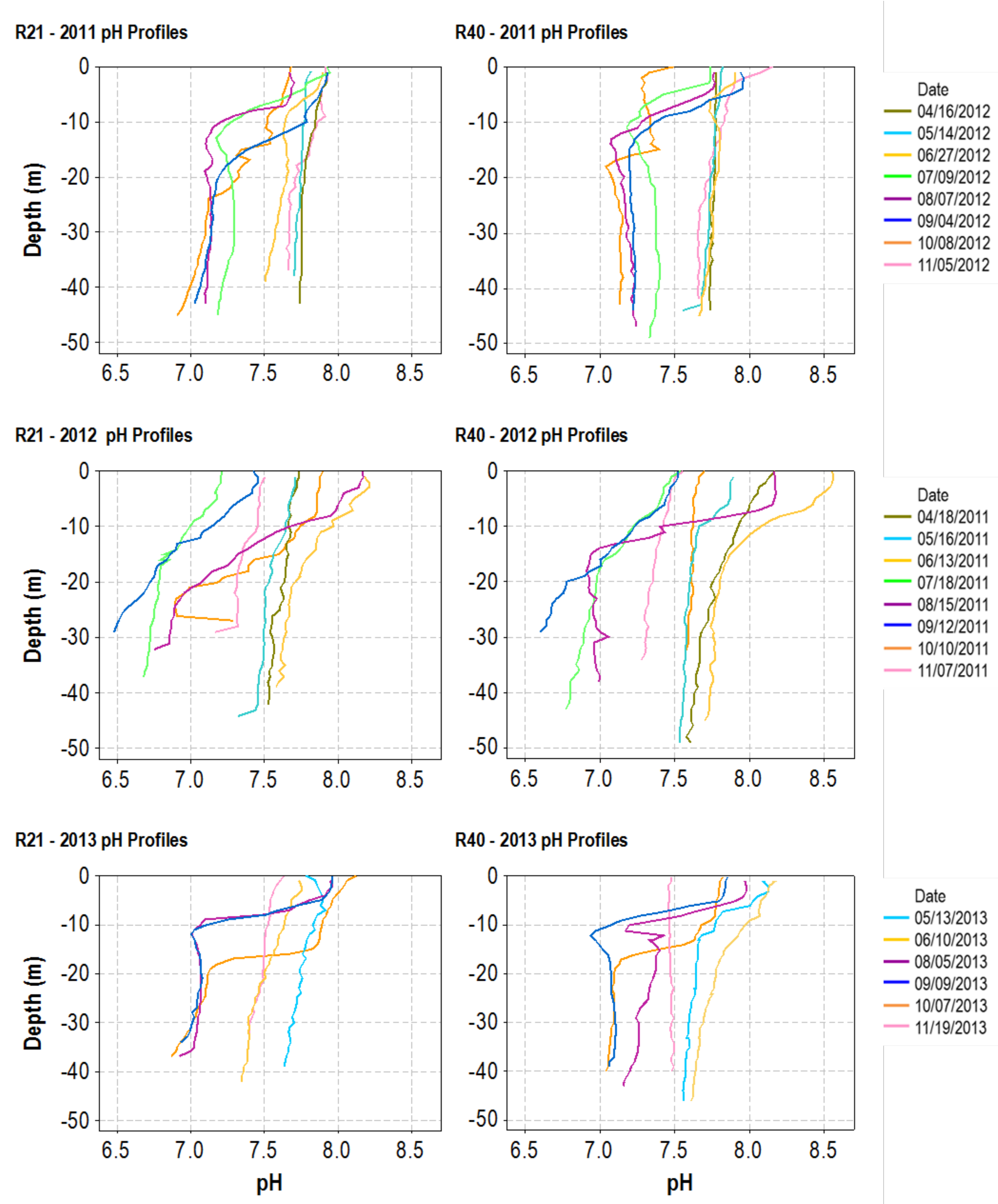


Figure 4.9 – pH profiles measured at Spring Canyon Dam (R21) and Soldier Canyon Dam (R40) during the 2011, 2012, and 2013 monitoring season showing the typical seasonal dynamics of dissolved oxygen concentrations in Horsetooth Reservoir.

4.2 General Chemistry

4.2.1 Alkalinity, Hardness and Major Ions

Alkalinity is a measure of a water body's ability to neutralize or buffer acids. Alkaline compounds include bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), and hydroxide (OH^-) salts of major ions (Ca, Mg, K, and Na). These alkalis interact with free hydrogen ions in water to remove hydrogen ions thereby increasing reservoir pH. Similarly, hardness is a measure of the total concentration of the major ions calcium and magnesium in water. Hardness is typically measured as a concentration of calcium carbonate ($CaCO_3$), and because of this, alkalinity and hardness have similar concentrations. Watershed geology plays an integral role in the alkalinity and hardness of streams, lakes and reservoirs. Both are introduced to surface water through the weathering of minerals in rocks and soils, and through certain plant processes.

Alkalinity and hardness concentrations influence the effectiveness of the drinking water treatment process. Furthermore, high alkaline water produces a bitter and slippery feel to drinking water and requires specific removal techniques in the treatment process to mitigate these effects. Similarly, hard water can result in adverse effects, such as scaling, to water treatment plant equipment and domestic water supply distribution systems. The following bullet points provide key findings over the three year monitoring period:

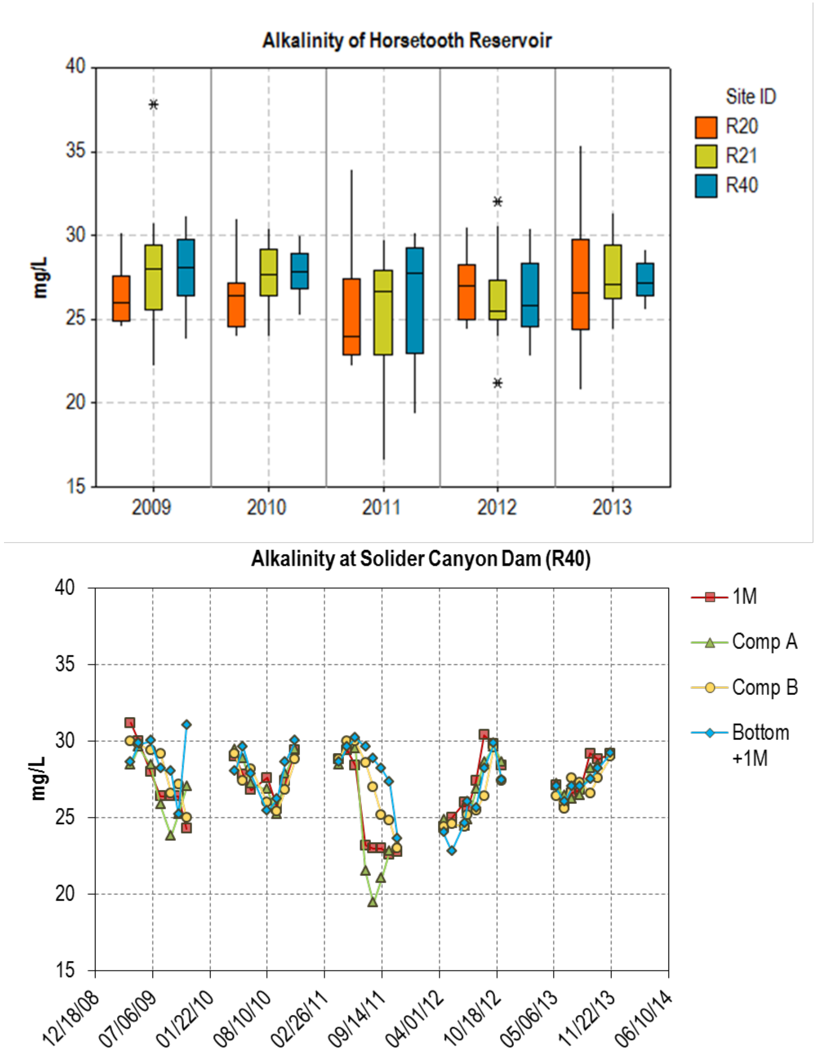


Figure 4.10 – Box plots of alkalinity concentrations measured at Horsetooth Reservoir monitoring sites from 2009-2013 (above) and alkalinity concentrations measured at various depths at Solider Canyon Dam (below).

- Alkalinity and hardness concentrations were consistent across monitoring locations and followed closely to seasonal trends during the 2011, 2012, and 2013 monitoring seasons (Figure 4.10).
- Alkalinity concentrations ranged from 16.6 mg/L to 35.4 mg/L and hardness concentrations were between 17.16 mg/L and 33.11 mg/L.
- The lowest concentrations of both alkalinity and hardness occurred in 2011. These seasonal minimums were likely a result of Big Thompson River snowmelt water contributions from the Hansen Feeder Canal suggested by lower than expected specific conductivity values in the metalimnion (see in section 4.1.3 Specific Conductivity).
- The lowest concentrations were observed in the Comp A (5-15m) grab samples providing more evidence of a snowmelt water influence from the Hansen Feeder Canal inflow on the metalimnion.

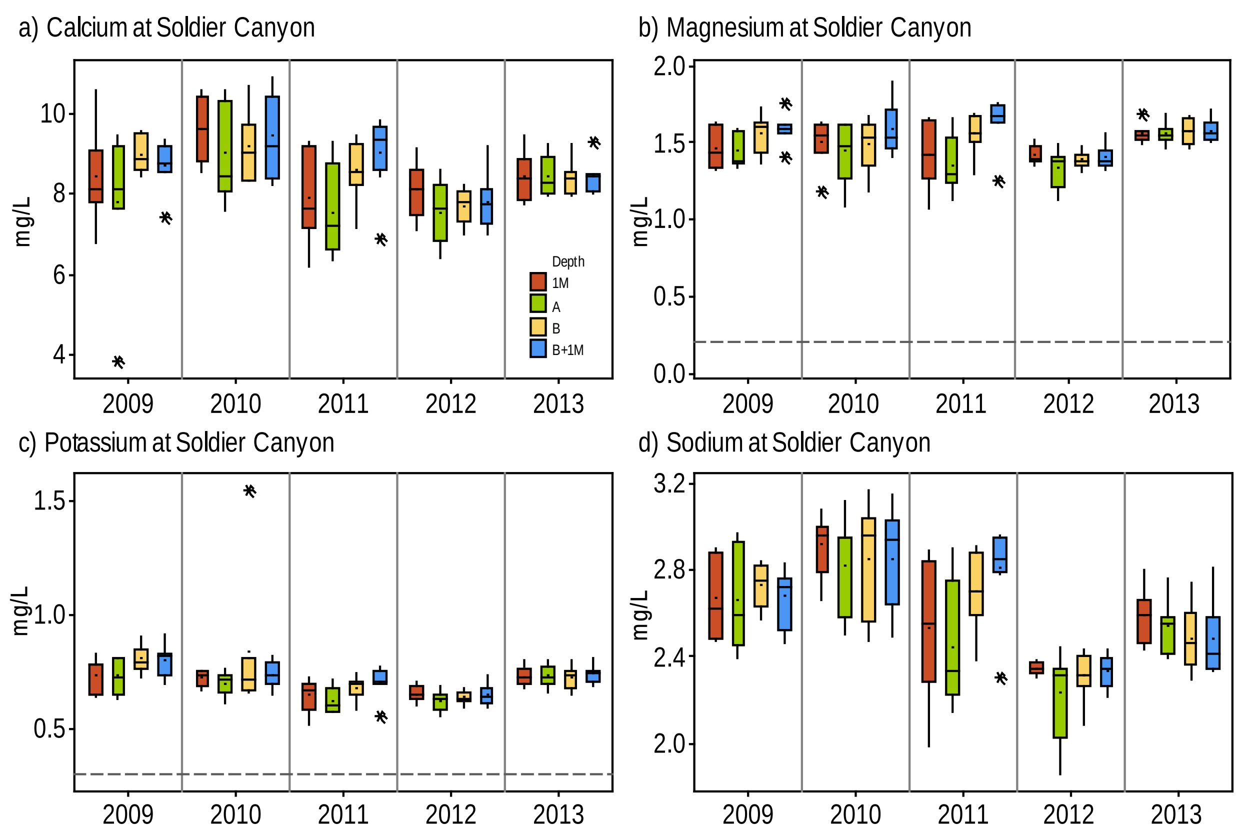


Figure 4.11 – Box plots of a) calcium, b) magnesium, c) potassium, and d) sodium concentrations measured at the Solider Canyon Dam monitoring site in Horsetooth Reservoir from 2009-2013.

The major cations monitored in Horsetooth Reservoir include sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}), and the major anion monitored is sulfate (SO_4^{2-}). As discussed in section 4.1.3, these ions influence the specific conductance of Horsetooth Reservoir. In general terms, major ions are dissolved salts (thereby contributing to water salinity) and in high concentrations can have adverse effects on water supply if not identified and treated. The following bullet points provide key findings over the three year monitoring period:

- Major ion concentrations monitored over the 2011, 2012, and 2013 monitoring periods were similar to the five year average concentrations and did not differ across monitoring locations.
- Ion concentrations had the greatest variability in 2011, which is likely related to inflow water from the Hansen Feeder Canal.
- Concentrations were generally highest near the surface and bottom, with the lowest concentrations observed in the metalimnion.
- Sodium concentrations showed a noticeable decrease in 2012 (Figure 4.11d). The cause of this decrease is unknown, but may be related to abnormally dry conditions during 2012.
- Sulfate concentrations were below the reporting limit in all years.

4.2.2 Total Organic Carbon

Total organic carbon (TOC) is a measured of the total concentration of dissolved and particulate organic matter in water. Total organic carbon is derived from both terrestrial and aquatic origins. Terrestrial TOC originates from soils and plant materials that are leached and/or delivered to the reservoir and canal system during storms and spring runoff, whereas aquatic-derived TOC originates from algal production and subsequent decomposition within the reservoir.

Total organic carbon is an important indicator of water quality, particularly as it relates to water treatment. Water treatment requires the effective removal of TOC because the interaction between residual TOC and disinfectants can form regulated DBPs. Disinfection by-products are strictly regulated due to their potential to be carcinogenic. Increases in source water TOC concentrations pose concern due to the potential for higher residual TOC (post-filtration) and increased for DBP formation potential.

Total organic carbon concentrations in Horsetooth Reservoir vary throughout the water column and between different monitoring locations. Generally, TOC concentrations are higher in the epilimnion and metalimnion compared to the hypolimnion (Figure 4.12). Concentrations are lower at the start of the monitoring season and increase to peak concentrations in early to late summer. Late season increases in bottom TOC occasionally occur at both Spring Canyon and Solider Canyon Dams. The following bullets provide key findings for TOC data measured during the 2011, 2012, and 2013 monitoring season. Concentrations in Comp A and Comp B were consistent with concentrations in the top one meter (1M) and bottom one meter (Bottom +1M). Comp A concentrations typically follow similar trends to one meter concentrations and Comp B concentrations generally follow similar trends to bottom one meter concentrations (Figure 4.11). Therefore, the following discussion will focus on findings from top and bottom TOC data unless a noteworthy observation was detected.

- Total organic carbon concentrations ranged from 3.08 mg/L mg/L to 4.87 mg/L during the three year monitoring period.
- The highest TOC concentrations were typically observed in the epilimnion while the lowest concentrations were observed in the hypolimnion.
- In contrast to most years, 2012 peak TOC concentrations were observed in the hypolimnion at Spring Canyon Dam rather than at the surface (Figure 4.12).
- 2013 TOC concentrations in the bottom one meter did not follow the seasonal pattern of a late summer peak followed by a decrease in the fall, as seen in previous years. Rather, concentrations fell to a minimum in late summer, but then increased during October and November.

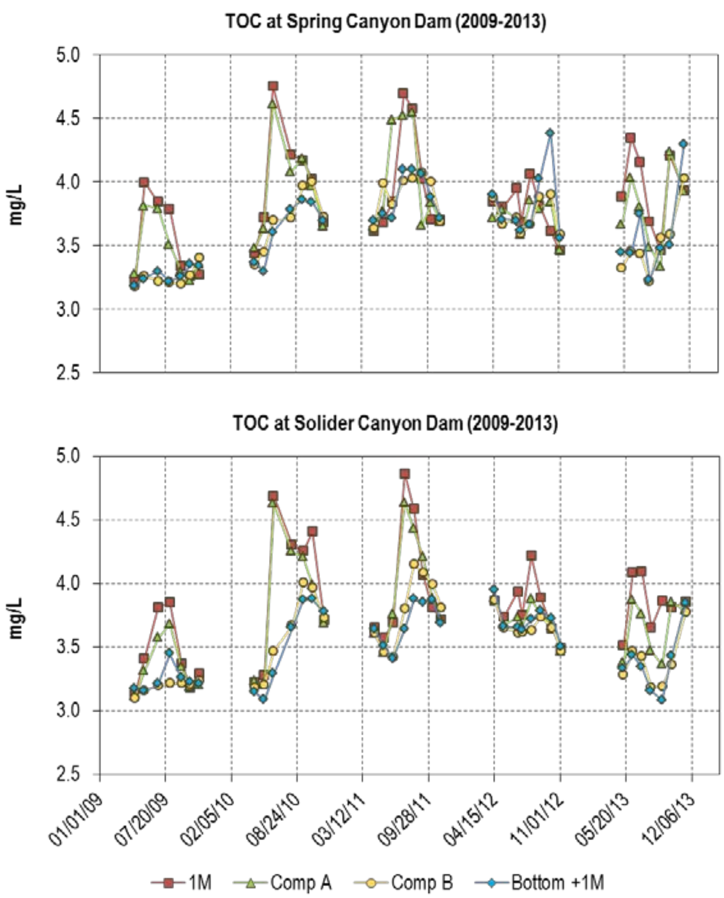


Figure 4.12 – Total organic carbon (TOC) concentrations measured at at Spring Canyon Dam (R21) and Solider Canyon Dam (R40) from 2009 to 2013.

4.2.3 Total Dissolved Solids and Turbidity

Total dissolved solids (TDS) is a measure of the total composition of inorganic and organic constituents in a water body. Major cations and anions are primary elements that compose TDS, and as such, TDS is highly correlated with specific conductivity. Similar to specific conductivity, TDS is an important water quality parameter to monitor because it acts as an indicator of water quality change. Potential sources of TDS to Horsetooth Reservoir include both natural and anthropogenic causes, such as leaking septic systems, storm water runoff, watershed weathering and soil erosion. No known health effects are related to TDS, but high concentrations may influence the drinkability and aesthetics of drinking water.

Total dissolved solids was not measured at Spring Canyon Dam in 2009 and 2010, but was added to the parameter list for 2011-2013. Seasonal and spatial trends in TDS concentrations are typically not observed in Horsetooth Reservoir (Figure 4.13). Changes in TDS concentrations are likely influenced by the timing, duration, and source of water supplied via the Hansen Feeder Canal. The following bullets provide key findings for TDS monitored during 2011, 2012, and 2013:

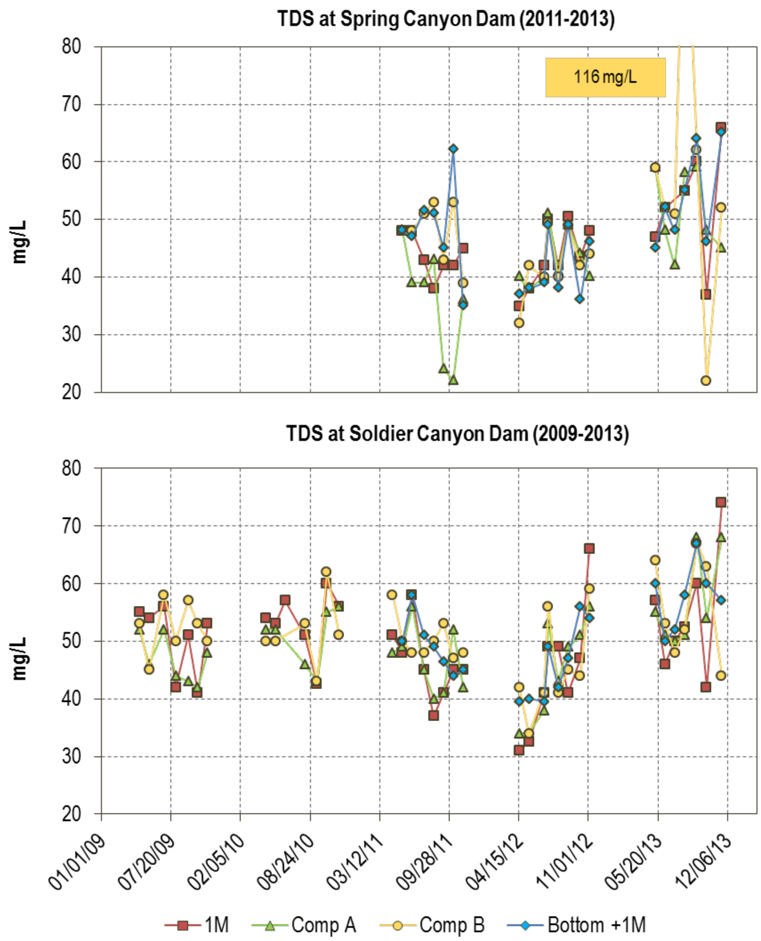


Figure 4.13 – Total dissolved solids concentrations measured at Spring Canyon Dam (R21) and Solider Canyon Dam (R40) from 2009 to 2013.

- TDS concentrations ranged from 22 mg/L to 116 mg/L over the three year monitoring period.
- The lowest concentrations were observed in October of 2011 and 2013 at Spring Canyon Dam.
- The highest concentration was observed in August of 2013.
- Seasonal trends in TDS were not observed, but concentrations were generally similar through the depth of the water column.
- A noticeable increase in TDS was observed throughout the 2012 monitoring season at Solider Canyon Dam.
- TDS concentrations in 2013 were elevated compared to the previous four years. (2009-2012).

Turbidity is a measurement of the amount of light capable of passing through water. This water quality parameter is often monitored to track changes in water clarity, which is influenced by the presence of floating algae as well as suspended solids introduced to surface waters through various land use activities, including runoff and erosion, and urban storm water runoff and drainage from agricultural lands. Turbidity levels can signal changes in land use activity or reservoir productivity. For water treatment, turbidity is an important indicator of the amount suspended material that is available to harbor pollutants such as heavy metals, bacteria, pathogens, nutrients, and organic matter.

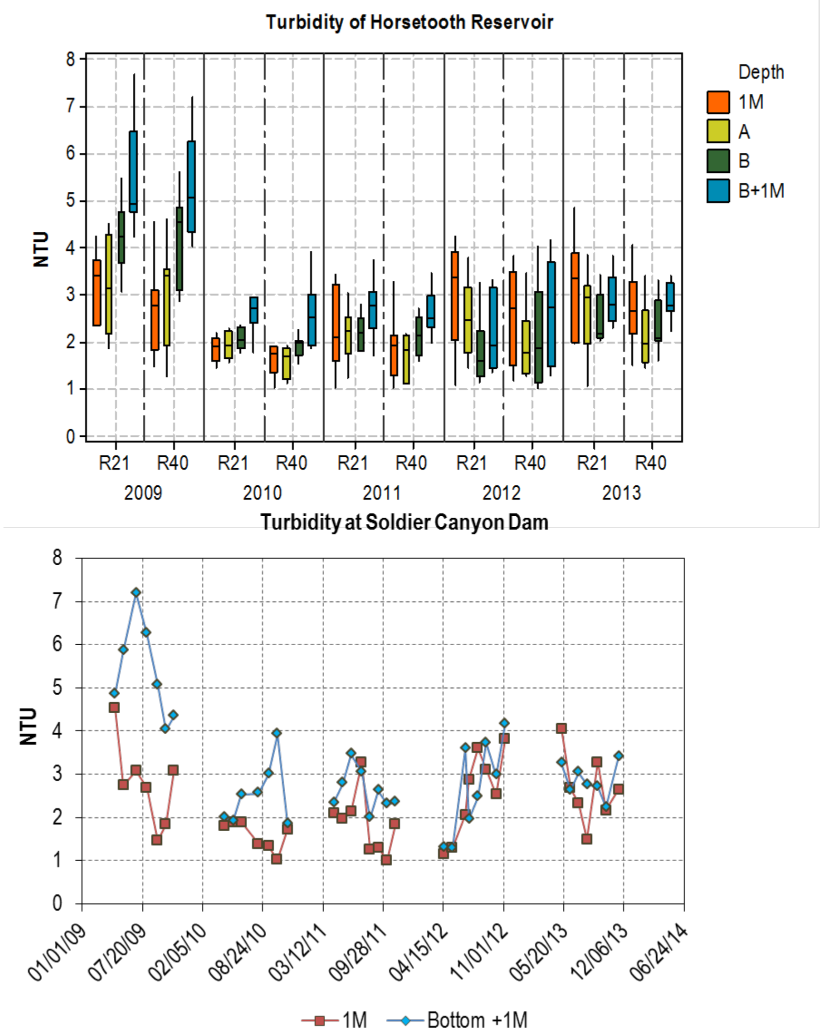


Figure 4.14 – Box plots of turbidity measured at Horsetooth Reservoir monitoring sites from 2009-2013 (above) and turbidity measured at various depths at Solider Canyon Dam (below).

Reservoir processes are significantly influenced by changes in turbidity. Suspended material absorbs more solar radiation producing warmer water temperatures, and warmer water is less proficient at holding DO than colder water. In addition, less light penetrates turbid water resulting in decreased photosynthesis rates and DO production (see figure 4.3). Therefore, it is important to monitor turbidity in order to identify potential changes in reservoir process that may pose threats to aquatic organisms and water supply.

Horsetooth Reservoir turbidity is characteristically low. The following bullets provide key findings for turbidity data measured during the 2011, 2012, and 2013 monitoring season:

- The lowest turbidity values were observed in 2011 in both the epilimnion and hypolimnion. As the 2011 monitoring season progressed, turbidity decreased near the surface of the reservoir, while turbidity near the bottom correspondingly increased.
- The highest turbidity levels were observed in 2012, which was likely associated with the warm, dry conditions that persisted throughout the monitoring season. These conditions lead to greater algal

and phytoplankton production in the reservoir (see figure 4.26 in section 4.5.2) influencing turbidity levels in 2012 (Figure 4.14)

- Turbidity values in 2013 were similar to most years, but levels were elevated in November following the September flood event, which resulted in highly turbid flood water from the Big Thompson Watershed entering Horsetooth Reservoir via the Hansen Feeder Canal (Figure 4.14).
- Generally, turbidity varied throughout the water column and during the monitoring season in all years.
- Turbidity decreased moving down the reservoir from Spring Canyon Dam to Solider Canyon Dam, possibly suggesting influence from Hansen Feeder Canal inflow water.

4.3 Nutrients

Figure 4.15 – Characteristic green water resulting from an algae bloom.

Nutrients are elements required by aquatic organisms to grow and survive. In aquatic ecosystems, nutrients are typically limited in availability, regulating the growth and survival of aquatic organisms and plants. Nitrogen and phosphorus are the primary nutrients in aquatic ecosystems, and the limited presence of these nutrients regulates reservoir productivity. In excess, nitrogen and phosphorus lead to nutrient pollution and eutrophication resulting in undesirable changes to water quality, and serious environmental and human health issues. Eutrophication is the enrichment of a water body with nutrients. Excess nutrients amplify algal growth leading to a rapid population increase referred to as a "bloom." Algae blooms are easily identified by color change of the polluted water, which normally is perceived as a bright or fluorescent green (Figure 4.15). Consequently, eutrophication decreases oxygen production due to limited photosynthesis and increases oxygen consumption when algae die and decompose. Low concentrations of oxygen can have adverse effects on aquatic ecosystems and water supply. Potential drinking water quality and treatment problems associated with algae include:

- Production of T&O compounds (such as geosmin)
- Increased TOC concentrations, indirectly resulting in increased DBP
- Production of toxins by cyanobacteria
- Filter clogging issues at the water treatment facility
- The release of heavy metals (primarily manganese) and nutrients from reservoir bottom sediments

4.3.1 Nitrogen

In aquatic ecosystems, ammonia (NH_3) and nitrate (NO_3) are the primary forms of nitrogen available to bacteria, fungi, and plants. Ammonia is released during the decomposition of organic matter, and in the presence of oxygen, converted to NO_3^- in a process called *nitrification.* Nitrite (NO_2) is an intermediate step in nitrification. As DO levels are depleted and anoxic conditions develop near the reservoir bottom, nitrification ceases and ammonium (NH_4^+) accumulates. Additional processes occur under anoxic conditions including *ammonification* ($NO_3^- \rightarrow NH_4^+$), *denitrification* (bacterial reduction of $NO_3^- \rightarrow N_2$), and the release of NH_4^+ from bottom sediments (Figure 4.16). Ammonia (NH_3^+) is quantified in the lab and used as a surrogate for NH_4^+ concentrations in Horsetooth Reservoir.

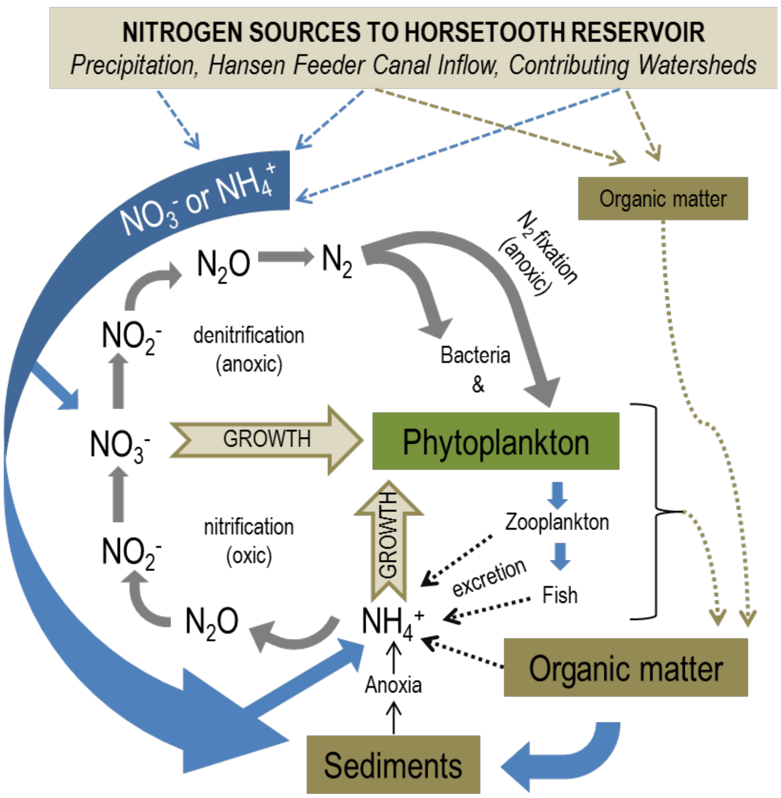


Figure 4.16 – Conceptual diagram of the nitrogen cycle in aquatic ecosystems.

Sources of nitrogen to Horsetooth Reservoir include Hansen Feeder Canal inflows, direct inflows from the local adjacent watershed, biological nitrogen fixation by certain cyanobacteria, and atmospheric deposition (nitrogen in precipitation) of nitrogen into the reservoir and contributing watersheds.

Nitrogen compounds in Horsetooth Reservoir display regular seasonal patterns. Nitrate and NH_4^+ concentrations in Comp A and Comp B samples follow similar seasonal trends to concentrations near the reservoir surface and reservoir bottom, respectively. Therefore, the following results will focus on NO_3 and NH_4^+ concentrations near the surface and bottom of the reservoir. Nitrite is found in relatively low concentrations in Horsetooth Reservoir, but is consistently below the reporting limit and therefore not discussed in this report. The following bullets illustrate findings for NO_3 and NH_3 data collected during the 2011, 2012, and 2013 monitoring season (Figures 4.16 and 4.17):

- The highest NO_3 and NH_3 concentrations were typically observed at Spring Canyon Dam, which was probably influenced by Hansen Feeder Canal inflow because Spring Canyon Dam is first major impediment of inflow. Consequently, organic matter from the inflow accumulates and decays releasing nitrogen in its various forms depending on oxygen availability.
- NO_3 and NH_3 concentrations monitored near the reservoir surface were generally below reporting limits for most of the monitoring season in all years suggesting uptake by algae occupying the epilimnion (Figures 4.17 and 4.18). Depletion of nitrogen near the reservoir surface can potentially result in blooms of cyanobacteria because their ability to fix free nitrogen provides for a competitive advantage over other phytoplankton.
- NO_3 concentrations were greater near the reservoir bottom compared to near the reservoir surface and gradually increase throughout the monitoring season, peaking in October before fall turnover (Figures 4.17 and 4.18). NO_3 concentrations increase as organic matter settles releasing NH_3 as a byproduct of decomposition.
- NO_3 concentrations were normally observed above reporting limit by the end of the monitoring season in all years as a result of reservoir turnover and mixing of NO_3 from the hypolimnion to the epilimnion.
- The lowest epilimnetic NO_3 concentrations were typically observed in August at both Spring Canyon and Soldier Canyon. Exceptions occurred in August of 2011 and 2012 at Spring Canyon, when spikes in epilimnetic NO_3 were observed (Figure 4.17b).
- The highest peak hypolimnetic NO_3 concentration was observed in 2013, which was the greatest level over the five year observation period.
- The lowest peak hypolimnetic NO_3 concentration was observed in 2012, which was the lowest level over the five year observation period.
- In contrast, NH_3 concentrations remained near the reporting limit, but occasionally concentrations were observed above reporting limit. These events usually occurred in the late summer and fall when DO concentrations were depleted in the hypolimnion as conditions became anoxic in the hypolimnion (Figure 4.16). Changes in the nitrogen cycle during anoxic conditions resulted in decreasing NO_3 concentrations and the accumulation of NH_3 until fall turnover.
- Epilimnetic and hypolimnetic NH_3 concentrations fluctuated around the reporting limit throughout the monitoring season.
- The late season increase in NH_3 at the bottom of Spring Canyon Dam in 2012 (Figure 4.18b) was likely influenced by prolonged low oxygen concentrations that resulted in the accumulation of NH_4^+ (Figure 4.19). A spike in NH_3 was not observed at Solider Canyon Dam because DO was not completely depleted in the hypolimnion. Ammonia was well mixed at both sites by the November 5th as a result of reservoir turnover.
- Elevated NH_3 concentrations at Spring Canyon Dam were observed in October 2013 following the September flooding event.
- There was a notable increase in NH_3 at both sites in 2012 and 2013.

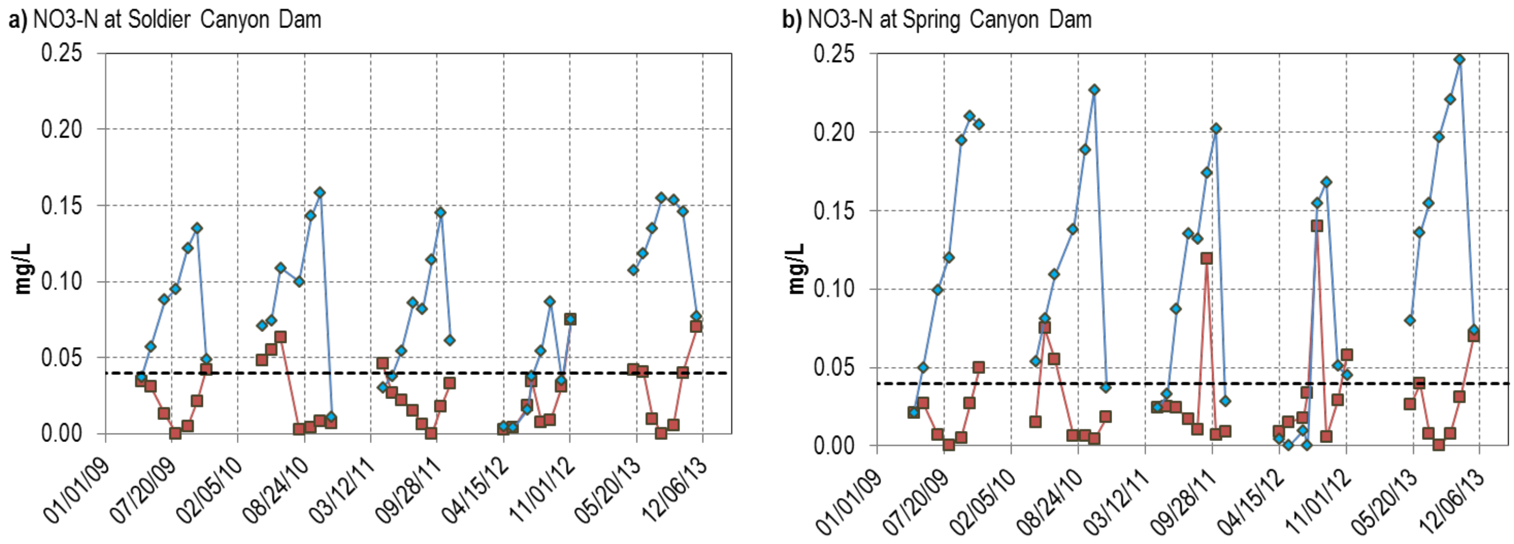


Figure 4.17 – Concentrations of nitrate at a) Soldier Canyon Dam and b) Spring Canyon Dam in Horsetooth Reservoir from 2009 through 2013.

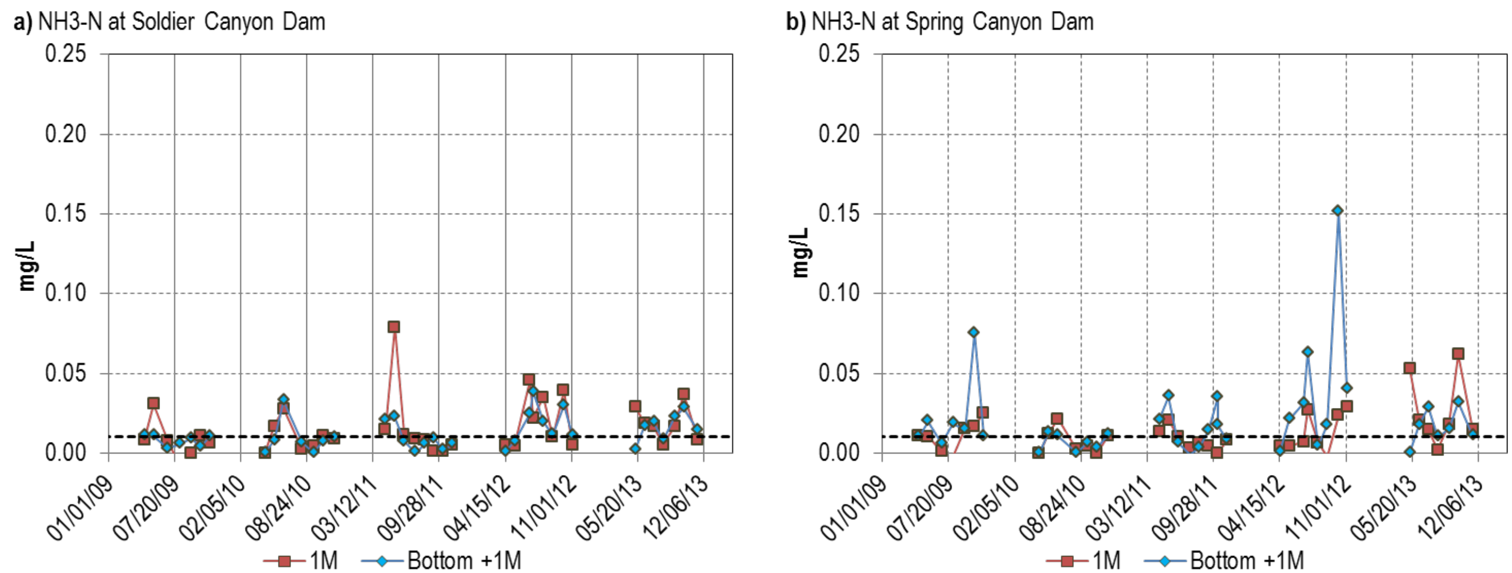


Figure 4.18 – Concentrations of ammonia at a) Soldier Canyon Dam and b) Spring Canyon Dam in Horsetooth Reservoir from 2009 through 2013.

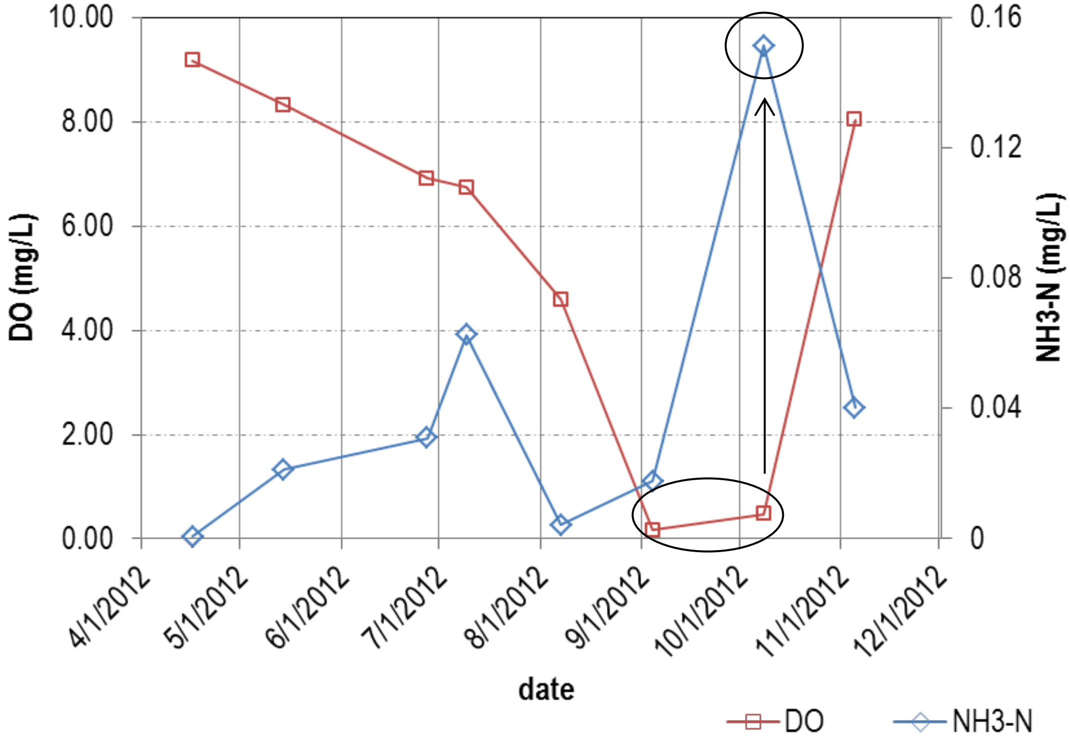


Figure 4.19 – Hypolimnetic ammonia and DO concentrations at Spring Canyon Dam illustrating the influence of depleted DO concentrations on the release of ammonia from Reservoir bottom sediments.

4.3.2 Phosphorus

Total phosphorus and ortho-Phosphate (PO_4) are the two forms of phosphorus measured as part of the FCU Horsetooth Reservoir Water Quality Monitoring Program. Sources of phosphorus in Horsetooth Reservoir include Hansen Feeder Canal inflows and direct inflows from the local adjacent watershed. Within Horsetooth Reservoir's water supply watersheds, anthropogenic sources of phosphorus include wastewater treatment plant effluent, leaking septic systems, and agricultural runoff and return flows.

Total phosphorus includes dissolved, particulate, absorbed, organic, and inorganic forms of phosphorus. It is considered the best water quality parameter to evaluate when quantifying phosphorus in a body of water because of the dynamic nature of the phosphorus cycle and ability of phosphorus to transform. Ortho-Phosphate (inorganic soluble phosphorus) is available for direct uptake by algae. Phosphorus is released from sediments to the water column under low oxygen conditions. The following bullets illustrate findings for TP and PO_4 data collected during the 2011, 2012, and 2013 monitoring season (Figures 4.20 and 4.21):

- TP and PO_4 concentrations were typically low in Horsetooth Reservoir in all monitoring years.
- TP concentrations near the reservoir bottom increased through the summer and into the fall as phosphorus was transported to the hypolimnion with the sedimentation of inorganic particles and organic matter from the epilimnion and metalimnion. The increase was also influenced by the release of PO_4 from bottom sediments as DO levels decreased.
- TP concentrations fluctuated and were slightly greater than the reporting limit throughout the monitoring season in all years
- Peak TP concentrations were observed earlier in 2013 on September 9th at both sites.
- PO_4 concentrations in the epilimnion and hypolimnion were comparable in all years. PO_4 concentrations in the epilimnion were frequently below the reporting limit of 0.005 mg/L for the entire monitoring season for all years except 2012, when concentrations were observed just above the reporting limit.
- PO_4 concentrations in the epilimnion were generally low because PO_4 is readily taken up by algae as it becomes available.
- In contrast, PO_4 concentrations in the hypolimnion increased throughout the monitoring season into the fall as DO concentrations decreased and phosphorus was released from reservoir bottom sediments.
- PO_4 was well mixed throughout the water column after fall turnover in all years.

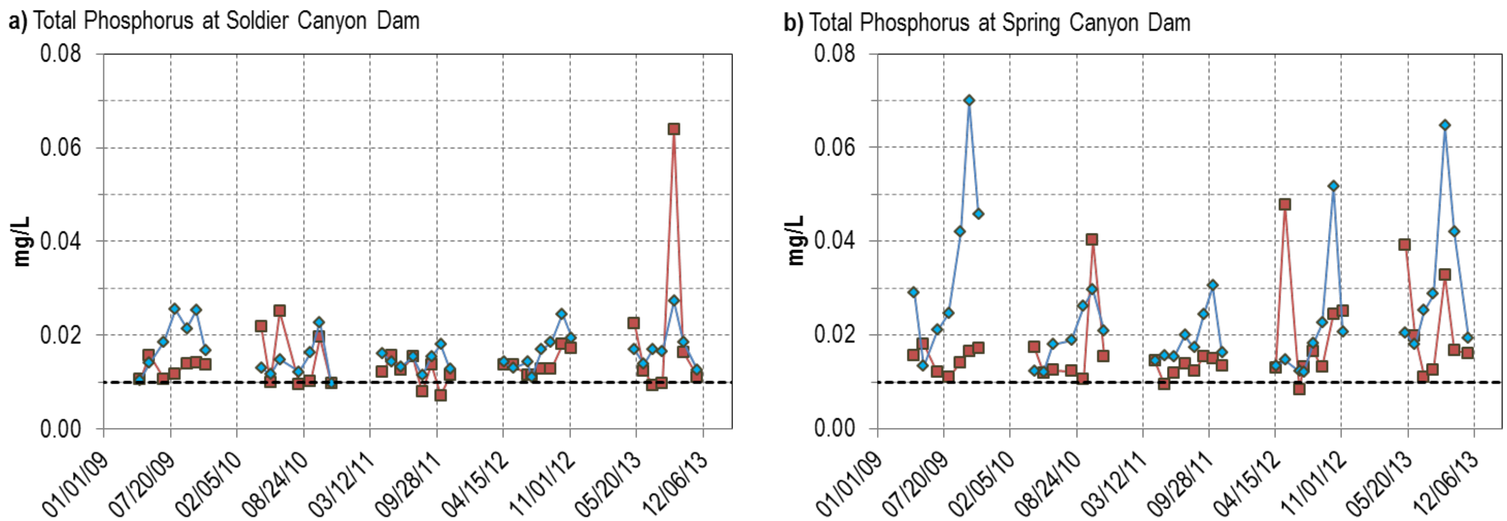
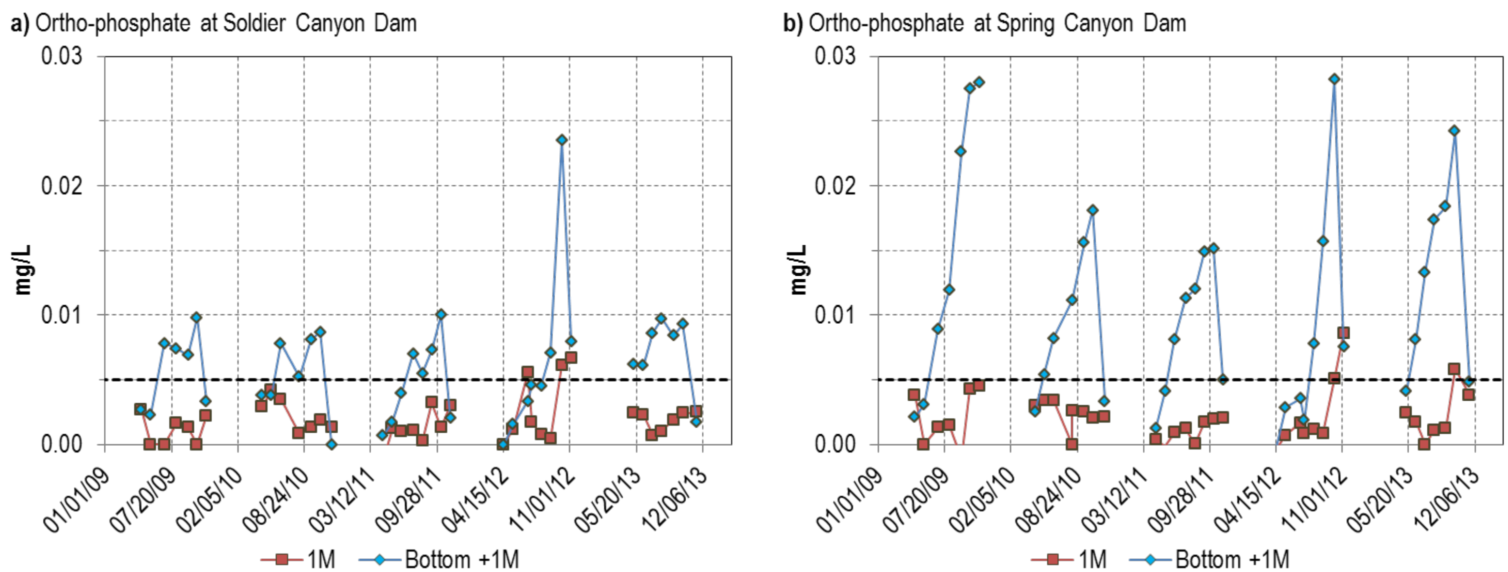


Figure 4.20 – Concentrations of total phosphorus at a) Soldier Canyon Dam and b) Spring Canyon Dam in Horsetooth Reservoir from 2009 through 2013.



4.4 Metals

Metals drive biochemical processes to sustain life in aquatic ecosystems. In excess, however, they can be toxic to both humans and aquatic organisms. Metal toxicity is influenced by several water quality parameters including temperature, pH, hardness, alkalinity, suspended solids, redox potential, and dissolved organic carbon. The natural source of metals to water bodies is through weathering of soils and rocks in the contributing watersheds. Anthropogenic sources include mining, municipal and industrial wastewater, storm water runoff, agriculture, and atmospheric deposition. Horsetooth Reservoir and the contributing watersheds are protected from most anthropogenic sources, and therefore, metal concentrations are generally low.

The metals monitored in the Horsetooth Reservoir Monitoring Program during the 2011, 2012, and 2013 monitoring years included aluminum, arsenic, iron, lead, manganese, mercury, and silver. As arsenic, lead, mercury, and silver concentrations were well below reporting limits in all years, they are not discuss in this report. In contrast to these low level metals, aluminum is one of the most abundant metallic elements in Horsetooth Reservoir and is commonly detected at low concentrations. However, no known health effects are associated with the presence of aluminum in drinking water supplies, and therefore, aluminum data are not discussed in this report.

Total and dissolved metal concentrations were monitored in Horsetooth Reservoir. Dissolved concentrations represent the bioavailable fraction of metal in the water column, while total concentrations include both dissolved and particulate fractions of metals that are bound to organic and inorganic compounds. The presence of inorganic and organic compounds in water reduces the toxicity of metals because metals are capable of binding to these compounds.

Metals are an important parameter to monitor not only because they can pose potential health risk, but also because certain metals require additional attention in the water treatment process as they cause aesthetic issues and may impart a metallic taste to treated water. The primary concern for the water treatment facility is the release of these metals from bottom sediments in the late summer and early fall when DO concentrations have been depleted near the reservoir bottom. The CDPHE has adopted numeric standards established under the Clean Water Act and Safe Drinking Water Act. Drinking water standards recognize maximum permissible concentrations for metals in natural water bodies for the protection of human health.

Iron and manganese are the metals most commonly detected above reporting limit and are closely monitored due to annual decreases in DO at the bottom of the reservoir. The low oxygen conditions are suitable for iron and manganese bound to bottom sediments to become more soluble increasing concentrations near the reservoir bottom and the City of Fort Collins water supply intake structure. The following bullets summarize manganese concentrations in Horsetooth Reservoir during the 2011, 2012, and 2013 monitoring seasons (Figure 4.22):

- Manganese and iron concentrations in the epilimnion decreased through the monitoring season in all years as reservoir primary productivity increased and these metals were utilized in biochemical processes.
- Total manganese and iron concentrations in the hypolimnion increased through the monitoring season as DO concentrations approached anoxic conditions (Figures 4.22 and 4.23).
- Total and dissolved peak hypolimnetic manganese concentrations were observed in September and October, which corresponded with seasonal minima near the reservoir surface.
- Dissolved concentrations did not follow seasonal trends, but the highest concentrations were typically located in the hypolimnion near the reservoir bottom and the lowest were generally found near the surface of the reservoir in the epilimnion.
- The highest peak concentrations in both total and dissolved manganese over the three year period were observed in October of 2012. Concentrations were nearly an order of magnitude greater than peak concentrations in other years. The notable increase was likely a result of the prolonged anoxic conditions in the hypolimnion (as was observed in the relationship between DO and NH3 in Figure 4.19).
- In 2012, the drinking water standard for dissolved manganese of 50 ug/L was exceeded at both sites and the maximum concentration at Spring Canyon Dam exceeded the chronic water quality standard for aquatic life (917 ug/L – 1151 ug/L). In addition, the concentration of dissolved manganese at Spring Canyon Dam on November 4th was 50.41 µg/L which slightly exceeded the 50 ug/L drinking water quality standard.

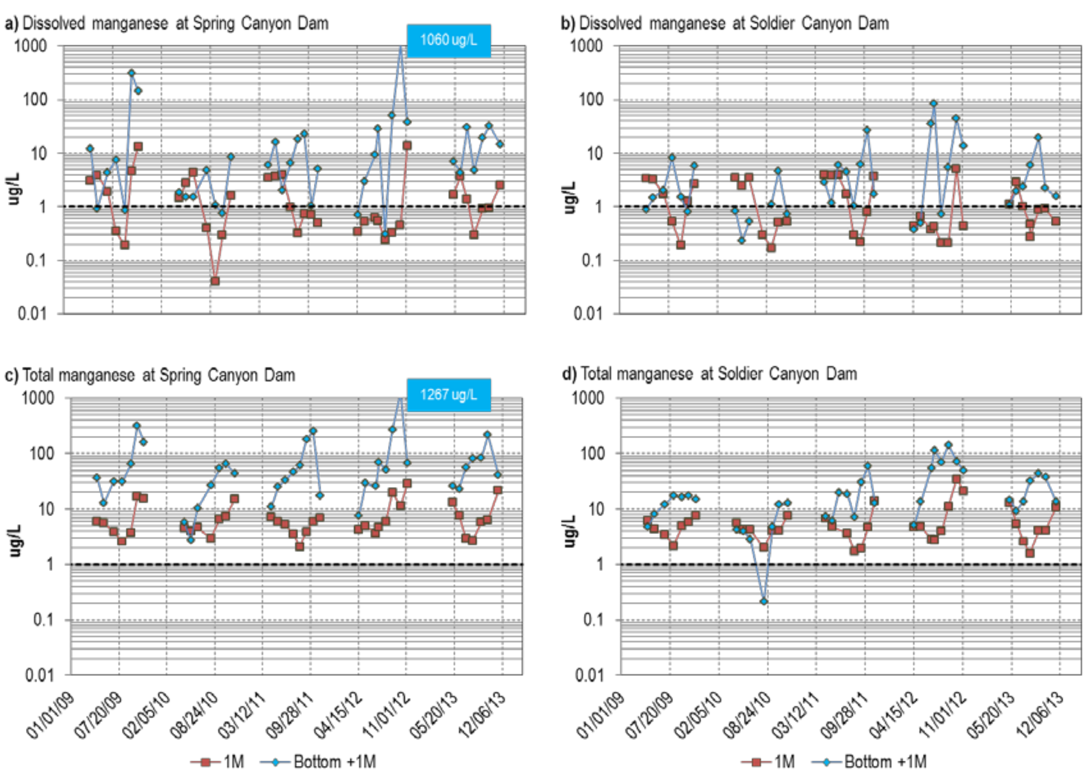


Figure 4.22 – Manganese (total and dissolved) concentrations measured Horsetooth Reservoir from 2009 through 2013.

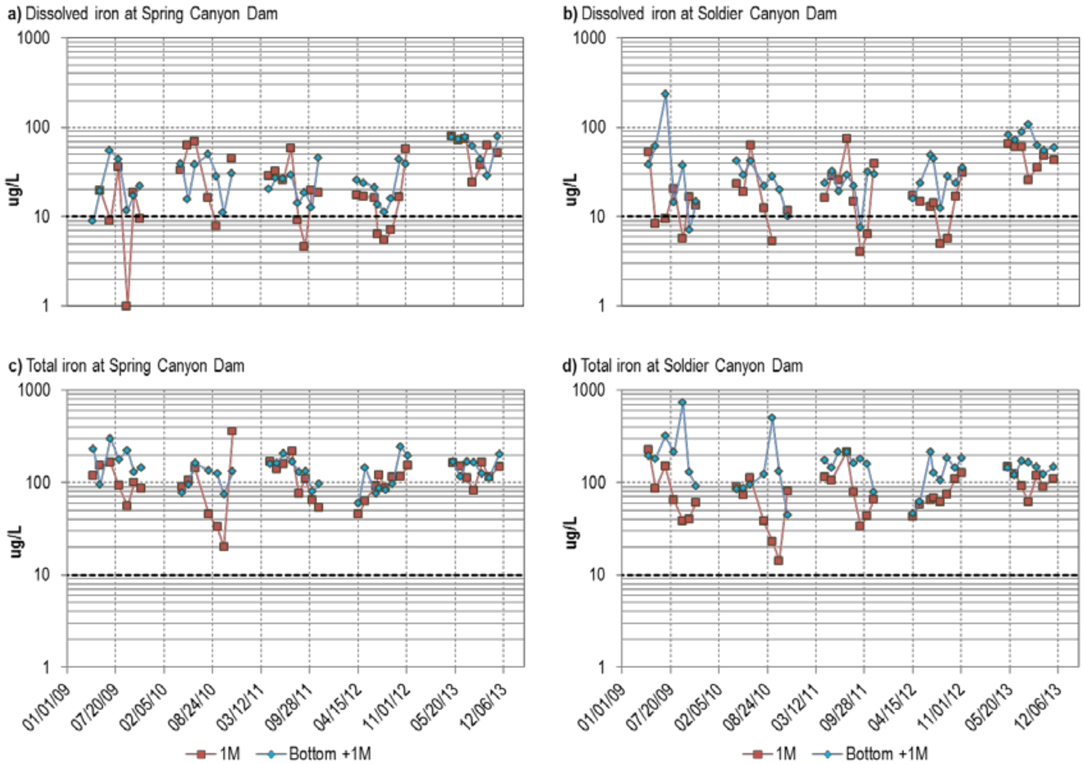


Figure 4.23 – Iron (total and dissolved) concentrations measured Horsetooth Reservoir from 2009 through 2013.

- Iron concentrations (dissolved and total) generally did not differ much between the epilimnion and hypolimnion.
- Seasonal trends were not commonly detected during the three year monitoring period (2011-2013), but iron concentrations in the epilimnion were usually the lowest when hypolimnetic concentrations were at a maximum.
- Concentrations were similar between monitoring locations.
- Peak hypolimnetic iron concentrations were generally observed in June.
- Dissolved iron concentrations were elevated in 2013 compared to 2011 and 2012 levels.

4.5 Reservoir Productivity

4.5.1 Phytoplankton

Phytoplankton are microscopic, free floating algae and cyanobacteria that can be carried into Horsetooth Reservoir from the Hansen Feeder Canal or produced directly in Horsetooth Reservoir. Phytoplankton are the foundation of the food web in lakes and reservoirs, and provide a valuable means for monitoring water quality because of their high sensitivity to environmental change. Beginning in 2009, phytoplankton identification and enumeration have been conducted by Dick Dufford, with identification to the *species* level (when possible). The following illustrates findings from samples collected one meter below the surface in 2011 through 2013; however, 2013 data were only available through July. Samples were also collected in the metalimnion and hypolimnion, but no apparent differences were observed between sampling depths.

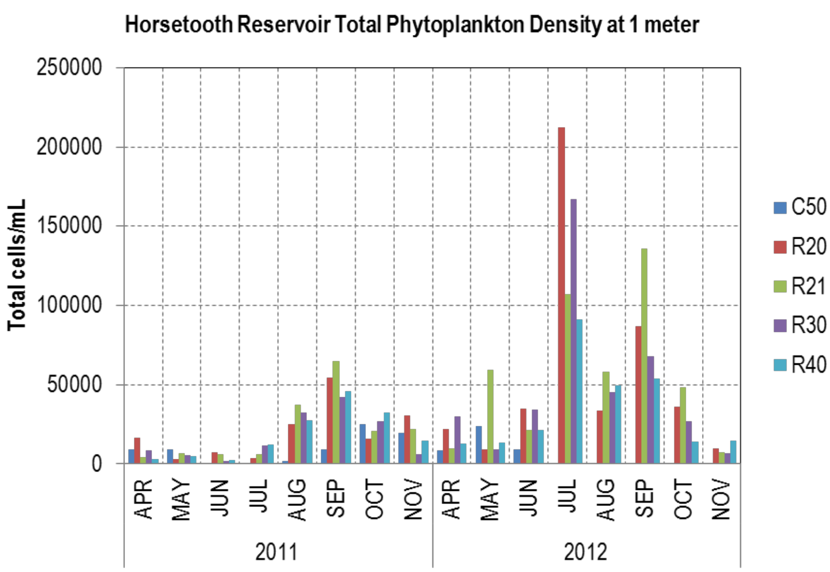


Figure 4.24 – Horsetooth Reservoir total phytoplankton density during 2011 and 2012.

The phytoplankton density in the inflow from the Hansen Feeder Canal was generally low and would therefore have little or no direct influence on phytoplankton counts within Horsetooth Reservoir. Within the reservoir, significant increases in total phytoplankton density occurred in August and September of 2011 and in July of 2012. Cell counts appeared to be significantly higher in 2012 compared to 2011, likely related to differences in environmental conditions including climate differences between years (Figure 4.24).

Chlorophytes (green algae) were the dominating algal group found in Horsetooth Reservoir during the spring and early summer months (April through June) in 2011 and 2013 (Figures 4.25a and 4.25c). This algal group was also identified in the 2012 spring season months, but only composed approximately 50% of the total phytoplankton, while the remaining 50% was primarily Cyanophytes (blue-green algae). In contrast to 2011 when Chlorophytes dominated through June, Chlorophytes were only observed until May in 2012. Geosmin producing species of blue green algae comprised a very small fraction of the total phytoplankton count in all years, generally one percent or less (down to zero) of the total density.

Figure 4.25 – Relative abundance (based on # cells/mL) of phytoplankton groups found in the a) 2011, b) 2012, and c) 2013 1-meter samples from Horsetooth Reservoir. Note that data from 2013 are incomplete.

4.5.2 Chlorophyll-a

Chlorophyll-a is the green pigment in plant cell walls responsible for photosynthesis. Monitoring chlorophyll-a provides an indirect measurement of the quantity of photosynthesizing plants (algae or phytoplankton) that are actively respiring and photosynthesizing in the lake at the time of monitoring. The cycle of chlorophyll-a containing plants influence the physical, chemistry and biological characteristics of water. As discussed in section 4.1.2, photosynthesizing plants are a source for oxygen production in the reservoir epilimnion during the day, but during the night and following death and decay of algae and phytoplankton oxygen is consumed by microorganisms during through respiration and decomposition. Other influences on water chemistry associated with algal production in lakes and reservoirs include changes to pH and the release of nutrients, which may further stimulate algal growth. The clarity of the water can also be influenced by increased populations of algae. Observations of decreasing Secchi depth measurements throughout the monitoring season commonly indicate increasing algal production in the epilimnion. Therefore, chlorophyll-a monitoring in Horsetooth Reservoir provides information on the trophic state or biological productivity (discussed in section 4.5.4 Trophic State).

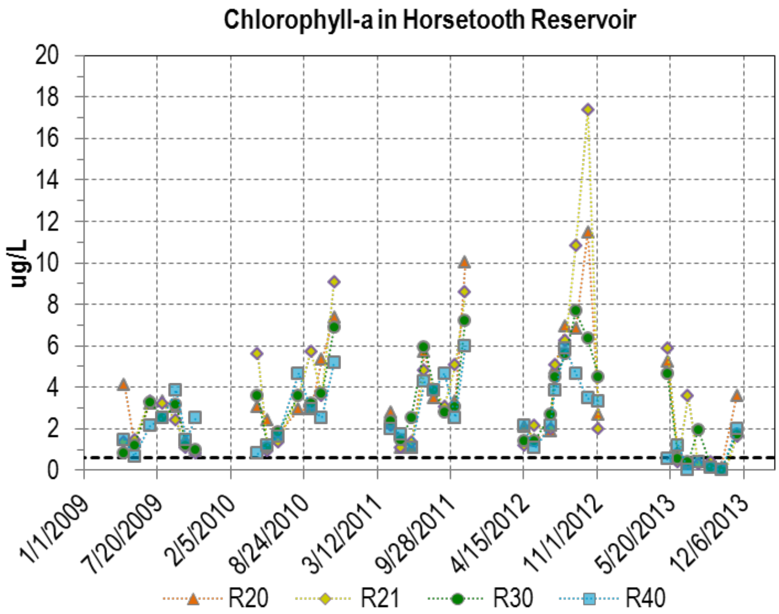


Figure 4.26 – Chlorophyll-a concentrations found at Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Solider Canyon Dam (R40) from 2009 to 2013.

Chlorophyll-a concentrations vary from year to year and peak anytime between July and October and in some years peak again following or during fall turnover (Figure 4.26). The following bullets summarize chlorophyll-a concentrations in Horsetooth Reservoir during the 2011, 2012, and 2013 monitoring seasons (Figure 4.26):

- Chlorophyll-concentrations in 2011 followed a similar pattern to 2010.
- Peak concentrations in 2012 were the highest concentrations over the five year record.
- In contrast to 2012, chlorophyll-a concentrations in 2013 were the lowest concentrations observed over the five year period. These concentrations were unusually low for Horsetooth Reservoir and results are being investigated. It is expected that the cause of these low values is due to sample handling or analytical error rather than due to a change in reservoir productivity.

4.5.3 Secchi Depth

The clarity or transparency of Horsetooth Reservoir is measured using a Secchi disk. The Secchi disk is a circular disk attached to a calibrated line that is lowered vertically down the water column until the disk is no longer visible. The depth at which the disc disappears is the Secchi depth transparency, recorded as depth below the surface in meters. Secchi depth varies seasonally due to the presence of turbid particles (organic or inorganic) and algae in the water. Secchi depth is a valuable tool for assessing the trophic state or biological productivity in Horsetooth Reservoir.

Secchi depth was inversely correlated with chlorophyll-a concentrations during the 2011 and 2012 monitoring periods. For example, as chlorophyll-a concentrations increased Secchi depth decreased. This trend was particularly noticeable in 2011 when Secchi depth approached a five year minimum of 1 meter at Spring Canyon Dam corresponding to five year maximum chlorophyll-a concentrations. In general, Secchi depth ranged from 1.2 meters to 4.0 meters over the three year monitoring period (2011 to 2013) (Figure 4.27.)

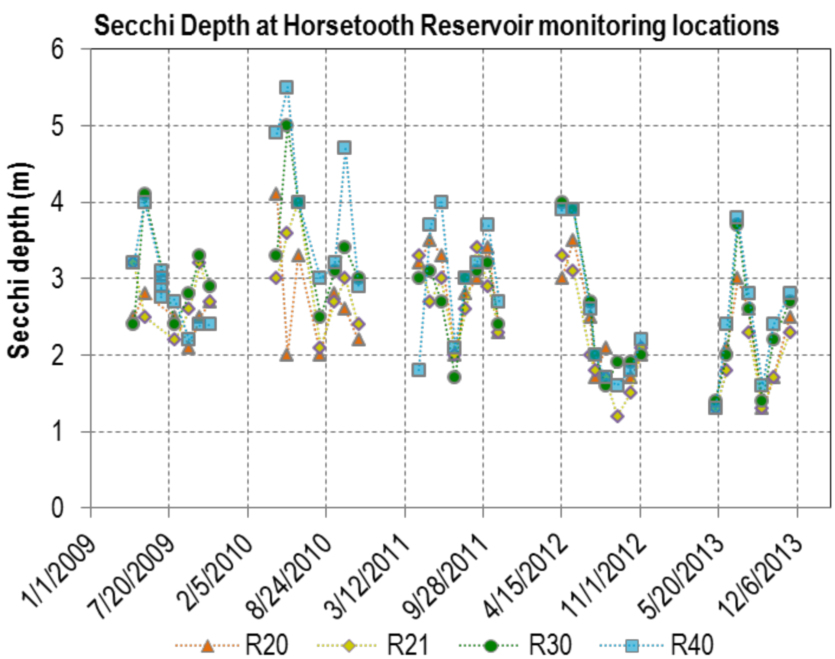


Figure 4.27 – Secchi depths observed at Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon

4.5.4 Trophic State

Water bodies are classified into three tropic states primarily related to concentrations of nutrients, plant production rates and abundance. *Eutrophic* lakes are high in nutrient concentrations, and high in plant production rates abundance (chlorophyll-a >7.3 µg/L), while *oligotrophic* lakes are low in nutrient concentrations, and low in plant production rates and abundance (chlorophyll-a <2.6 µg/L). *Mesotrophic* lakes are in the middle of these two trophic states and typically have concentrations of chlorophyll-a that range between 2.6 µg/L and 7.3 µg/L. The Trophic State Index (TSI) can be calculated based on chlorophyll-a data according to the equation (Carlson, 1977) (Figure 4.28a):

$$TSI\ (CHL) = 30.6 + 9.81\ \ln[\text{Chlor-a in } \mu g/L]$$

Similarly, the TSI can be calculated using Secchi depth readings and TP concentrations. Depths of two meters to four meters (TSI values between 50 and 40) fall into the mesotrophic range, while Secchi disk readings of 0.5 meters to two meters (TSI values between 70 and 50) fall in the eutrophic range. The TSI is calculated based on Secchi depth (SD) according to the following equation (Carlson, 1977) (Figure 4.28b):

$$TSI\ (SD) = 60 - 14.41\ \ln(\text{SD in meters})$$

Total phosphorus concentrations of 12-24 µg/L (TSI values between 50 and 40) fall into the mesotrophic range, while TP concentrations of 24-96 µg/L (TSI values between 70 and 50) fall in the eutrophic range. The TSI is calculated based on TP according to the following equation (Carlson, 1977) (Figure 4.28c):

$$TSI\ (TP) = 4.15 + 14.42\ \ln(TP)$$

The tropic state of Horsetooth Reservoir over the three year period was generally mesotrophic for all TSI indices (Figures 4.28a-c) when evaluating median TSI indices. Values were variable and occasionally corresponded with eutrophic and oligotrophic tropic conditions. It is important to note that based on the 2013 chlorophyll-a data, Horsetooth Reservoir would be characterized as oligotrophic, however, Secchi depth and TP suggest a mesotrophic state. These results provide further evidence of questionable chlorophyll-a data in 2013, and therefore, results should be noted as suspect until a further review is completed.

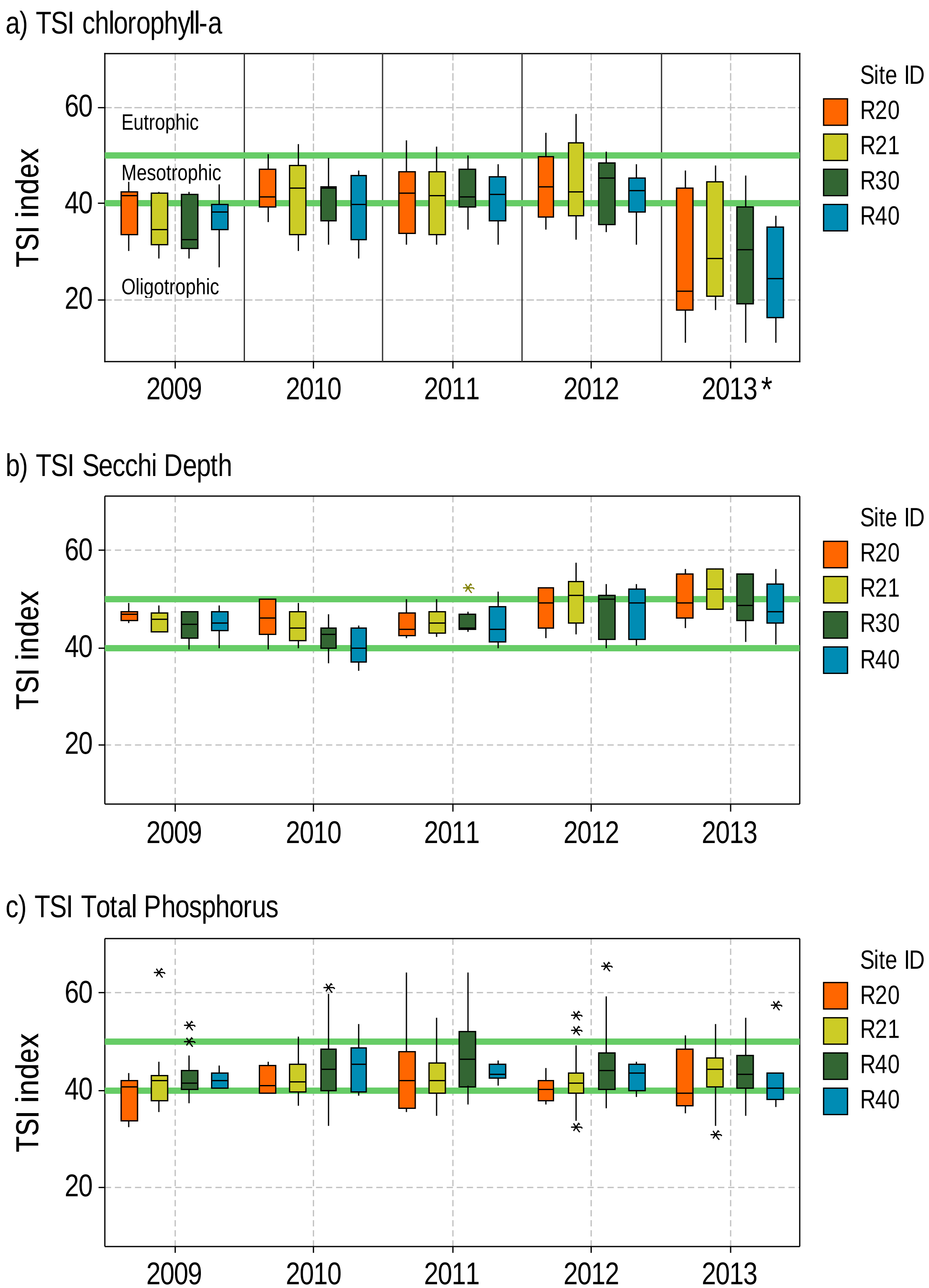


Figure 4.28 – Tropic state indices calculated from a) chlorophyll-a concentrations, b) Secchi depths, and c) total phosphorus concentrations from 2009 to 2013. *Data are skewed due error introduced through analytical techniques.

5.0 HANSEN FEEDER CANAL WATER QUALITY

The following sections summarize Hansen Feeder Canal water quality data collected by FCU including the continuous real-time monitoring sonde data and grab sample data. The data may provide insight to significant water quality issues observed in Horsetooth Reservoir.

5.1 Continuous Real-Time Monitoring

The City of Fort Collins operates and maintains a multi-parameter YSI probe (sonde) with continuous monitoring at the C50 Hansen Feeder Canal monitoring location. The C50 sonde continuously measures water temperature, DO, and specific conductance, and reports these values every four hours beginning at 00:00 (12:00am) daily. Specific conductivity and pH are also measured from weekly Hansen Feeder Canal grab samples and are discussed as general parameters below.

5.1.1 Water Temperature

Water temperature experiences diurnal fluctuations as well as seasonal changes. Temperatures generally increase until late summer, followed by a decline in late fall and winter. Winter temperatures were just above freezing over the three year monitoring period, while maximum temperatures approached 22.0^{o}C. Temperature fluctuations can also be related to the operation of the CBT system and changes in source water flows to Hansen Feeder Canal.

5.1.2 Dissolved Oxygen

Dissolved oxygen decrease in concentration through late summer and then increases to maximum concentrations in the winter months. Dissolved oxygen concentrations are inversely related to water temperature (i.e., saturation decreases with increasing temperature), and the decreases and increases in DO concentrations generally follow temperature fluctuations. On a daily basis, the minimum DO values occur in the early morning. Minimum concentrations were near 6.0 mg/L over the three year monitoring period while maximum concentrations approached 13.5 mg/L.

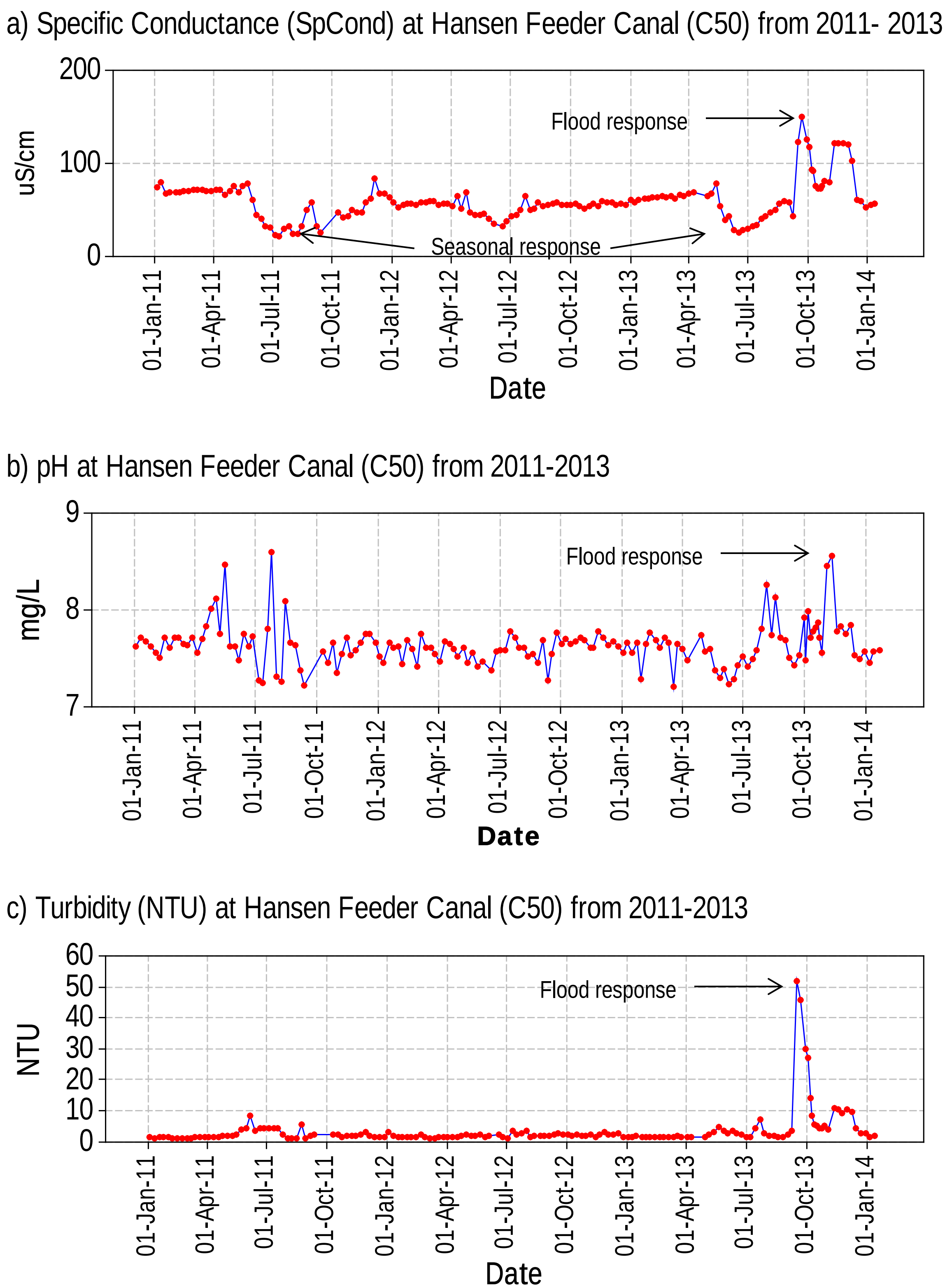


Figure 5.1 – Weekly samples for a) specific conductivity, b) pH, and c) turbidity measured from the Hansen Feeder Canal from 2011 through 2013.

5.2 General Parameters

5.2.1 Specific Conductivity

Specific conductivity generally exhibits a small seasonal response with snowmelt runoff. Specific conductance values decreased during the spring as a result of dilution of flows in the Big Thompson River water by snowmelt waters. This was particularly noticeable in 2011 as a result of a historic snowpack and a longer conveyance time of CBT snowmelt water into Horsetooth Reservoir. Specific conductivity ranged between approximately 20 µS/cm and 80 µS/cm over the three year period until the September 2013 flood event. The flooding resulted in increased conductivity values greater than 100 µS/cm peaking at 150 µS/cm. Elevated specific conductivity values began to decrease to baseline conditions in late October, but were elevated again after releases from the Olympus Dam that began on November 4th. Specific conductivity returned to expected seasonal values by mid-December (Figure 5.1a).

5.2.2 pH

pH values ranged between 7.0 and 9.0 over the three year period. Diurnal fluctuations were observed in pH, which is related to changes in water temperature in the Hansen Feeder Canal. Elevated pH values were observed throughout the monitoring period, but specifically following the September 2013 flooding and these increased pH values correspond to increased concentrations of alkalinity (Figure 5.1b).

5.2.3 Turbidity

Turbidity values in the Hansen Feeder Canal were frequently below 10 NTU, but occasional spikes occurred likely as a result of increased canal flow and re-suspension of sediment located in the canal system. The September 2013 flood caused an increase in turbidity in the Hansen Feeder Canal. The increase in turbidly was triggered by hillslope and stormflow erosion, and re-suspension of in channel sediment within the CBT watershed (Figure 5.1c).

5.3 Grab Samples

5.3.1 Alkalinity

Alkalinity concentrations ranged between approximately 7 mg/L and 35 mg/L during the three year monitoring period. Seasonal patterns in alkalinity were observed with lower concentrations in the spring due to dilution from snowmelt runoff and higher concentrations in the fall and late winter. The seasonal response from snowmelt runoff in 2012 was not as pronounced as concentrations were higher than 2011 and 2013. The lower dilution and higher alkalinity concentrations were likely associated with drought conditions experienced in 2012 and the limited quantity of water conveyed via the Hansen Feeder Canal (Figure 5.2a).

5.3.2 Total Dissolved Solids

Total dissolved solids ranged between approximately 15 mg/L and 60 mg/L during the three year monitoring period. Seasonal patterns were observed with concentrations decreasing during the late spring and early summer, and then increasing from late fall through winter. Concentrations were typically lowest in late June and July after spring snowmelt. Total dissolved solids did respond to drought conditions in 2012 and flooding in September 2013. Total dissolved solids concentrations decreased to a three year minimum in July of 2012, while the three year maximum was reached during flooding in September of 2013 when concentrations peaked to near 120 mg/L (Figure 5.2b).

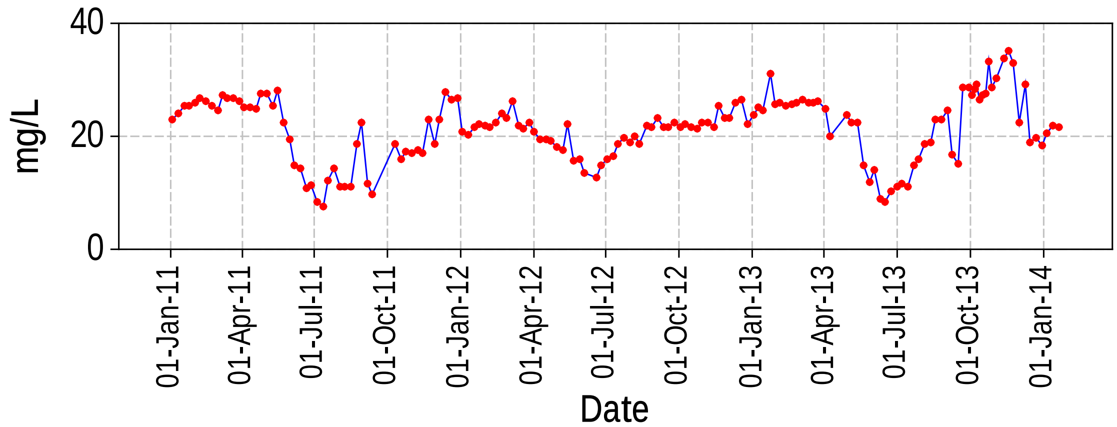
5.3.3 Total Organic Carbon

The Hansen Feeder Canal is the primary source of water to Horsetooth Reservoir thereby delivers a significant amount of TOC to the reservoir. Water delivered from the Hansen Feeder Canal is a mix of water from the west slope (via Adams Tunnel) and the Big Thompson River, and therefore, represents characteristics of both sources. During most of the year, TOC concentrations in Hansen Feeder Canal range from 3.0 mg/L to 4.0 mg/L (Figure 5.2c). These baseline conditions are very similar to concentrations in the Adams Tunnel because most of the water in the Hansen Feeder Canal is from the Adams Tunnel. The Hansen Feeder Canal TOC increases to values greater than the Adams Tunnel TOC during the spring snowmelt runoff period (May to June) if the Big Thompson River contributes a significant fraction of the total flow into the Hansen Feeder Canal. This was observed in 2011 following historic snow fall. Total organic carbon concentrations ranged between approximately 1.5 mg/L and 7.0 mg/L during the three year monitoring period excluding the flood response in 2013 (Figure 5.2c). A seasonal increase was observed in all years caused by snowmelt runoff, which produced peak concentrations of approximately 7.0 mg/L in 2011 and 10.1 mg/L in 2013. The snowmelt response in 2012 was much less due to drought and low snowpack conditions and therefore, peaked at approximately 5.3 mg/L. Following snowmelt runoff, TOC concentrations in Hansen Feeder Canal were approximately 5.0 mg/L. Total organic carbon concentrations were found to be elevated to a three year maximum concentration of approximately 17 mg/L following the September 2013 flooding event. A secondary elevated response was observed in December when water was released from the Olympus Dam (Figure 5.2c).

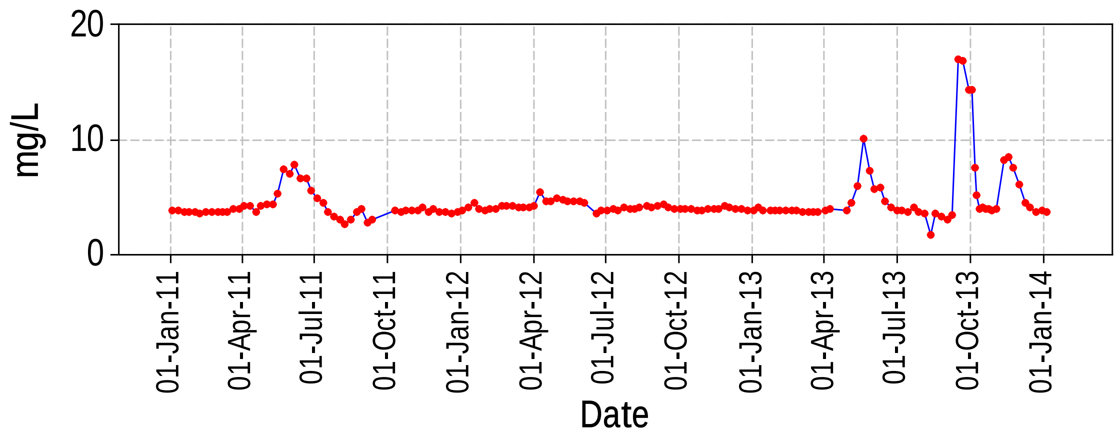
5.3.4 Nutrients

Nutrients (NH_4, NO_2, NO_3, Total Kjeldahl Nitrgoen, PO_4, and TP) did not show seasonal responses during the three year monitoring period. Most nutrients fluctuated near detection limit, but occasional spikes were observed, which may be related to changes in Hansen Feeder Canal flow. Increased flows may cause suspension of nutrients accumulated in sediments deposited along the canal system. A flood response was evident for NH_4, NO_3, and TKN, but not NO_2 (Figure 5.3). Nitrite concentrations were continuously below reporting limit for the three monitoring years. Total nitrogen would have exceeded the regulatory standard of 1.2 mg/L for cold, flow waters (~1.5 mg/L). The impact on HT reservoir nutrient status depends on the load delivered to the reservoir and the volume of the reservoir at that time.

a) Alkalinity at Hansen Feeder Canal (C50) from 2011-2013



b) Total Organic Carbon (TOC) at Hansen Feeder Canal (C50) from 2011- 2013



c) TDS at Hansen Feeder Canal (C50) from 2011- 2013

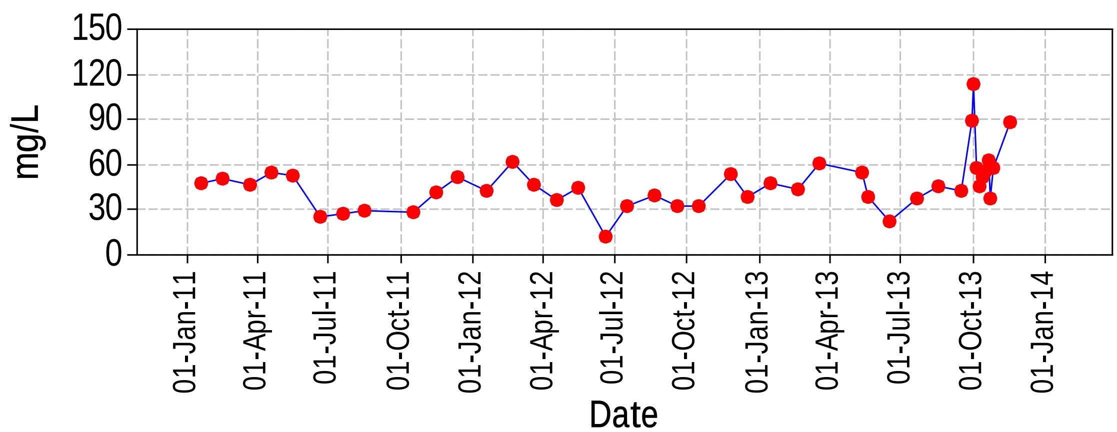


Figure 5.2 – Grab sample data from 2011 through 2013 obtained from the Hansen Feeder Canal for a) alkalinity, b) TOC, and c) TDS.

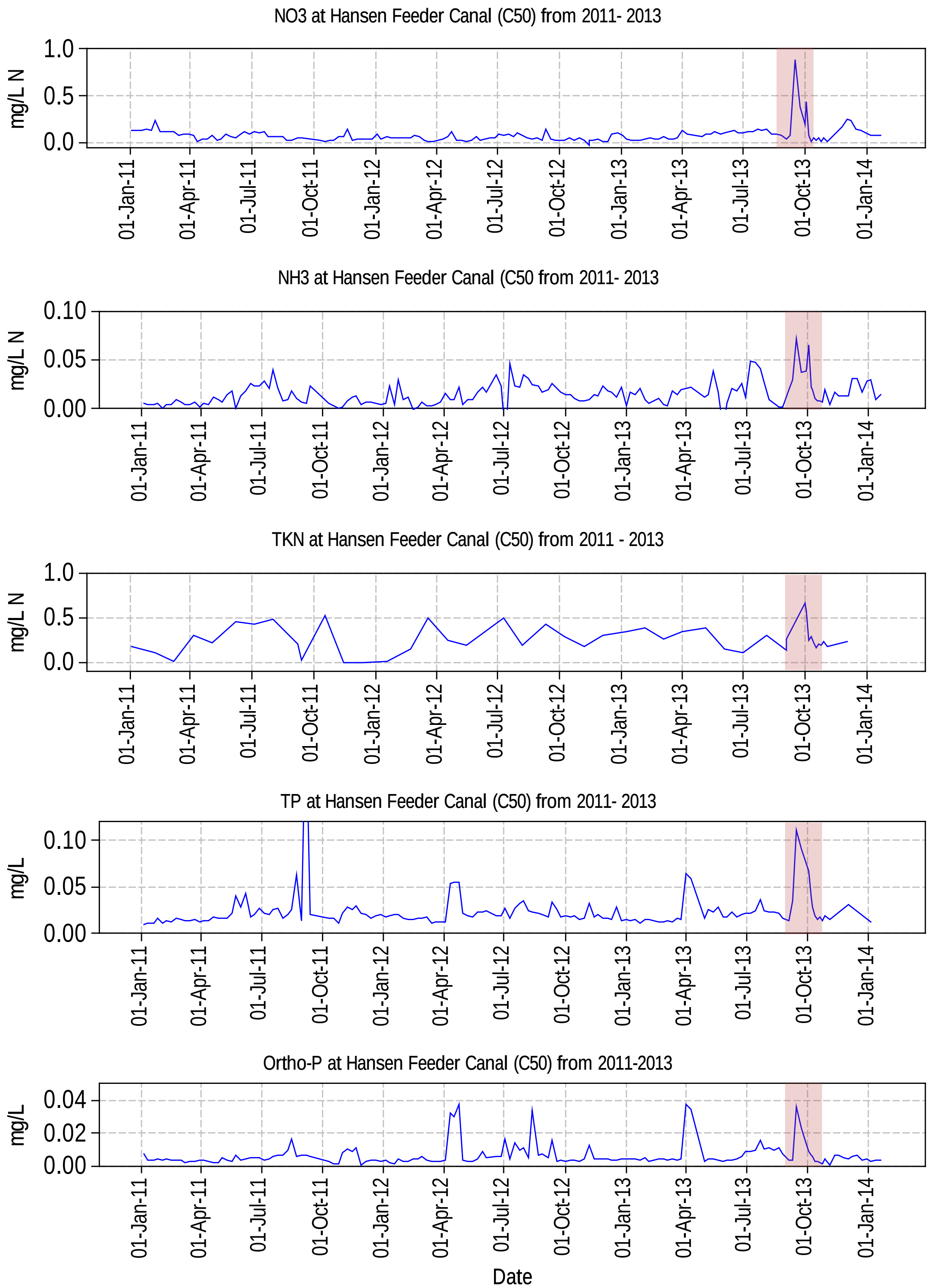


Figure 5.3 – Nutrient grab sample data from 2011 through 2013 obtained from the Hansen Feeder Canal. The red boxes indicate the flood response from the September 2013 flooding event.

5.4 Nutrient and Total Organic Carbon Mass Loading

Loading estimates from the Hansen Feeder Canal provide insight on the relative impact of TOC and nutrient inputs from CBT source waters on Horsetooth Reservoir water quality. Mass loads of TOC and nutrients entering Horsetooth Reservoir from the Hansen Feeder Canal were calculated using daily flow data and weekly concentrations measured by the FCWQL. Monthly and annual mass loads were calculated using the time-interval method. In this method, the constituent concentration measured on a specific day (Day_i) is assumed to apply to each day within the time interval that is defined by the midpoint between Day_i and the next sampling day (Day_{i+1}). In this manner, all days of the year have either a measured or assumed concentration. The constituent mass load for the year is estimated as the sum of the products of the daily (measured or assumed) concentration (C_d) and the daily flow (Q_d):

$$Annual\ Mass\ Load = \sum_{d=1}^{365} (Q_d\ x\ C_d)$$

Total organic carbon loading for a given month varied greatly between years. In general, Horsetooth Reservoir experienced the highest loadings in May, June, and July in all years, while the lowest load contributions occurred in August. The highest TOC load was approximately 225 tons/month and was observed in June of 2011 during a period of higher than normal flows due to the historic snowfall of the 2010/2011 winter. In contrast to 2011, the greatest TOC loads in 2012 occurred in October. Total organic carbon loading in September of 2013 increased as a result of the flood event, however, monthly loading was similar to September 2012 (Figure 5.4). Despite unusually high TOC concentrations as a result of the September 2013 flood, flooding did not translate to large loads being delivered to Horsetooth Reservoir due to flow regulation during the event.

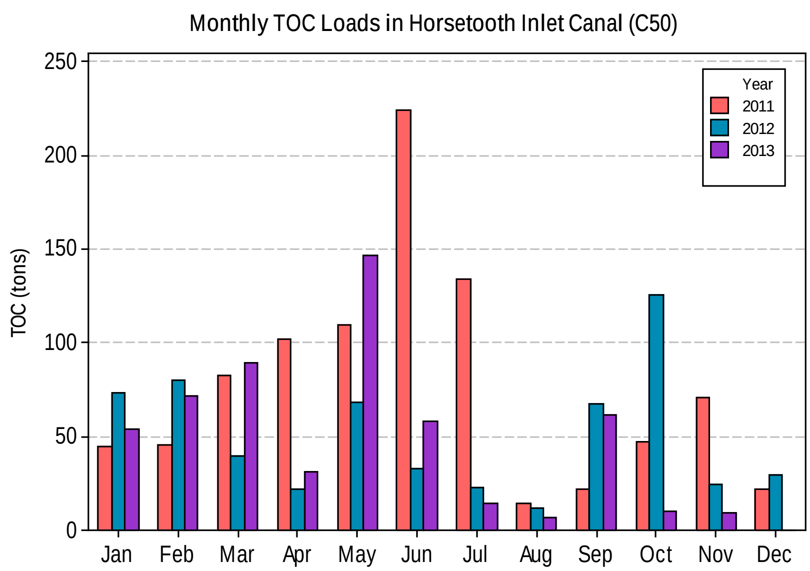


Figure 5.4 – Monthly total organic carbon loads from Hansen Feeder Canal to Horsetooth Reservoir for 2011, 2012, and 2013.

Nutrient loading into Horsetooth Reservoir from the Hansen Feeder Canal was similar to TOC loading. Horsetooth Reservoir experienced the highest nutrient loadings in May, June, and July in 2011 and 2013. Nutrient loading during these months in 2012 were exceptionally low compared to 2011 and 2013, while loading during the fall months were higher compared to 2011 and 2013. This observation was consistent with TOC loading and associated with late season water supply demand due to drought conditions that persisted in 2012. Nutrient loading was influenced by the September flood event and all nutrient loads were higher in September compared to seasonal expectations. Although September loading was high, annual nutrient loads appeared to be unaffected (Figure 5.5).

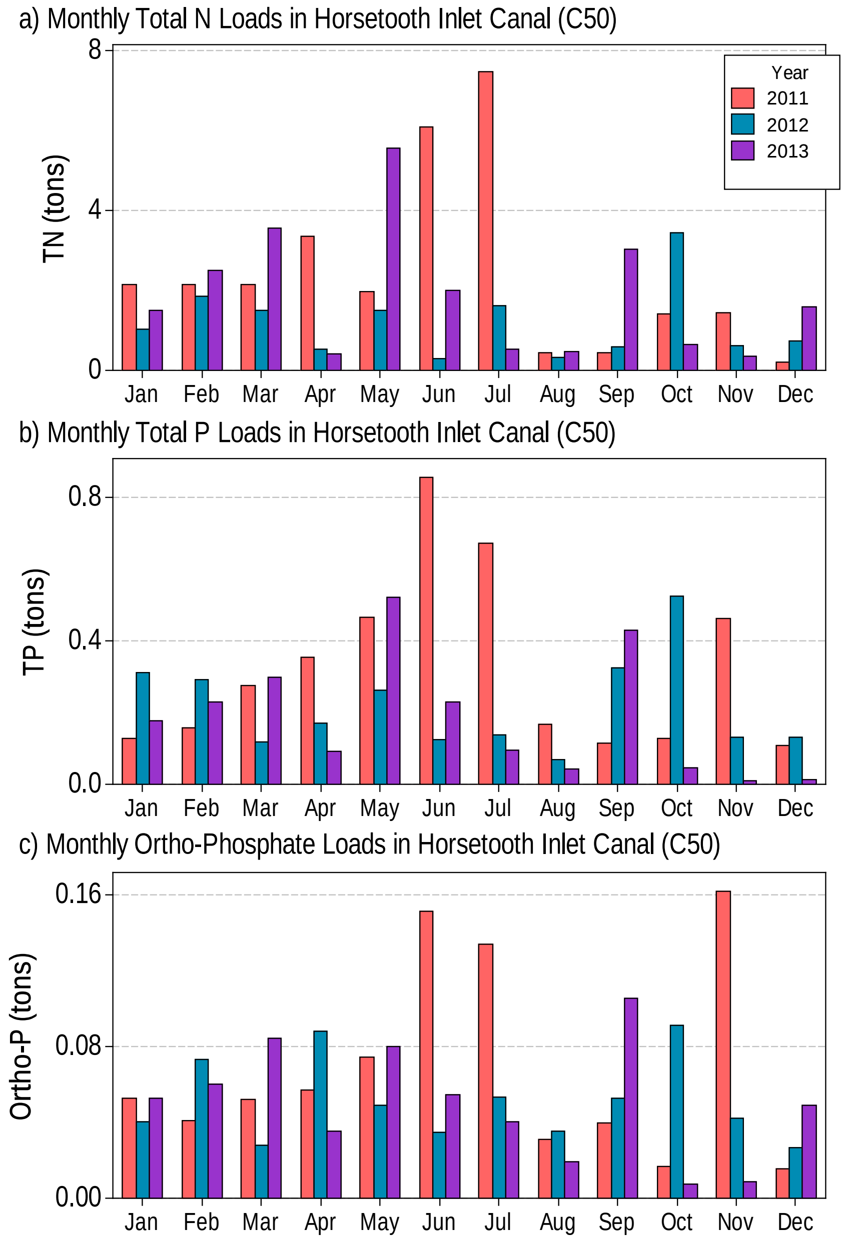


Figure 5.5 – Monthly loads of 1) TN, b) total phosphorus, and c) ortho-phosphate from Hansen Feeder Canal to Horsetooth Reservoir for 2011, 2012, and 2013.

6.0 FUTURE MONITORING

6.1 Northern Water & Fort Collins Utilities Collaboration

In 2013, NW water quality program and the FCU's Source Water Monitoring Program began discussing the feasibility of collaborating on Horsetooth Monitoring efforts. Both the FCU and NW currently monitor water quality in Horsetooth Reservoir and therefore, a collaborative effort would be more sustainable for both organizations. The collaborative effort would ultimately lead to FCU supporting NW's Horsetooth Reservoir monitoring efforts. Northern Water would maintain their program. Fort Collins Utilities would terminate their program, but continue to utilize data collected by NW to support the goals and objectives of the FCU Source Water Monitoring Program.

The FCU Source Water Monitoring Program conducted a statistical analysis to compare Horsetooth Reservoir water quality data collected by the FCU and NW. The main goal of the data comparison and statistical analysis was to confirm consistency between data sets, laboratory techniques, and field monitoring methods to ensure the integrity of maintaining the long-term data set that FCU has established since the start of their monitoring efforts in the late 1980s. In addition, in November 2013 both programs conducted a "side-by-side" monitoring event on the same date to verify field techniques, and eliminate factors that may influence water quality including time of day, seasonality, and weather. Data analysis and the "side-by-side" monitoring event confirmed consistency between monitoring programs. During the 2014 monitoring season, FCU and NW plan to conducted more "side-by-side" monitoring events to further validate consistency between monitoring programs. It is expected that the collaboration will begin in the 2015. Fort Collins Utilities will continue to Hansen Feeder Canal monitoring.

7.0 SUMMARY

The 2014 Horsetooth Reservoir Water Quality Monitoring Program Report documents information and data collected by FCU for 2011, 2012, and 2013 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. Specifically, the 2014 Report includes information and data on regulatory issues, relevant special studies, reservoir hydrology, Hansen Feeder Canal water quality and mass loads, Horsetooth Reservoir water quality, and issues of concern. A summary of key information, data, and/or findings presented for each of these general topics is provided below.

7.1 Regulatory Issues

- Horsetooth Reservoir was removed from the M&E List in 2012 for low DO in the metalimnion.
- Horsetooth Reservoir remains on the 2012 M&E List for aquatic life chronic standard exceedances of copper and arsenic.
- Horsetooth Reservoir remains on the 303(d) List for Aquatic Life Use due to the presence of mercury in fish tissue.
- The WQCD is currently in the process of developing numeric nutrient criteria for different categories of state surface waters. The Basic Standards and Methodologies (Regulation #31) became effective on January 31, 2013. Interim numeric standards have been proposed for TP and TN (section 31.17 of Regulation #31) for lakes and reservoirs. For cold water lakes and reservoirs greater than 25 acres (including Horsetooth Reservoir), the proposed interim TP standard is 25 µg/L, while the proposed interim TN standard is 426 µg/L. A chlorophyll-a standard of 8 µg/L has also been proposed for cold water lakes and reservoirs greater than 25 acres. The WQCD has proposed a lower chlorophyll-a standard of 5 µg/L to support DUWS.
- Horsetooth Reservoir exceeded the TN and chlorophyll-a nutrient standards in 2012 at all monitoring sites except Solider Canyon Dam. Over the five year period, 2012 was the only year to exceed the proposed nutrient standard and because the allowable exceedance frequency is 1-in-5-years, Horsetooth Reservoir is in compliance with the standards for TN and chlorophyll-a.

7.2 Special Studies and Issues of Concern

- Geosmin occurrence in Horsetooth Reservoir and upstream components of the CBT Project. Findings from the 2011, 2012, and 2013 geosmin monitoring program indicate the following:
    - In 2011, geosmin concentrations at all Horsetooth Reservoir monitoring sites were below 4 ng/L. Geosmin in the CBT system exceeded 4 ng/L on one occurrence. The highest geosmin concentration was 12.64 ng/L at Adams Tunnel on October 4th.
    - Geosmin concentrations in the hypolimnion of Horsetooth Reservoir exceeded the 4 ng/L threshold at all locations except the Inlet Bay Narrows in 2012. The highest concentration was 8.44 ng/L in the Dixon Canyon Dam hypolimnion on September 4th. Geosmin concentrations in the CBT system were below 4 ng/L on all monitoring dates.

- Geosmin concentrations in Horsetooth Reservoir exceeded the 4 ng/L threshold at all locations in 2013, but only on one occurrence. Geosmin concentrations in the CBT system exceeded 4 ng/L on one monitoring date at C10, C50, and M70. The highest concentration was 12.3 ng/L on August 7th at the Adams Tunnel.

- The wastewater treatment plant effluent from Estes Park Wastewater Treatment Plant is the primary source of many pharmaceuticals and personal care products (PPCP) to Horsetooth Reservoir via the Hansen Feeder Canal. Many of these compounds do not appear to be persistent in the aquatic environment since they do not consistently occur in downstream water samples. The most commonly detected PPCP in the Hansen Feeder Canal and Horsetooth Reservoir include cotinine, gemfibrozil, lamotrigine, metoprolol, and venlafaxine. Endocrine disruptors were not detected in the Hansen Feeder Canal or Horsetooth Reservoir. The only detected herbicide in Horsetooth Reservoir in 2011 was 2,4-D. Recreational contaminants including DEET, caffeine, sucralose, and triclosan, were all detected at low concentrations in Horsetooth Reservoir.

7.3 Horsetooth Reservoir Hydrology

- Inflow to Horsetooth Reservoir from the Hansen Feeder Canal was nearly continuous except during short periods each fall when the canal was shut down for annual maintenance. In 2011, inflow to Horsetooth Reservoir was increased from January through August corresponding to a historic snowpack in the mountains. Conversely, flows in 2012 during the runoff season were variable and short lived due to a historically low snowpack in the mountains. In flows in 2012 were increased in September through November.

7.4 Horsetooth Reservoir Water Quality

- *Sampling Events*. In 2011 and 2012, there were eight routine Horsetooth Reservoir sampling events, and in 2013, there were seven routine Horsetooth Reservoir sampling events.

- *Temperature Profiles*. The 2011, 2012, and 2013 temperature profiles showed development of thermal stratification. Thermal stratification was delayed in 2011 as a result of a cooler than average spring, historic snowpack, and longer than average runoff season. Thermal stratification began earlier in 2012 and 2013.

- *Dissolved Oxygen Profiles*. Similar to previous years, the DO profiles for 2011, 2012, and 2013 experienced depletion in both the metalimnion and hypolimnion. Dissolved oxygen depletion at the reservoir bottom was less significant in terms of magnitude and duration at Soldier Canyon than at Dixon Canyon and Spring Canyon because of the hypolimnetic withdrawal of water at Soldier Canyon, especially in 2012. The lowest DO concentrations occurred in 2012, while the highest concentrations were observed in 2011.

- *Specific Conductance Profiles*. The specific conductance of Hansen Feeder Canal water is significantly less than that of the ambient Horsetooth Reservoir water during the late spring and summer and can therefore be used as a tracer of the interflow process. The specific conductance profiles at Inlet Bay Narrows, Spring Canyon, Dixon Canyon, and Soldier Canyon all showed the presence of a specific conductance minima in the metalimnion in all years. The unusually low specific conductivity observed in the metalimnion in 2011 compared to 2012 and 2013 illustrate the influence of varying water sources on Horsetooth Reservoir water quality

- *pH*. Horsetooth Reservoir water ranges between 6.5 and 8.5. Seasonal maximum values were higher in 2012 and ranged from 7.16 at Inlet Bay Marina to 8.56 at Soldier Canyon Dam

- *General Chemistry*. Alkalinity, hardness, and major ion concentrations monitored over the 2011, 2012, and 2013 monitoring periods were similar to the five year average and did not differ across monitoring locations. Total organic carbon concentrations were lower in 2011 to 2012 compared to other years Total dissolved solids concentrations appear to be decreasing since 2009, but concentrations were elevated in 2013. Turbidity was similar to the five year average.

- *Nutrients*. Nutrient concentrations in 2011 and 2013 followed expected seasonal patterns. The peak hypolimnetic PO_4 concentration in 2012 at Solider Canyon Dam was likely associated with depleted oxygen levels and the release of PO_4 from bottom sediments. A spike in fall NO_3 concentrations in 2013 may be associated with the September flooding event.

- *Metals*. Dissolved and total manganese concentrations in the hypolimnion at Spring Canyon Dam were unusually high in 2012 as a result of depleted hypolimnetic DO and the release of manganese from reservoir bottom sediments. This increase was not observed for iron concentrations which were similar in all years.

- *Reservoir Productivity*.

    - Phytoplankton. Chlorophytes (green algae) were the dominating algal group found in Horsetooth Reservoir during the spring and early summer months (April through June) in 2011 and 2013. This algal group was also identified in the 2012 spring season months, but only composed approximately 50% of the total phytoplankton, while the remaining 50% was primarily Cyanophytes (blue-green algae). In contrast to 2011 when Chlorophytes dominated through June, Chlorophytes were only observed until May in 2012. Geosmin producing species of blue green algae comprised a very small fraction of the total phytoplankton count in all years, generally one percent or less (down to zero) of the total density.

    - Chlorophyll-a. Mean annual chlorophyll-a concentrations for Horsetooth Reservoir fall into the mesotrophic range. However, there is a wide range of values, with May samples often approaching the oligotrophic range (chlorophyll-a < 1 µg/L) and summer and fall samples sometimes approaching the eutrophic range (chlorophyll-a > 7.3 µg/L). The November 2011 and October 2012 samples for Spring Canyon and Inlet Bay were in the eutrophic range. Chlorophyll-a reached a five year maximum in 2012 at Spring Canyon Dam likely as a result of exceptionally warm temperatures and drought conditions. Chlorophyll-a concentrations in 2013 were unusually low for Horsetooth Reservoir and suspected to be erroneous data.

    - Secchi Depth. Secchi depth was inversely correlated with chlorophyll-a concentrations during the 2011 and 2012 monitoring periods. This trend was particularly noticeable in 2011 when Secchi depth approached a five year minimum of 1 meter at Spring Canyon Dam corresponding to five year maximum chlorophyll-a concentrations. In general, Secchi depth ranged from 1.2 meters to 4.0 meters over the three year monitoring period (2011 to 2013).

- Trophic State. The tropic state of Horsetooth Reservoir over the three year period was generally mesotrophic for all TSI indices.

7.5 Hansen Feeder Canal Water quality

- Winter temperatures were just above freezing over the three year monitoring period, while maximum temperatures approached 22.0ºC.
- Minimum concentrations of DO were near 6.0 mg/L over the three year monitoring period while maximum concentrations approached 13.5 mg/L.
- Specific conductivity ranged between approximately 20 µS/cm and 80 µS/cm over the three year period until the September 2013 flood event. The flooding resulted in increased conductivity values greater than 100 µS/cm peaking at 150 µS/cm.
- pH values ranged between 7.0 and 9.0 over the three year period.
- Elevated pH values were observed throughout the monitoring period, but specifically following the September 2013 flooding and theses increased pH values correspond to increased concentrations of alkalinity.
- Turbidity values in the Hansen Feeder Canal were frequently below 10 NTU, but occasional spikes occurred likely as a result of increased canal flow and re-suspension of sediment located in the canal system. The September 2013 flood caused an increase in turbidity in the Hansen Feeder Canal.
- Alkalinity concentrations ranged between approximately 7 mg/L and 35 mg/L during the three year monitoring period. The seasonal response from snowmelt runoff in 2012 was not as pronounced as concentrations were higher than 2011 and 2013.
- Total dissolved solids ranged between approximately 15 mg/L and 60 mg/L during the three year monitoring period. Total dissolved solids concentrations decreased to a three year minimum in July of 2012, while the three year maximum was reached during flooding in September of 2013 when concentrations peaked to near 120 mg/L.
- Total organic carbon concentrations in Hansen Feeder Canal range from 3.0 mg/L to 4.0 mg/L. A seasonal increase was observed in all years caused by snowmelt runoff. The snowmelt response in 2012 was much less due to drought and low snowpack conditions. The 2013 flood event resulted in elevated TOC concentrations, but concentrations returned to near baseline conditions shortly after flood waters receded. A second, smaller peak occurred when flows out of Lake Esters resumed on November 4th. Average conditions returned in mid-December.
- Nutrients concentrations (NH_4, NO_2, NO_3, TKN, PO_4, and TP) did not show a strong seasonal signal during the three year monitoring period. Most nutrients fluctuated near detection limit, but occasional spikes were observed, which may be related to changes in the mix of contributing flows in the Hansen Feeder Canal.

7.6 Nutrient and Total Organic Carbon Mass Loading

- The highest TOC load, approximately 225 tons/month, was observed in June of 2011, which experienced higher than normal flows due to the historic snowfall of the 2010/2011 winter.
- The largest TOC loads over the 2009-2013 period occurred in October of 2012, with a contribution of approximately 125 tons.
- The unusually high TOC concentrations observed during the September 2013 flood did not translate to exceptionally large TOC loads due to the timely shut down of the canal flows into Horsetooth Reservoir at the onset of the flooding.
- The highest nutrient loadings to Horsetooth Reservoir typically occurred during spring and early summer, specifically, in May, June, and July. However, in 2012, the largest monthly nutrient loads occurred later in the fall rather than summer.

8.0 REFERENCES

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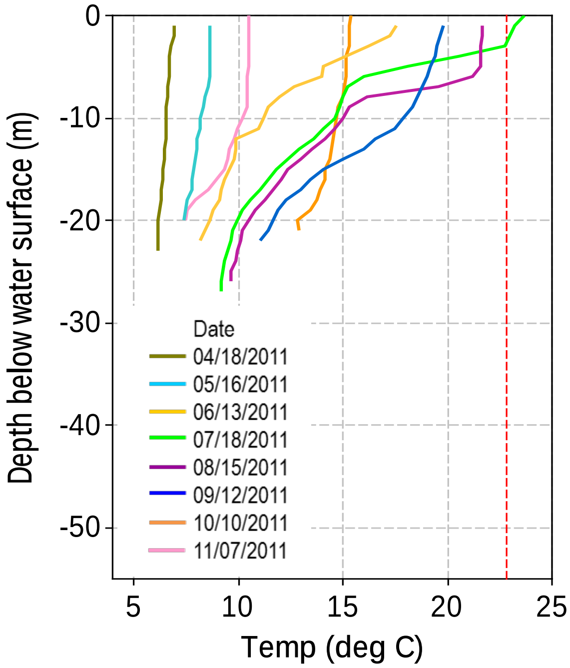
APPENDIX A: FCWQL Analytical methods, reporting limits, sample preservation, and holding time

			Limit	vation	Time
Micro-biological	Total Coliform, *E.coli* - QT	SM 9223 B	0	cool, 4C	6 hrs
	Giardia & Cryptosporidium (CH Diagnostics)	EPA 1623	0	cool, 4C	4 days
	Algae I.D. (Phyto Finders)	SM 10200E.3, SM 10200F.2c1		Lugol's Solution, cool, 4C	12 mo
General & Misc.	Alkalinity, as $CaCO_3$	SM 2320 B	2 mg/L	cool, 4C	14 days
	Chlorophyll a	SM10200H modified	0.6 ug/L	cool, 4C	48 hrs
	Hardness, as $CaCO_3$	SM 2340 C	2 mg/L	none	28 days
	Specific Conductance	SM 2510 B		cool, 4C	28 days
	Total Dissolved Solids	SM 2540 C	10 mg/L	cool, 4C	7 days
	Turbidity (NTU)	SM2130B,EPA180.1	0.01 units	cool, 4C	48 hrs
Nutrients	Ammonia - N	Lachat 10-107-06-2C	0.01 mg/L	H_2SO_4	28 days
	Nitrate	EPA 300 (IC)	0.04 mg/L	cool, 4C (eda)	48 hrs
	Nitrite	EPA 300 (IC)	0.04 mg/L	cool, 4C (eda)	48 hrs
	Total Kjeldahl Nitrogen	EPA 351.2	0.1 mg/L	H_2SO_4 pH<2	28 days
	Phosphorus, Total	SM 4500-P B5,F	0.01 mg/L	H_2SO_4 pH<2	28 days
	Phosphorus, Ortho	SM 4500-P B1,F	0.005 mg/L	filter, cool 4C	48 hrs
Major Ions	Calcium	EPA 200.8	0.05 mg/L	HNO_3 pH <2	6 mos
	Chloride	EPA 300 (IC)	1.0 mg/L	none (eda)	28 days
	Magnesium, flame	EPA 200.8	0.2 mg/L	HNO_3 pH <2	6 mos
	Potassium	EPA 200.8	0.2 mg/L	HNO_3 pH <2	6 mos
	Sodium, flame	EPA 200.8	0.4 mg/L	HNO_3 pH <2	6 mos
	Sulfate	EPA 300 (IC)	5.0 mg/L	cool, 4C (eda)	28 days
Metals	Cadmium	EPA 200.8	0.1 ug/L	HNO_3 pH <2	6 mos
	Chromium	EPA 200.8	0.5 ug/L	HNO_3 pH <2	6 mos
	Copper	EPA 200.8	3 ug/L	HNO_3 pH <2	6 mos
	Iron, (total & dissolved)	EPA 200.8	10 ug/L	HNO_3 pH <2	6 mos
	Lead	EPA 200.8	1 ug/L	HNO_3 pH <2	6 mos
	Nickel	EPA 200.8	2 ug/L	HNO_3 pH <2	6 mos
	Silver	EPA 200.8	0.5 ug/L	HNO_3 pH <2	6 mos
	Zinc	EPA 200.8	50 ug/L	HNO_3 pH <2	6 mos
TOC	TOC	SM 5310 C	0.5 mg/L	H_3PO_4 pH <2	28 days
Analysis conducted by City of Fort Collins Water Quality Lab (FCWQL), unless otherwise noted.					
Reporting Limit = lowest reportable number based on the lowest calibration standard routinely used.					

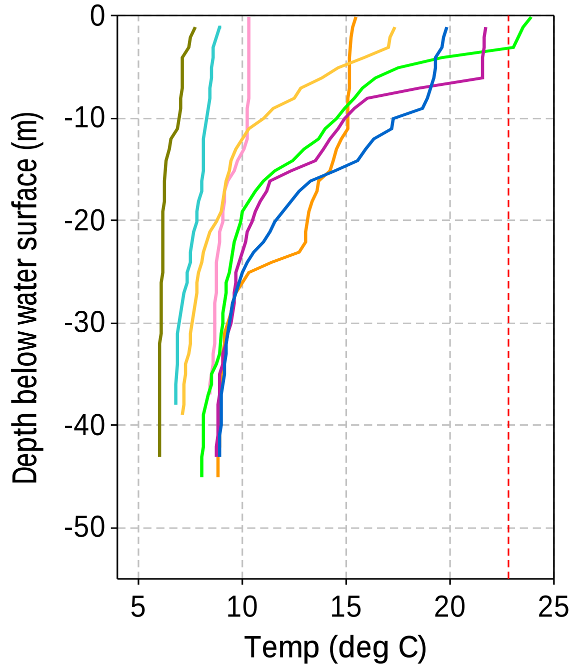
APPENDIX B: Reservoir Profiles

Horsetooth Reservoir Temperature Profiles (2011-2013)

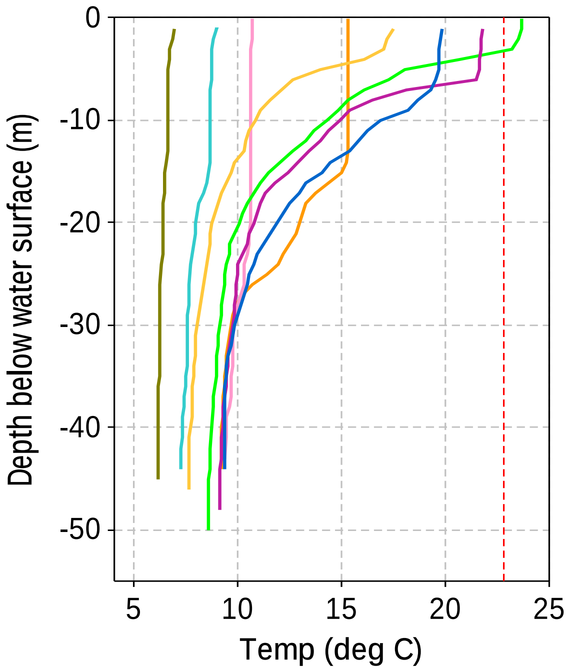
R20



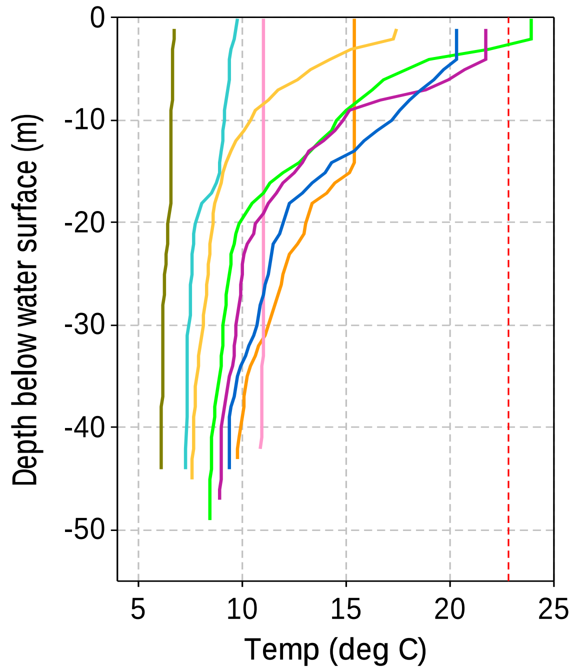
R21



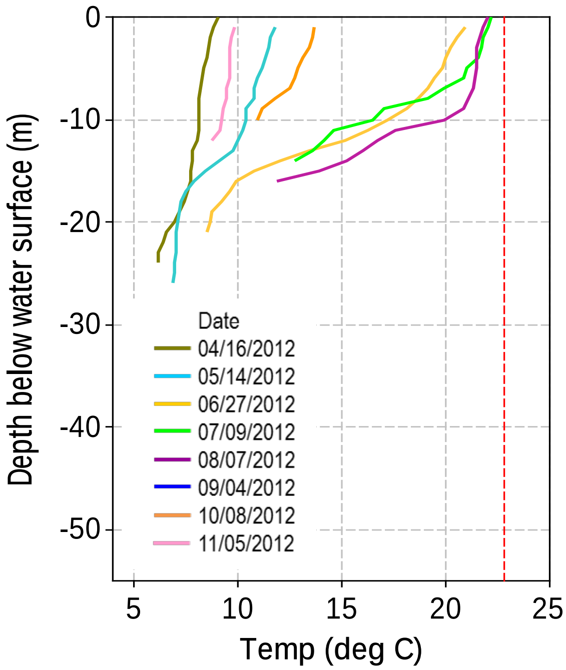
R30



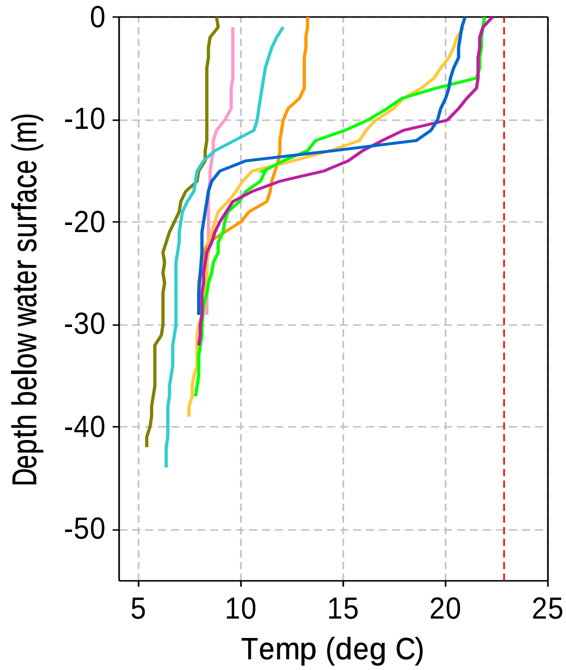
R40



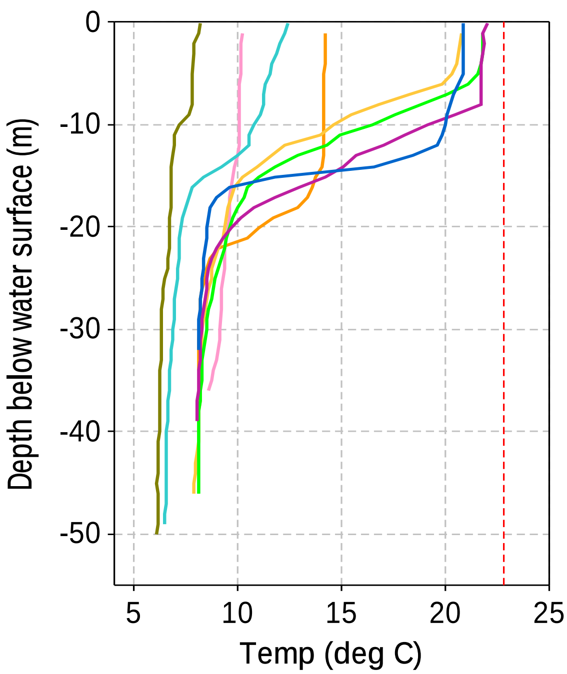
R20



R21



R30



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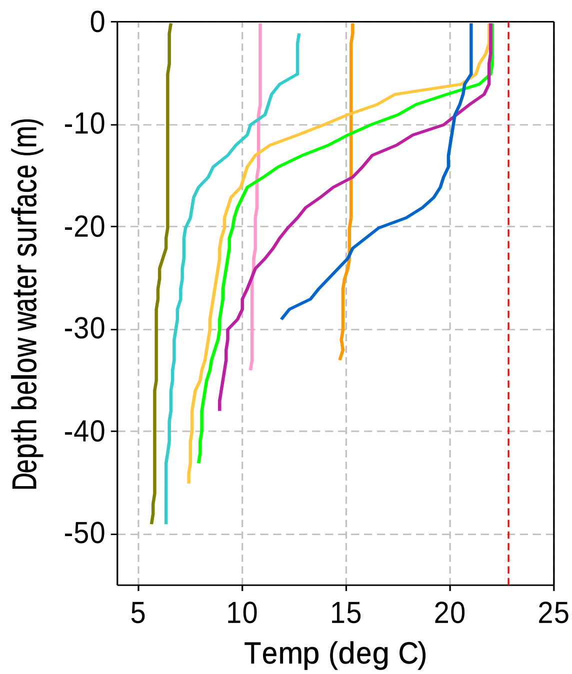
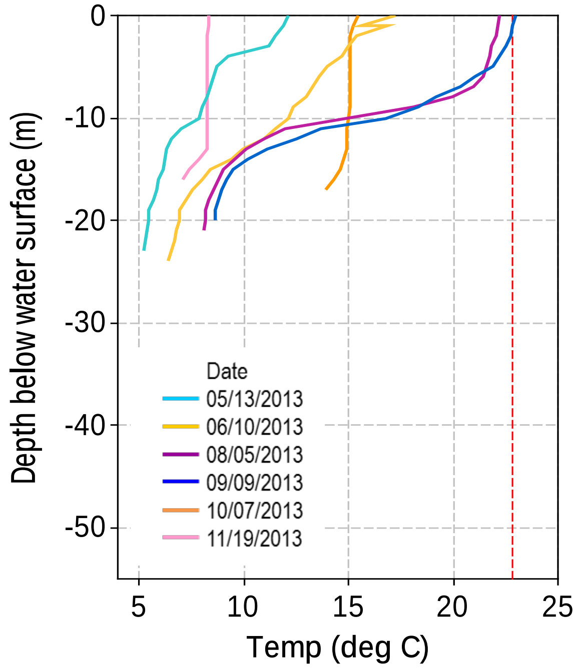


R20



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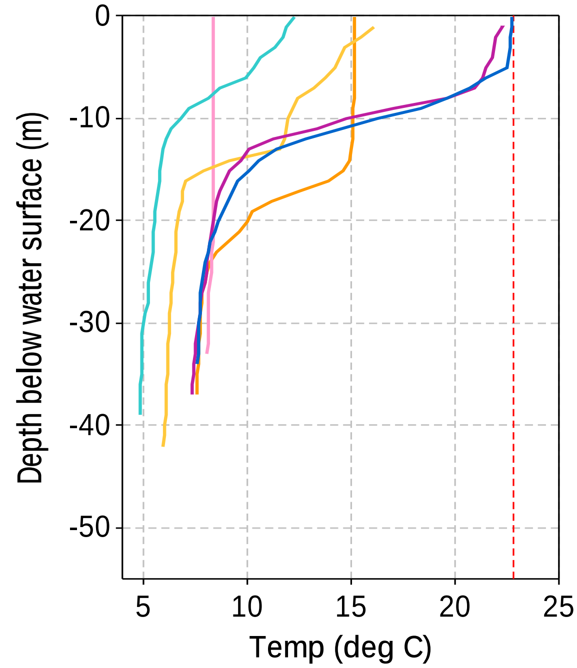

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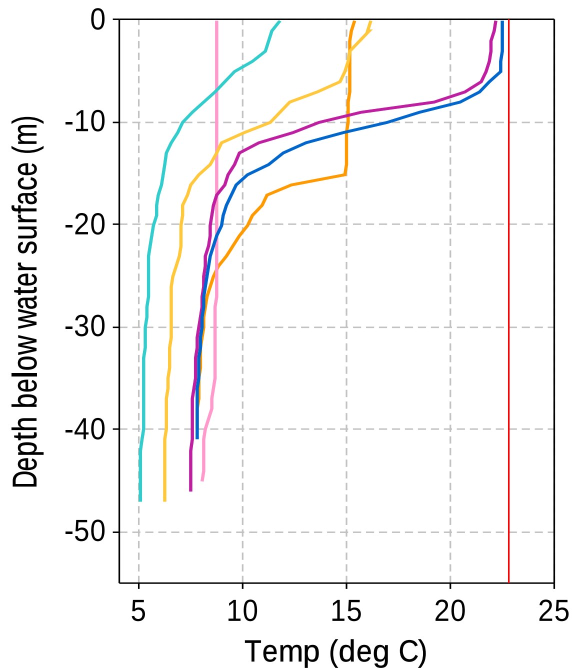

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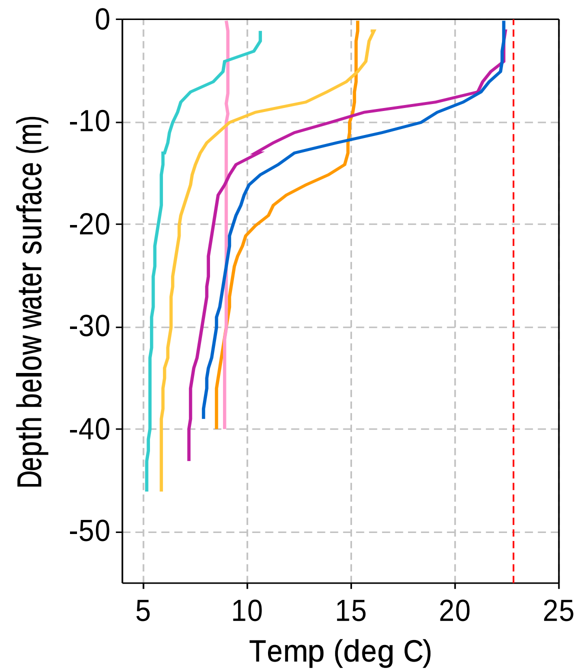
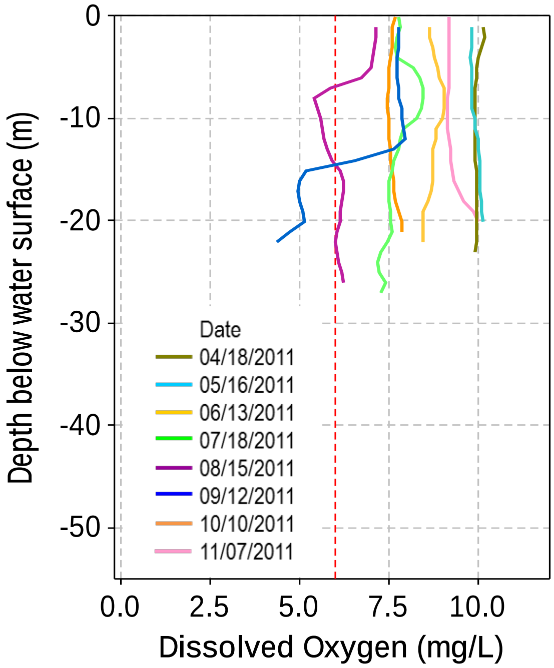
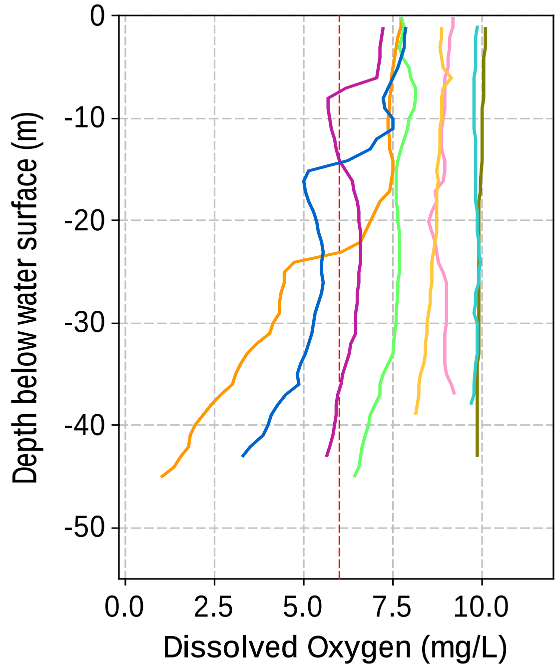


HORSETOOTH RESERVOIR DISSOLVED OXYGEN PROFILES (2011-2013)

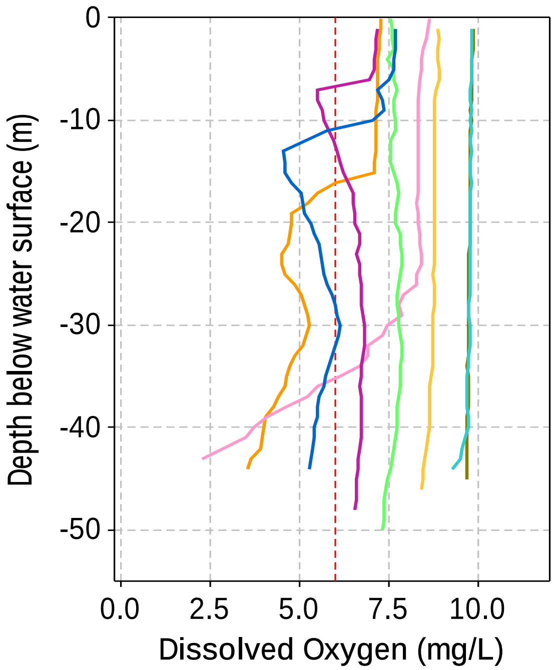
R20



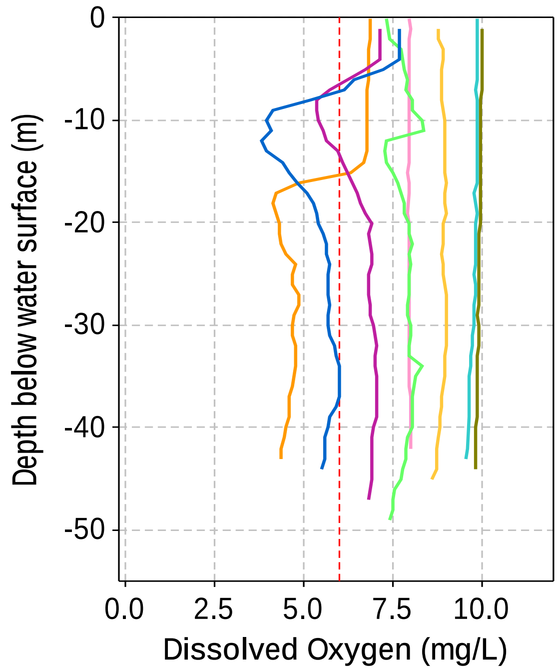
R21

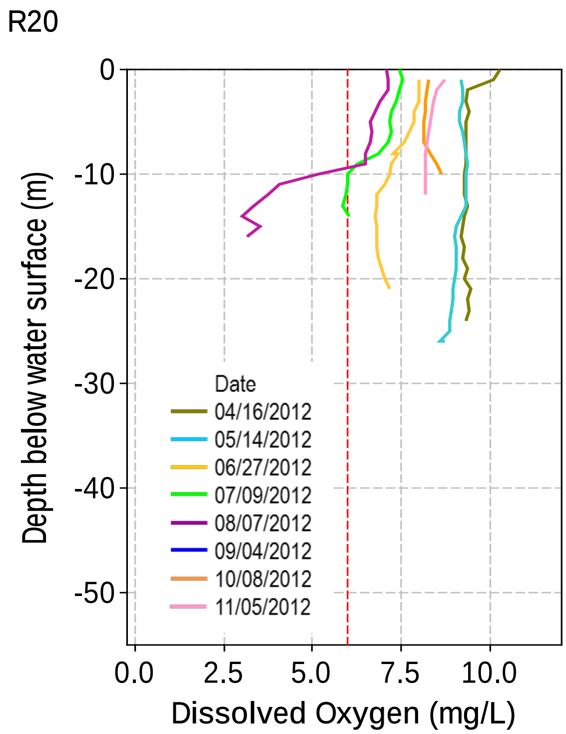


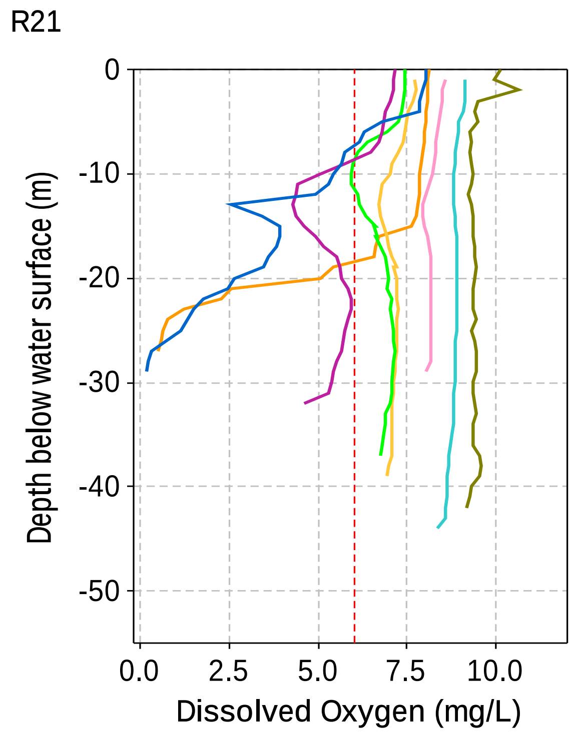
R30

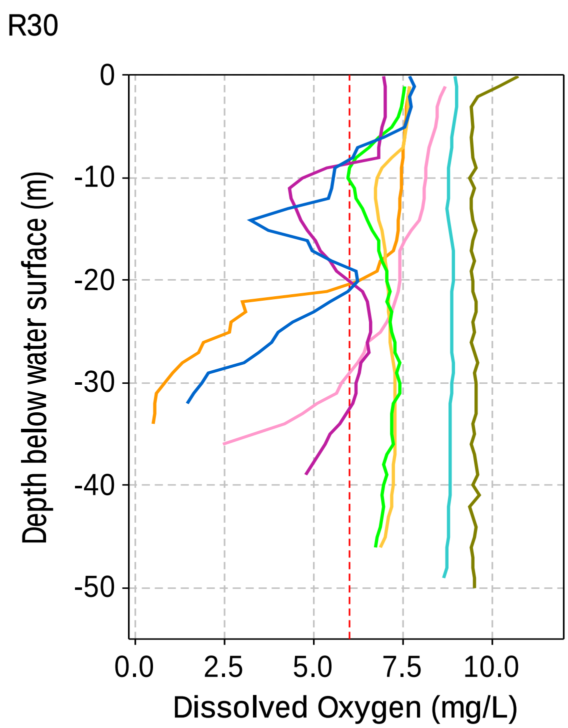


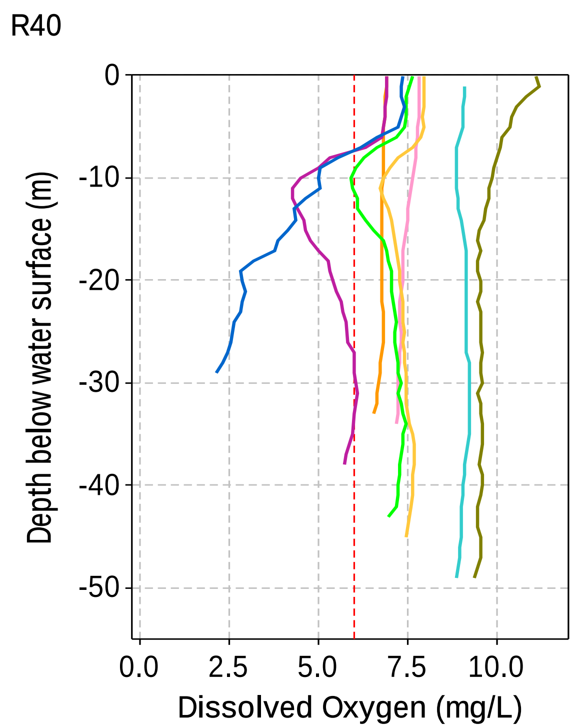
R40



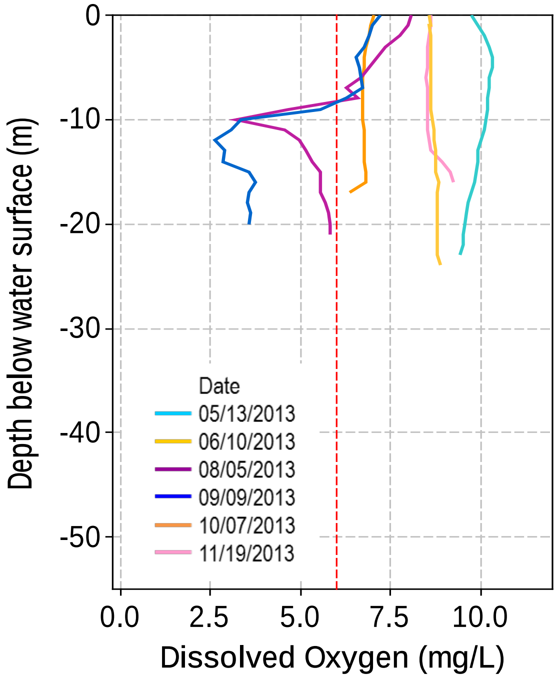

R20
Depth below water surface (m)
0
-10
-20
-30
-40
-50
0.0
2.5
5.0
7.5
10.0
Dissolved Oxygen (mg/L)
Date
04/16/2012
05/14/2012
06/27/2012
07/09/2012
08/07/2012
09/04/2012
10/08/2012
11/05/2012


R21
Depth below water surface (m)
0
-10
-20
-30
-40
-50
0.0
2.5
5.0
7.5
10.0
Dissolved Oxygen (mg/L)


R30
Depth below water surface (m)
0
-10
-20
-30
-40
-50
0.0
2.5
5.0
7.5
10.0
Dissolved Oxygen (mg/L)


R40
Depth below water surface (m)
0
-10
-20
-30
-40
-50
0.0
2.5
5.0
7.5
10.0
Dissolved Oxygen (mg/L)

R20



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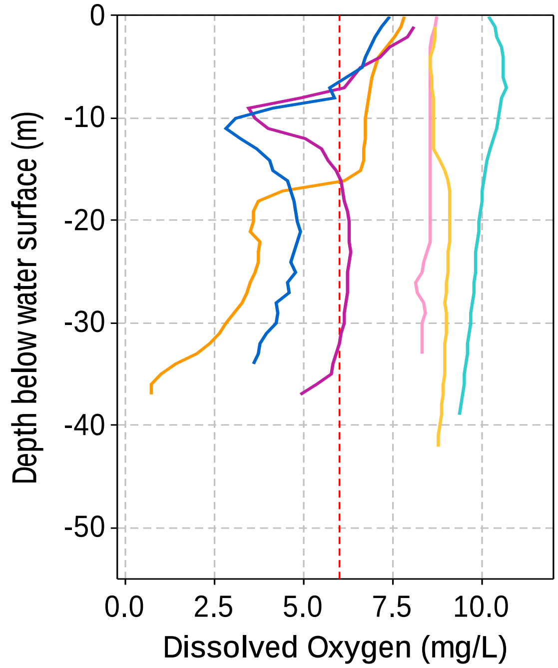

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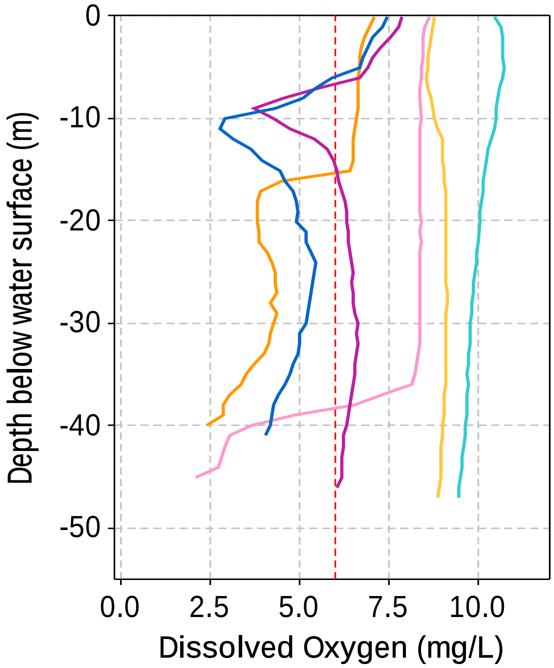

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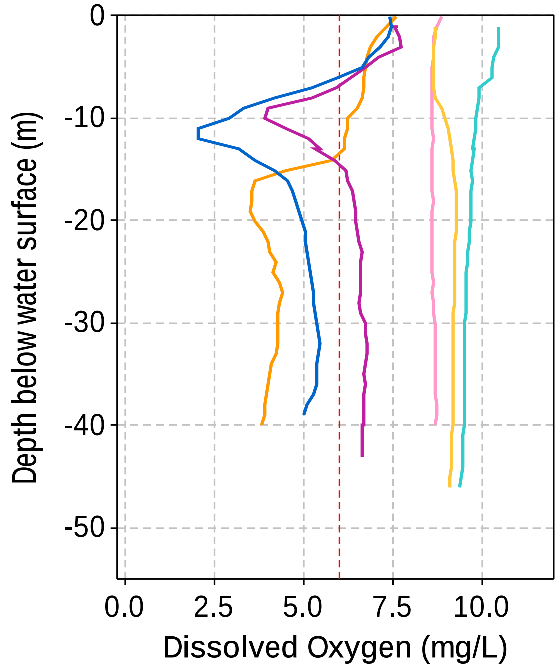
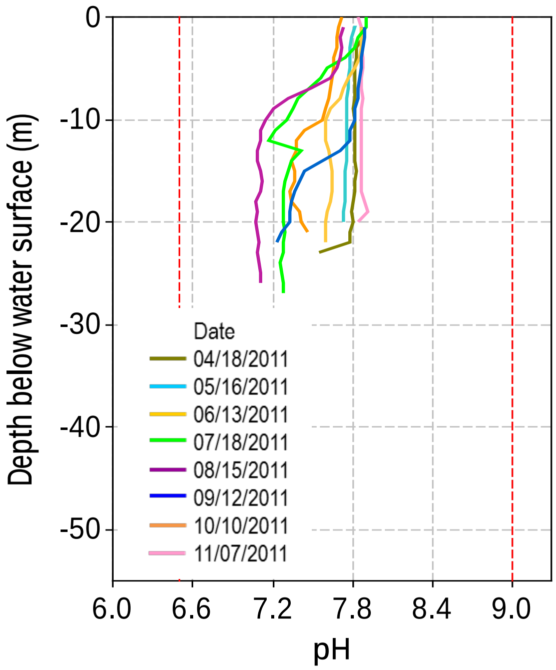


Horsetooth Reservoir pH Profiles (2011-2013)

R20



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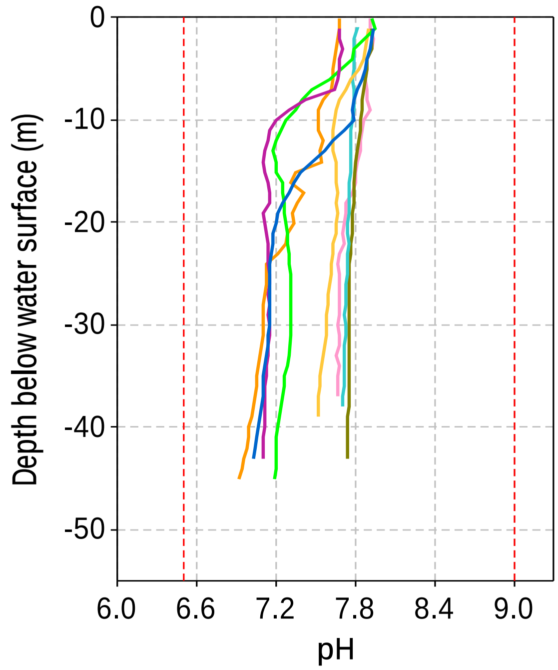

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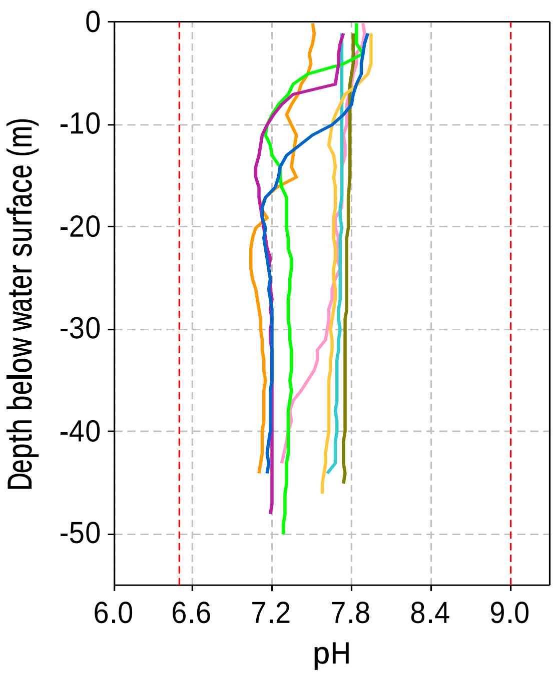

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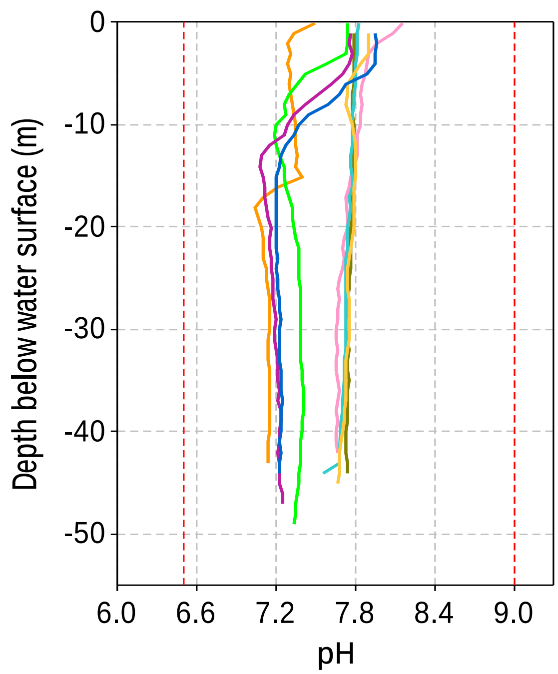
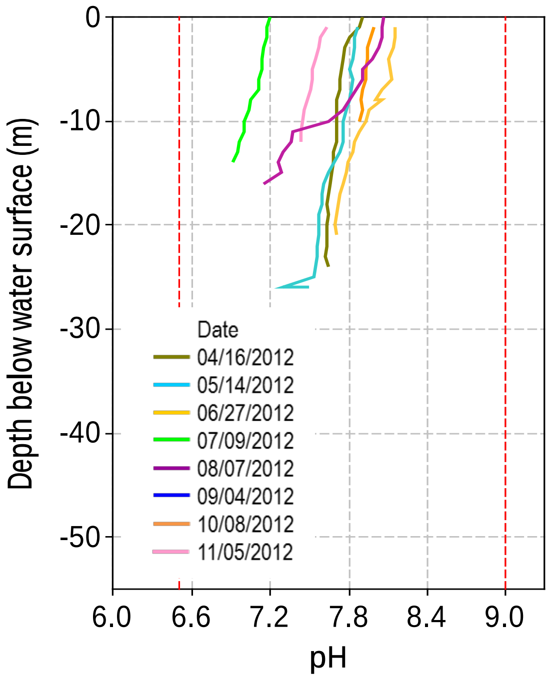


R20



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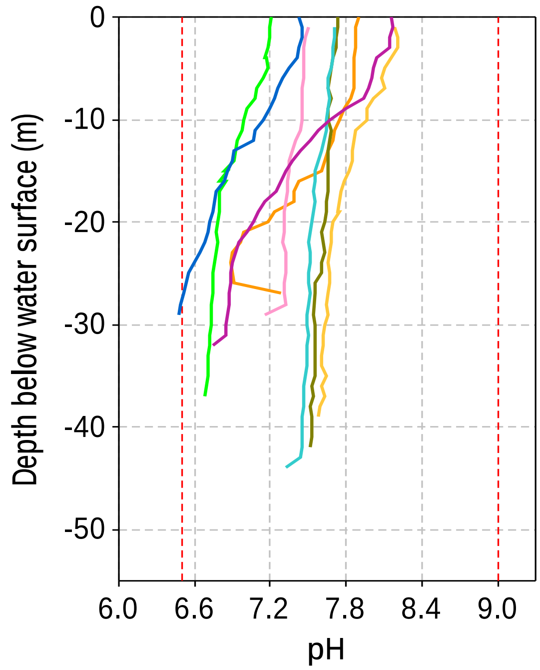

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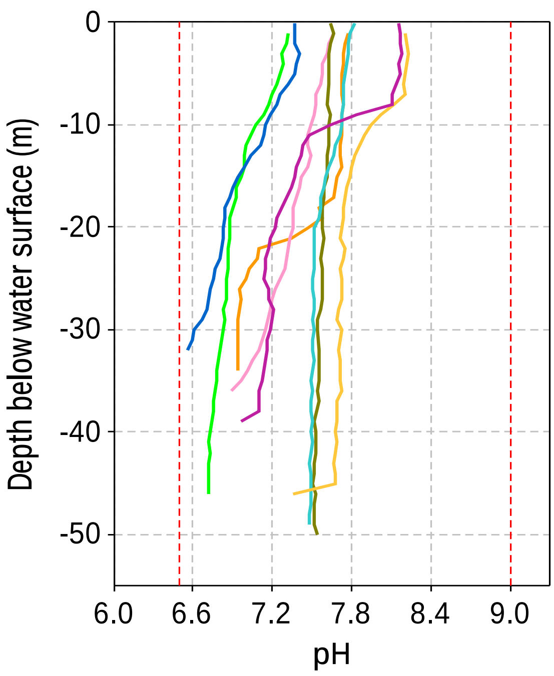

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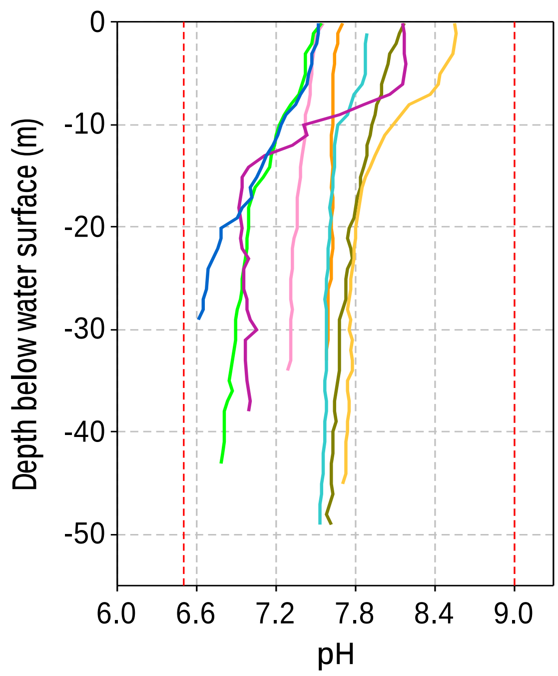

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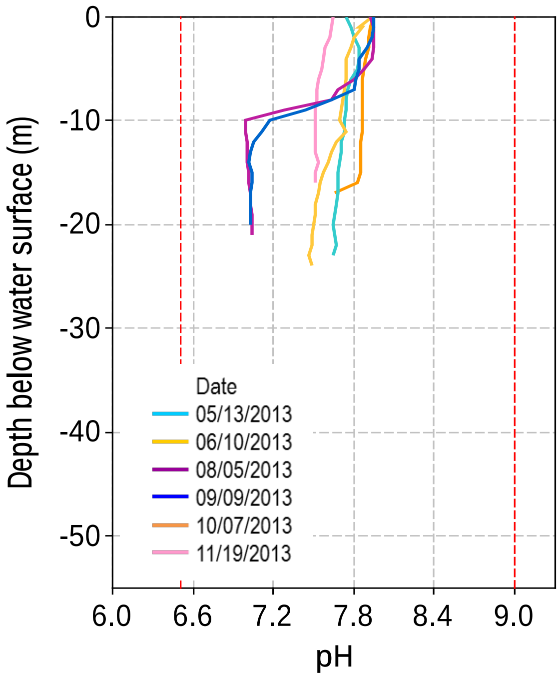

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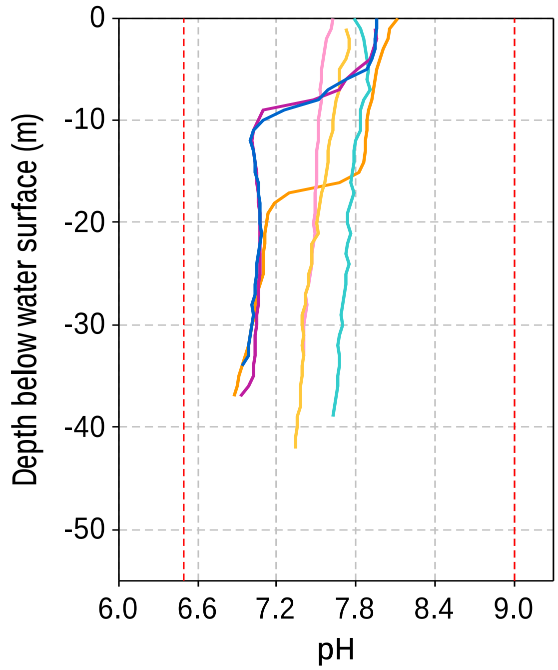
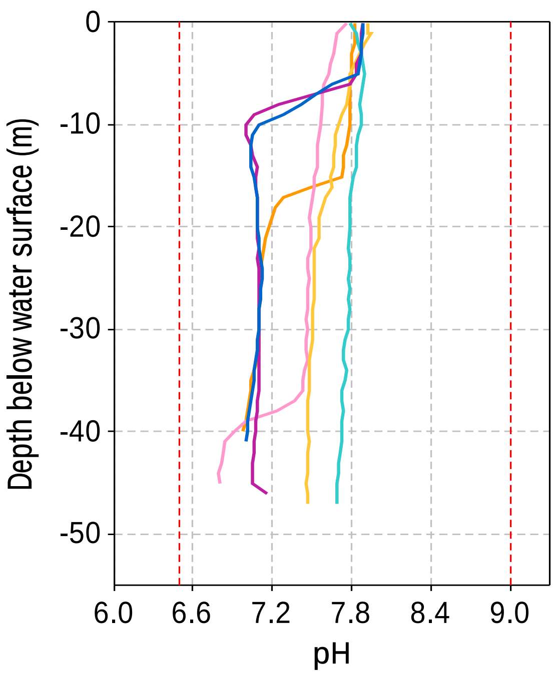


R30



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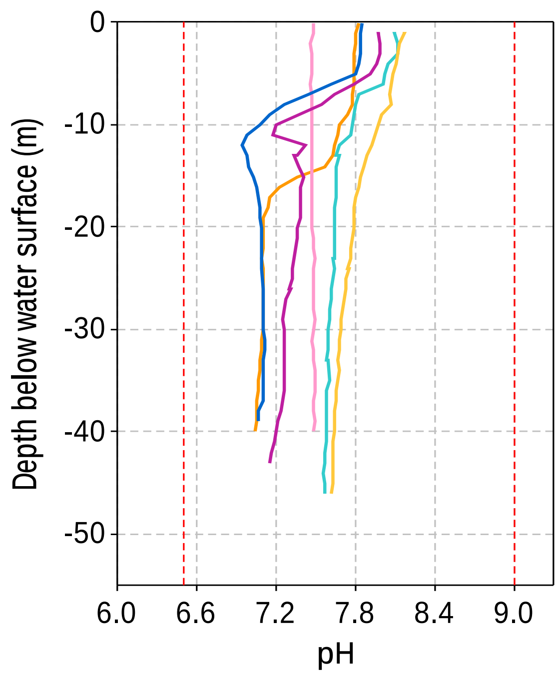
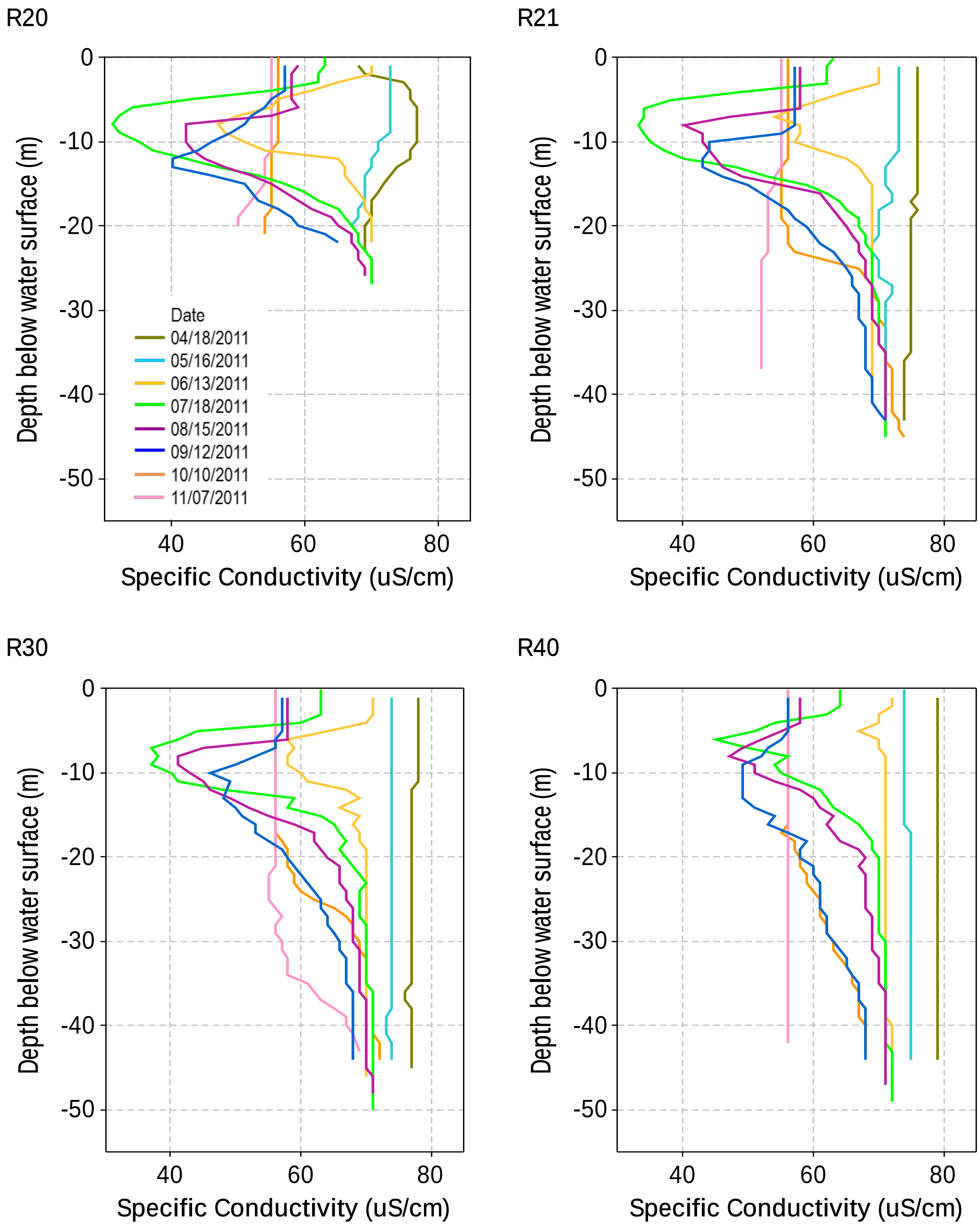
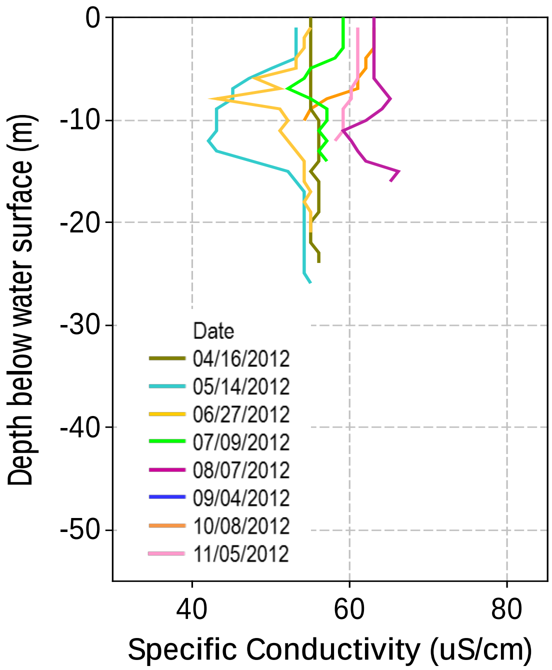


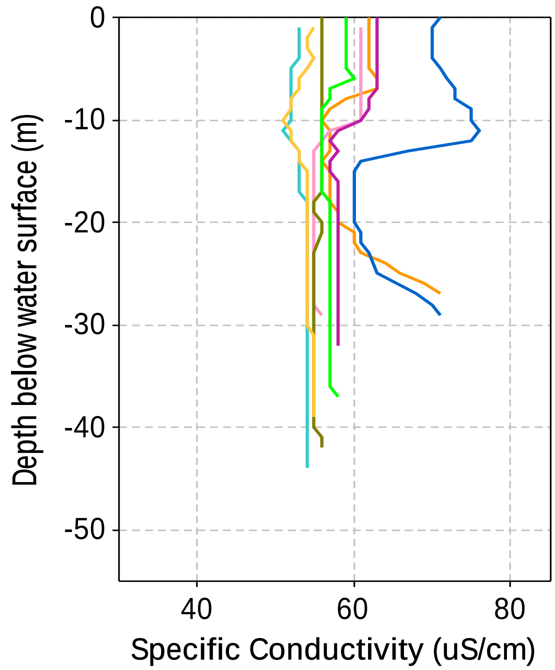
HORSETOOTH RESERVOIR SPECIFIC CONDUCTANCE PROFILES (2011-2013)



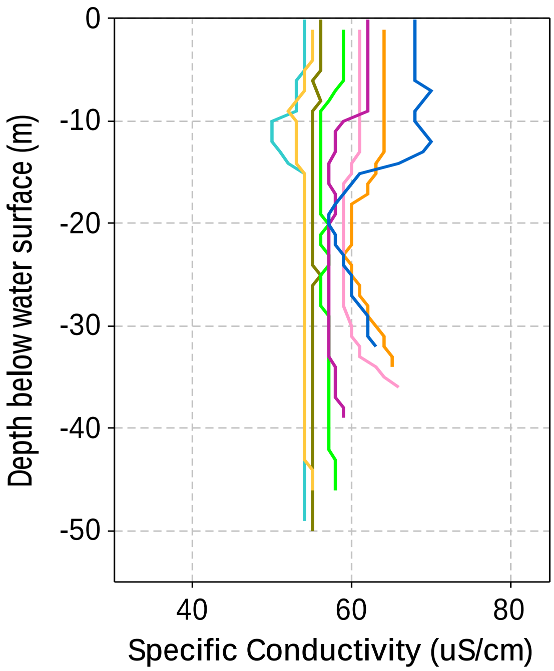
R20



R21



R30



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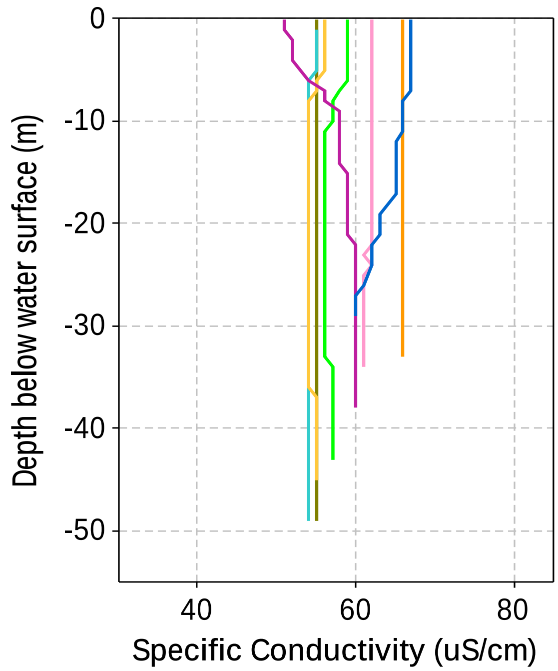
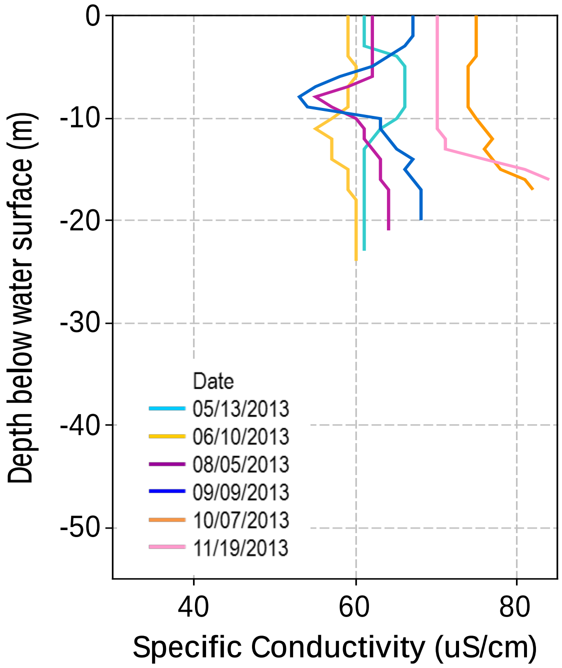
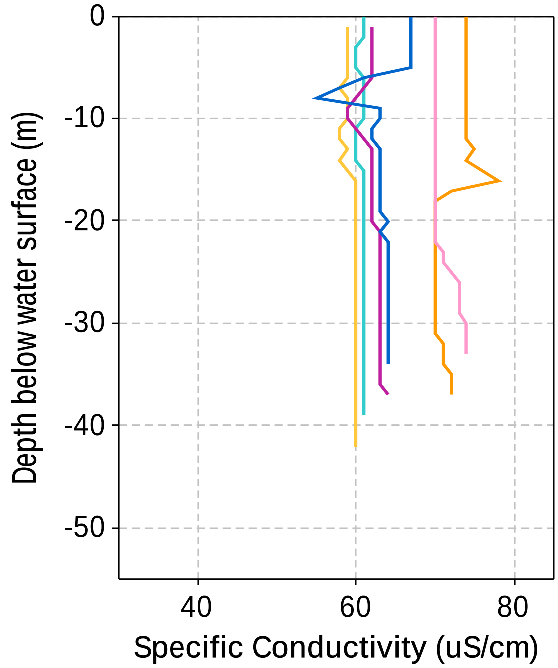


R20



R21



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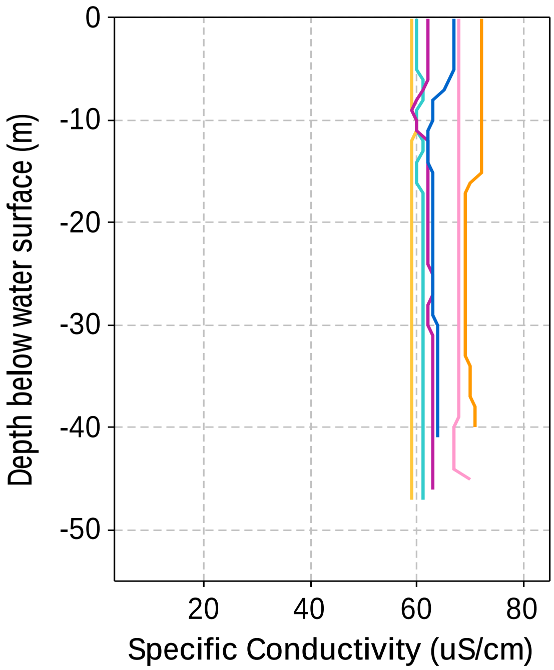

R40