City of Fort Collins Utilities

2010 Horsetooth Reservoir Water Quality Monitoring Program Report

City of Fort Collins
Water Resources
& Treatment Services

Prepared by:

Judy Billica, P.E., Ph.D., Senior Process Engineer
Jill Oropeza, Watershed Specialist

August 2, 2011

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 2010 Horsetooth Reservoir Water Quality Monitoring Program Report (2010 Report) documents data and information collected and assessed by FCU during the period of 2005 through 2010 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. The 2010 Report includes information and data on regulatory issues, issues of concern, reservoir hydrology, Hansen Feeder Canal water quality and mass loads, Horsetooth Reservoir water quality, and relevant special studies.

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 2010 included seven routine sampling events.

Review of data for the 2010 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 2010 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 2010 dissolved oxygen profiles show depletion in both the metalimnion (middle depth of the reservoir) and hypolimnion (bottom depths) as the season progresses.

The most significant Horsetooth Reservoir water quality finding for 2010 was the increase in total organic carbon (TOC) concentrations within the reservoir and at the Fort Collins Water Treatment Facility (FCWTF). This increase was due to the large TOC load that was delivered via the Hansen Feeder Canal during the 2010 spring runoff period. The TOC of raw Horsetooth Reservoir water at the FCWTF peaked on October 12, 2010 at 4.2 mg/L. Concentrations at the FCWTF then began decreasing, but at the end of 2010 they were still significantly above the five-year (2005 to 2009) average TOC concentration of 3.2 mg/L.

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 Project. FCU is collaborating with other entities on special studies that include: characterizing the naturally occurring TOC in Horsetooth Reservoir and upstream waters, and the relationship of this TOC to the formation of disinfection byproducts at the Fort Collins Water Treatment Facility; determining the presence of contaminants of emerging concern (including pharmaceuticals and personal care products); conducting hydrodynamic water quality modeling of Horsetooth Reservoir; and watershed wildfire assessments.

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 2010 M&E List for low dissolved oxygen 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 is currently working on the development of nutrient standards (including total phosphorus, total nitrogen, and chlorophyll-a) that would apply to Horsetooth Reservoir.

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

- Low dissolved oxygen concentrations in the metalimnion and hypolimnion.
- Recurring episodes of the taste and odor compound geosmin.
- Changes in TOC concentrations or characteristics that may increase the formation of disinfection byproducts during water treatment.
- Potential impacts from proposed water supply projects.
- Watershed impacts related to bark beetles, including the increased risk of high severity wildfires.
- Potential for the spread of invasive mussels to Horsetooth Reservoir.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF ABBREVIATIONS & ACRONYMS

#/100 mL	number per 100 milliliters
%	percent
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
cysts/L	cysts per liter
D.O.	Dissolved Oxygen
DBP	Disinfection By-Product
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
EDC	Endocrine Disrupting Chemical
EEM	Excitation and Emission Matrix
EPA	Environmental Protection Agency
FCU	Fort Collins Utilities
FCWQL	Fort Collins Water Quality Lab
FCWTF	Fort Collins Water Treatment Facility
HAA5	Haloacetic Acid
HAA5FP	Haloacetic Acid Formation Potential
kDa	kiloDalton
L/mg-m	Liter per milligram meter (units for SUVA)
LC/MS-MS	Liquid Chromatography with Tandem Mass Spectrometry
LC/TOF-MS	Liquid Chromatography – Time of Flight – Mass Spectrometry
m	meter
M&E List	Colorado’s Monitoring & Evaluation List
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
MPB	Mountain Pine Beetle
ng/L	nanograms per liter (equivalent to parts per trillion)

NH_4	Ammonia
nm	nanometers
NO_2	Nitrite
NO_3	Nitrate
NTU	Nephelometric Turbidity Units
^{o}C	degrees Celsius
PARAFAC	Parallel Factor Analysis
PCP	Personal Care Product
PO_4^{-3}	Ortho-phosphate
ppt	parts per trillion
PRAM	Polarity Rapid Assessment Method
PWSR	Protected Water Supply Reservoir
SCFP	Soldier Canyon Filter Plant (Tri-Districts)
SHAA5FP	Specific Haloacetic Acid Formation Potential (HAA5FP/DOC)
STTHMFP	Specific Total Trihalomethane Formation Potential (TTHMFP/DOC)
SUVA	Specific UV Absorbance (UV_{254}/DOC)
T&O	Taste & Odor
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen (calculated from TKN + nitrate + nitrite)
TOC	Total Organic Carbon
TP	Total Phosphorus
TSI	Trophic State Index
TTHM	Total Trihalomethane
TTHMFP	Total Trihalomethane Formation Potential
UCLA	University of California at Los Angeles
ug/L	micrograms per liter
UL	Underwriters Laboratories
uS/cm	microSeimens per centimeter
USFS	United States Forest Service
USGS	United States Geological Survey
UV_{254}	Ultraviolet absorbance at 254 nm
WQCD	Water Quality Control Division
WTP	Water Treatment Plant

1.0 BACKGROUND

1.1 Monitoring Program Goals and Scope of the 2010 Report

The 2010 Report summarizes Horsetooth Reservoir and Hansen Feeder Canal water quality data collected and assessed by the Fort Collins Utilities (FCU) in 2010 and provides a comparison with water quality data collected during the preceding five year period of 2005-2009. Relevant hydrologic data collected during this time period are also summarized and estimates of annual Reservoir hydraulic residence time are made. Hansen Feeder Canal flows are used with weekly measurements of total organic carbon to calculate loads to Horsetooth Reservoir. Finally, this report provides a summary of special projects, regulatory issues, and issues of concern related to Horsetooth Reservoir water quality. The 2010 Report is the second annual report produced by the FCU and, together with the 2009 Report (Billica and Oropeza, 2010) and the initial Horsetooth Reservoir Monitoring Program document (Billica and Oropeza, 2009), they 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 a source water for the City of Fort Collins Water Treatment Facility (FCWTF). The Tri-Districts Soldier Canyon Filter Plant (SCFP) 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 the 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 drinking water sources. The program should provide data to:

- 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 should provide 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 (CDPH&E) for surface waters used as drinking water supplies

- Detect changes in water quality due to land use activities in the watershed to support watershed protection efforts
- Assess the health (trophic state) of Horsetooth Reservoir on a seasonal and annual basis

Some of the important Horsetooth Reservoir water quality issues that have directly impacted the FCU over the years include low dissolved oxygen levels and associated high dissolved manganese concentrations at the bottom of the reservoir; increasing concentrations of total organic carbon; and recurring episodes of geosmin, a taste and odor 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 Colorado Water Conservancy District (NCWCD; also referred to as Northern Water). Water quality monitoring of the Big Thompson River and components of the Colorado-Big Thompson Project upstream of Horsetooth Reservoir (including the Hansen Feeder Canal) is currently being conducted by the Big Thompson Watershed Forum, the U.S. Geological Survey, and Northern Water (see http://www.btwatershed.org and http://www.ncwcd.org). This report only summarizes, assesses, and presents water quality data collected by FCU.

1.2 Watershed Description

Horsetooth Reservoir is located directly west of the City of Fort Collins, Colorado. The reservoir was formed by the construction of Horsetooth, Soldier Canyon, Dixon Canyon and Spring Canyon dams by the U.S. Bureau of Reclamation (USBR) and is part of the USBR's Colorado-Big Thompson (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 the NCWCD.

The water in Horsetooth Reservoir 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 and Table 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 for the system. 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 Colorado-Big Thompson (CBT) Project, Windy Gap Project, and Horsetooth Reservoir.

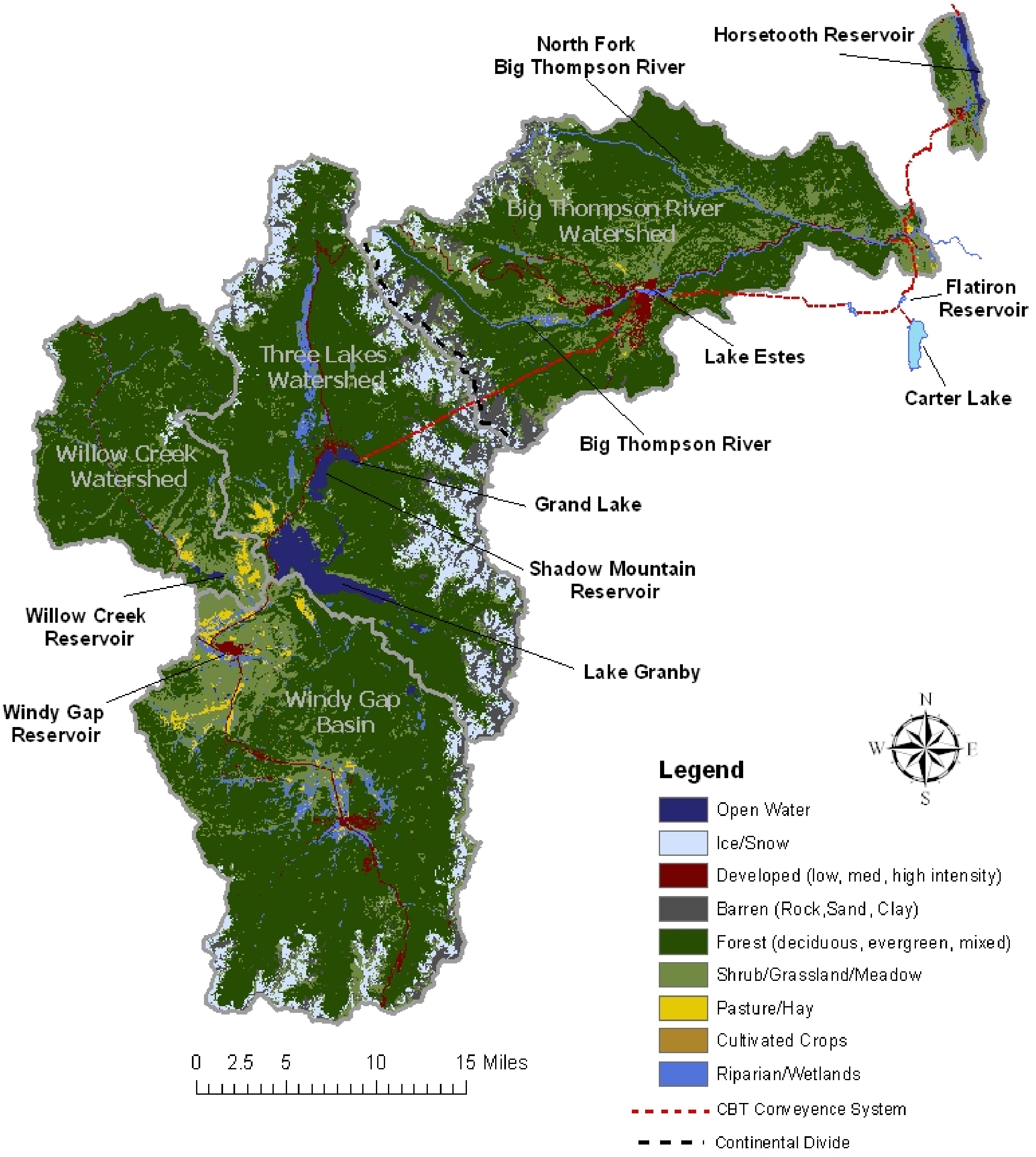


Table. 1-1. Land use/land cover types for the major watersheds associated with Horsetooth Reservoir.

Land Cover Type	Three Lakes Watershed		Willow Creek Watershed		Windy Gap Watershed		Big Thompson River Watershed upstream of Dille Tunnel		Horsetooth Reservoir Local Watershed		Combined Watershed Area	
	sq miles	%	sq miles	%	sq miles	%	sq miles	%	sq miles	%	sq miles	%
Open Water	14.4	4.6%	0.5	0.4%	0.5	0.2%	0.8	0.3%	1.6	9.4%	17.8	1.6%
Perennial Ice/Snow	43.2	13.8%	1.4	1.0%	15.9	4.9%	13.4	4.3%	--	0.0%	73.9	6.7%
Barren Land (rock/sand/clay)	31.3	10.0%	0.6	0.4%	10.6	3.3%	21.2	6.7%	--	0.0%	63.7	5.7%
Developed (low, med, high intensity)	2.9	0.9%	0.7	0.5%	6.4	2.0%	8.9	2.8%	0.6	3.5%	19.5	1.8 %
Forest (deciduous, evergreen, mixed)	185.6	59.5%	114.9	81.1%	212.5	65.3%	201.9	64.3%	4.6	26.9%	719.5	64.8%
Shrub/Grassland/Meadow	26.5	8.5%	18.8	13.3%	60.6	18.6%	63.6	20.2%	9.1	53.2%	178.6	16.1%
Pasture/Hay	1.4	0.4%	2.2	1.6%	5.9	1.8%	1.1	0.35%	0.01	0.06%	10.6	0.96%
Cultivated Crops	--	0.0%	--	0.0%	--	0.0%	0.1	0.03%	--	0.0%	0.1	0.01%
Riparian/Wetlands	6.7	2.2%	2.4	1.7%	12.9	4.0%	3.1	1.0%	1.2	7.0%	26.3	2.4%
Total Watershed Area	312.0		141.5		325.3		314.1		17.1		1,110.0	

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, 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 for the Big Thompson River upstream of the Dille Tunnel (Figure 1-1) includes sub-drainages of the main stem 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 Table (1-1). 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." 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. Horsetooth Reservoir is a terminal reservoir of the CBT Project. 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 1-2. Horsetooth Reservoir water is also sampled at the Fort Collins Water Treatment Facility (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 1-2. 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

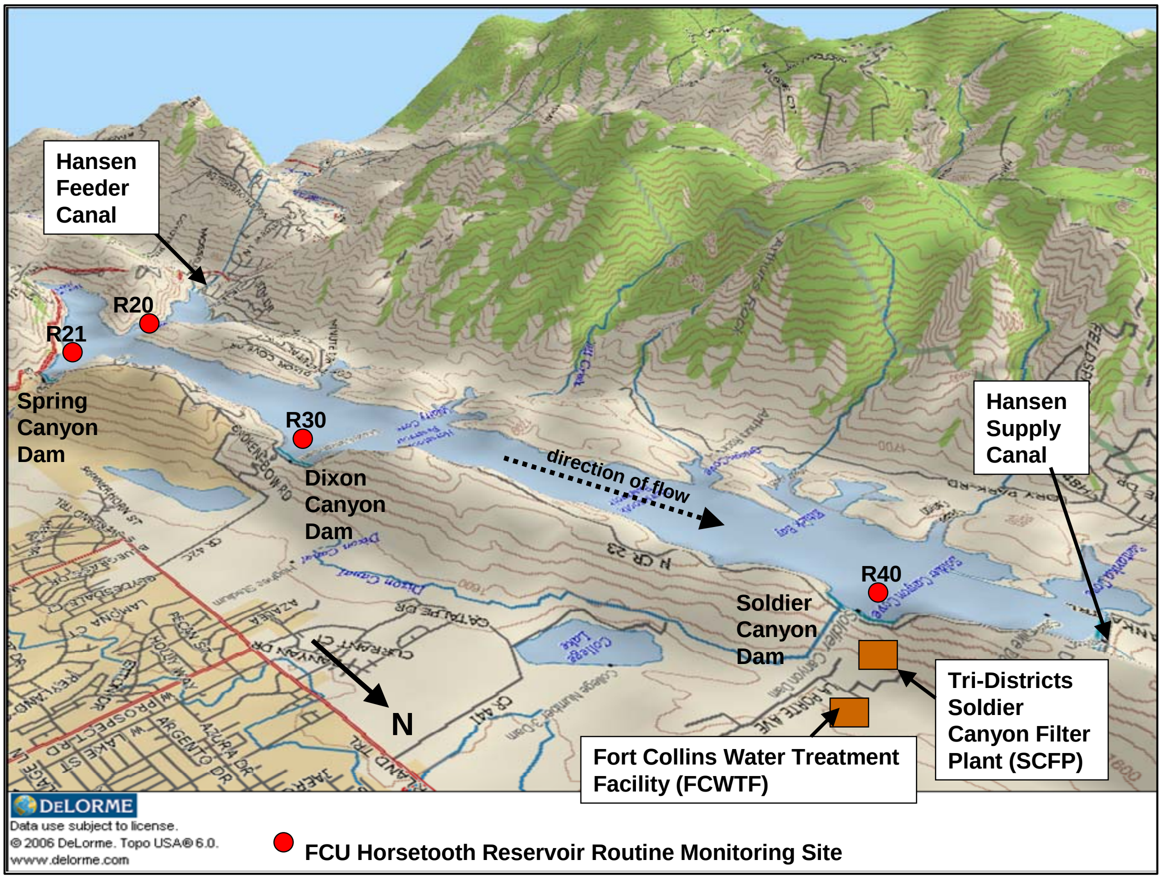


Figure 1-2. FCU Horsetooth Reservoir routine water quality monitoring sites.

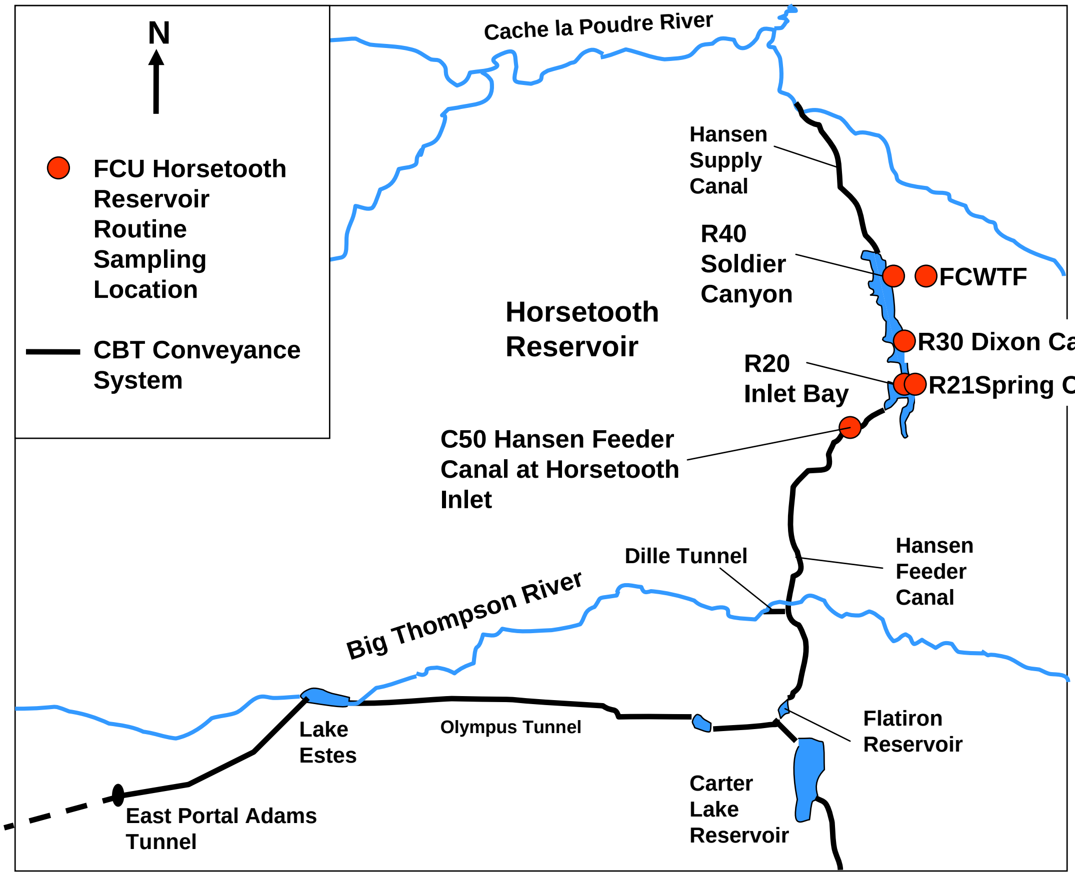


Figure 1-3. Overview map of FCU Horsetooth Reservoir routine water quality monitoring sites.

1.4 Sampling Frequency and Parameters

In 2010, there were seven routine Horsetooth Reservoir sampling events: April 19, May 17, June 14, August 9, September 13, October 11, and November 15. There were also five special sampling events at the Soldier Canyon Dam site (June 3, July 8, July 20, Aug 23, and Sept 27) associated with the Colorado Water Quality Control Division (WQCD) High Quality Water Supply Study described in Section 2.3.

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 for the Hansen Feeder Canal and Horsetooth Reservoir sites are outlined on Table 1-3. The frequency of analysis for the various parameters is indicated on this table. Those parameters shown with an “x” are analyzed during every routine sampling event. All analyses are conducted by the City of Fort Collins Water Quality Laboratory (FCWQL) except for phytoplankton identification and enumeration which is conducted by Mr. Richard Dufford (private consultant). The analytical methods, reporting limits, sample preservation, and sample holding times are outlined on Table 1-4.

Note that for the FCWQL, the “Reporting Limit” shown on Table 1-2 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 (EPA, 2003, slide 100). 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.

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)	2/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. 2009 Horsetooth Reservoir Routine Monitoring Parameters (continued).

	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
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										

Table 1-4. Analytical methods, reporting limits, sample preservation, and sample holding times (all analysis conducted by the FCWQL except phytoplankton).

	Parameter	Method	Reporting Limit	Units	Preservation	Holding Time
General & Misc.	Alkalinity, as $CaCO_3$	SM 2320 B	2	mg/L	none	14 days
	Color	SM 2120 B	2.5	Pt/Co	cool, 4C	48 hrs
	Geosmin	SM6040D, SPME/GC/MS		ng/L	cool, 4C	
	Hardness, as CaCO3	Lachat 10-301-31-1-A	2.5	mg/L	HNO_3 pH <2	28 days
	pH	SM 4500-H B	2.0 - 12.0	units	none	0.25hr
	Specific Conductance	SM 2510 B		µmhos/cm	none	28 days
	Temperature	SM 2500 A, B		°C	none	0.25 hr
	Total Dissolved Solids	SM 2540 C	10	mg/L	cool, 4C	7 days
	TOC	SM 5310 C	0.5	mg/L	HCl pH <2	28 days
	Turbidity (NTU)	SM2130B, EPA180.1	0.05	NTU	none	48 hrs
	VOC's	EPA 502.2	0.4	ug/L	Asc+HCl 4C	14 days
Nutrients & Phytoplankton	Ammonia - N	Lachat 10-107-06-2C	0.01	mg/L	filter, cool 4C	14 days
	Chlorophyll a	SM10200H modified	0.6	ug/L	cool, 4C	48 hrs
	Nitrate	EPA 300	0.02	mg/L	cool, 4C (eda)	48 hrs
	Nitrite	EPA 300	0.04	mg/L	cool, 4C (eda)	48 hrs
	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	14 days
	Phytoplankton (conducted by Mr. Richard Dufford)			cells/mL	Lugol's solution, cool, 4C	12 mo
	Total Kjeldahl Nitrogen	EPA 351.2	0.1	mg/L	H_2SO_4 pH<2	28 days
Major Ions	Calcium, flame	SM 3111 D	0.5	mg/L	HNO_3 pH <2	6 mos
	Chloride	EPA 300	1	mg/L	none (eda)	28 days
	Fluoride	EPA 300	0.04	mg/L	none (eda)	28 days
	Magnesium, flame	SM 3111 B	0.2	mg/L	HNO_3 pH <2	6 mos
	Potassium	SM 3111 B	0.2	mg/L	HNO_3 pH <2	6 mos
	Silica	SM 4500-Si C	2	mg/L	cool, 4C	28 days
	Sodium, flame	SM 3111 B	0.4	mg/L	HNO_3 pH <2	6 mos
	Sulfate	EPA 300	5	mg/L	cool, 4C (eda)	28 days
Microbiological	Total Coliform, E.coli - QT	SM 9223 B	0	cfu/100 mL	cool, 4C	8 hrs
	Fecal Strep	SM 9230 C	0	cfu/100 mL	cool, 4C	24 hrs
	Heterotrophic Plate Count	SM 9215 B	0	cfu/1.0 mL	cool, 4C	24 hrs
Metals	Aluminum	SM 3113 B	5	ug/L	HNO_3 pH <2	6 mos
	Antimony	SM 3113 B	2	ug/L	HNO_3 pH <2	6 mos
	Arsenic	SM 3113 B	2	ug/L	HNO_3 pH <2	6 mos
	Barium, GFAA	SM 3113 B	3	ug/L	HNO_3 pH <2	6 mos
	Beryllium	SM 3113 B	0.2	ug/L	HNO_3 pH <2	6 mos
	Cadmium	SM 3113 B	0.1	ug/L	HNO_3 pH <2	6 mos
	Chromium	SM 3113 B	0.5	ug/L	HNO_3 pH <2	6 mos
	Copper, GFAA	SM 3113 B	3	ug/L	HNO_3 pH <2	6 mos
	Iron, GFAA	SM 3113 B	10	ug/L	HNO_3 pH <2	6 mos
	Lead	SM 3113 B	1	ug/L	HNO_3 pH <2	6 mos
	Manganese, GFAA	SM 3113 B	1	ug/L	HNO_3 pH <2	6 mos
	Mercury	EPA 245.1	0.2	ug/L	HNO_3 pH <2	28 days
	Molybdenum	SM 3113 B	2	ug/L	HNO_3 pH <2	6 mos
	Nickel	SM 3113 B	2	ug/L	HNO_3 pH <2	6 mos
	Selenium	SM 3113 B	1	ug/L	HNO_3 pH <2	6 mos
	Silver	SM 3113 B	0.5	ug/L	HNO_3 pH <2	6 mos
	Thallium	EPA 200.9	1	ug/L	HNO_3 pH <2	6 mos
	Zinc, flame	SM 3111 B	25	ug/L	HNO_3 pH <2	6 mos

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 and findings from ongoing special studies. Special studies are designed to address specific long-term issues or new concerns that are outside of the scope of the routine monitoring program. Topics covered in this section include the following:

Section

2.1 Colorado's 2010 Section 303(d) and Monitoring and Evaluation (M&E) Lists
2.2 Proposed Colorado Nutrient Standards
2.3 Dissolved Organic Matter (DOM) Studies
2.4 Colorado Water Quality Control Division High Quality Water Supply Reservoir Study and Evaluation of Horsetooth Reservoir Data
2.5 Geosmin Occurrence in Horsetooth Reservoir and upstream components of the CBT Project
2.6 Northern Water Collaborative Emerging Contaminant Study
2.7 Northern Water Collaborative Horsetooth Reservoir Water Quality Modeling Study
2.8 Wildfires and Watershed Wildfire Assessments
2.9 Mountain Pine Beetles
2.10 Invasive Mussels

2.1 Colorado's 2010 Section 303(d) and Monitoring and Evaluation (M&E) Lists

Colorado's 2010 Section 303(d) List of impaired waters and 2010 Monitoring and Evaluation (M&E) List were adopted on March 9, 2010 and became effective on April 30, 2010. 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:

- **Dissolved Oxygen (D.O.) - M&E List:** In 2010, Horsetooth Reservoir was moved from the Section 303(d) List to the M&E List for D.O. The WQCD used 79 temperature and D.O. profiles collected by the USGS and NCWCD from 2003 to 2008 to make this determination.

- **Copper & Arsenic - M&E List:** Horsetooth Reservoir was placed on the M&E List in 2010 for copper and arsenic (aquatic life standards).

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

2.2 Proposed Colorado Nutrient Standards

The Colorado Water Quality Control Division (WQCD) is 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.

Interim numeric standards have been proposed for total phosphorus and total nitrogen for the mixed (top) layer of lakes and reservoirs. For cold water lakes and reservoirs greater than 25 acres (such as Horsetooth Reservoir), the proposed interim total P standard is 20 ug/L while the proposed interim total N standard is 410 ug/L. A chlorophyll-a standard of 8 ug/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), with an allowable exceedance frequency of 1-in-5 years.

The WQCD has proposed a lower chlorophyll-a standard to support a new Protected Water Supply Reservoirs (PWSR) sub-classification of the existing Water Supply use classification. The intent of this chlorophyll-a standard is to help maintain or reduce the disinfection byproduct (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 taste and odor control. The proposed interim numeric chlorophyll-a value is 5 ug/L (summer average chlorophyll-a in the mixed layers) with a one in five year exceedance frequency. The 5 ug/L is currently considered to be a preliminary (placeholder) value since the WQCD is completing data analysis to support a final proposed standard, including the analysis of data collected in 2010 for the High Quality Water Supply Study (see Section 2.4). The WQCD anticipates that the chlorophyll-a standard for Protected Water Supply Reservoirs would not automatically apply to all direct-use water supply reservoirs, but would be applied to individual reservoirs through the basin regulation rulemaking hearing process.

The rulemaking hearing to consider the adoption of the proposed phosphorus, nitrogen, and chlorophyll-a standards is currently scheduled for March 2012.

2.3 Total Organic Carbon (TOC) & Dissolved Organic Matter (DOM) Studies

Dissolved organic matter (DOM) (commonly measured as Total Organic Carbon (TOC)) is one of the most important water quality parameters for the source waters of the FCWTF, SCFP, and the Greeley Bellvue WTP. DOM is important because it can affect the optimization and efficiency of water treatment unit operations including coagulation and settling, and serves as the precursor for the formation of disinfection by-products (DBPs). DOM is a complex mixture of many different naturally occurring organic compounds, and measurements of bulk TOC do not tell us anything about the nature, source, composition, structure, or reactivity of the DOM. Additional (and sometimes more sophisticated) laboratory analysis is required to obtain information about the characteristics of DOM.

2.3.1 Overview of DOM Studies

A DOM characterization study was conducted in 2008 by Dr. Mel Suffet (Professor of Environmental Health Sciences at UCLA) and was jointly funded by the City of Fort Collins, City of Greeley, Tri-Districts, and the Northern Colorado Water Conservancy District. The study area included two sites within the Upper CLP watershed as well as Horsetooth Reservoir and associated components of the CBT Project. Laboratory analyses and parameters investigated for this study included:

- **Total Organic Carbon (TOC):** TOC for this study was determined at the FCWTF Process Control Laboratory using a Sievers 5310C Laboratory TOC Analyzer.

- **Ultraviolet absorbance at 254 nm (UV_{254}):** measures the amount of light absorbed at a wavelength of 254 nm; indicates presence of humic substances and aromatic (ringed organic molecules) groupings.

- **Specific UV Absorbance (SUVA):** SUVA (L/mg m) = $(UV_{254}/DOC) \times 100$; SUVA> 4 indicates high humic character, hydrophobic organics, aromatic, high molecular weight; SUVA < 2 indicates mostly non-humic, aliphatic characteristics (long-chain organic molecules), hydrophilic, low molecular weight; 2< SUVA <4 indicates a mix of DOM.

- **Fluorescence Spectroscopy:** provides data to assess the presence of humic-like and protein-like compounds and other DOM characteristics, and can be used to distinguish the origin of DOM (between terrestrial and algal sources). Fluorescence measurements for the 2008 UCLA Study were conducted at the University of Colorado at Boulder (CU). Three-dimensional fluorescence excitation and emission matrices (EEMs) were collected at CU and used to calculate several fluorescence parameters (Overall Fluorescence Intensity, Peak C Intensity, Peak C Location, Fluorescence Index, Redox Index).

- **Ultrafiltration:** molecular size (or weight) characterization. Ultrafiltration uses membranes with different pore sizes to quantify the fractions of DOM according to their molecular weight (<1 kDa, 1-5 kDa, 5-10 kDa and >10 kDa, where kDa is kiloDalton, and fractions > 5kDa are considered to be high molecular weight). Ultrafiltration in conjunction with DOC and UV_{254} analysis allows for the tracking of individual size fractions in the watershed and treatment plant. Higher molecular weight DOM is generally easier to remove by coagulation.

- **Polarity Rapid Assessment Method (PRAM):** polarity characterization. The polarity of DOM (charge and functional group content) influences its reactivity with coagulants and chlorine. PRAM was used in this study to characterize the polarity and charge of DOM by quantifying the amount of material adsorbed onto different solid-phase extraction sorbents (polar, non-polar and anionic sorbents).

- **Total Trihalomethane Formation Potential (TTHMFP):** TTHMFP is a measure of the presence of DBP precursors and reactivity of DOM to chlorine. Samples were analyzed for TTHMFP by the City of Fort Collins Water Quality Lab (Standard Methods 5710 and 4500-Cl.C.3m) and allowed for correlations to be tested and established between specific DOM characteristics and the presence of DBP precursors.

- **Specific TTHMFP (STTHMFP):** calculated by dividing TTHMFP concentration by the TOC concentration; STTHMFP provides information on the amount of TTHM formed per mg of TOC present in the sample.

A second study that built on the 2008 UCLA Study was funded in 2009 by the City of Fort Collins and the Water Research Foundation as a Tailored Collaboration Project with Dr. Scott Summers and other researchers at the University of Colorado at Boulder (CU): Water Research Foundation Project 04282 "Watershed Analysis of Dissolved Organic Matter and the Control of Disinfection By-Products." This project included the same study area as the 2008 UCLA Study, but focused on the use of fluorescence parameters and three-dimensional fluorescence EEMs to develop relationships between DOM characteristics in the watershed and DBP formation at the FCWTF. Laboratory analysis was also conducted for TOC, UV_{254}, TTHMFP (formed after 24 hours under uniform formation conditions), haloacetic acid formation potential (HAA5FP; formed after 24 hours under uniform formation conditions), and chlorine residual. Several parameters were calculated from the EEM data including overall fluorescence intensity, Peak A Intensity, Peak C Intensity, Fluorescence Index, and Humification Index. Parallel factor analysis (PARAFAC) modeling was used to statistically decompose the EEMs into individual or groups of fluorescent components to provide more information about the origin and character of DOM.

2.3.2 Summary of Horsetooth Reservoir and C-BT System Results

2008 UCLA Study Results. Fluorescence spectroscopy results for the 2008 UCLA Study, along with the TOC, UV_{254}, SUVA, TTHMFP, and STTHMFP data, are presented in detail in Chapter 3 of Beggs (2010). The findings from the ultrafiltration and PRAM analysis conducted at UCLA are still pending. The TOC, UV_{254}, SUVA, TTHMFP, and STTHMFP data (summarized on Figures 2-1 and 2-1) indicate the following with respect to Horsetooth Reservoir and associated CBT sites:

- **Time Series Plots:** The 2008 UCLA Study data set shows a slight increase in Horsetooth Reservoir TOC during the summer months compared to the spring and late fall (Figure 2-1-A), with an associated decrease in SUVA during the summer months, no obvious change in UV_{254}, and no consistent patterns in TTHMFP (Figures 2-1 -C, B, and D, respectively).

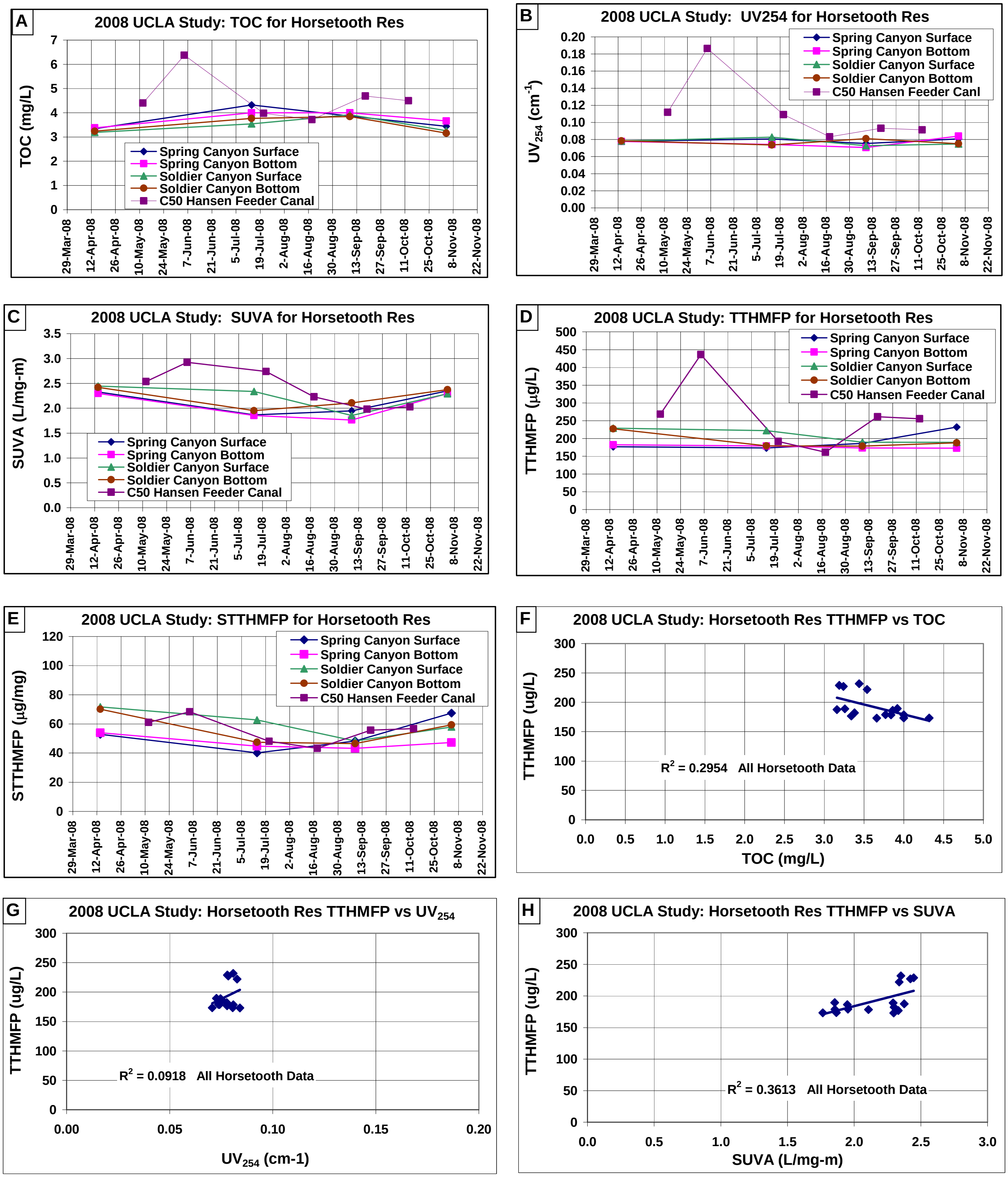


Figure 2-1(A-H). 2008 UCLA DOM Study Data: Plots of TOC, UV254, SUVA, TTHMFP and STTHMFP data collected for Horsetooth Reservoir.

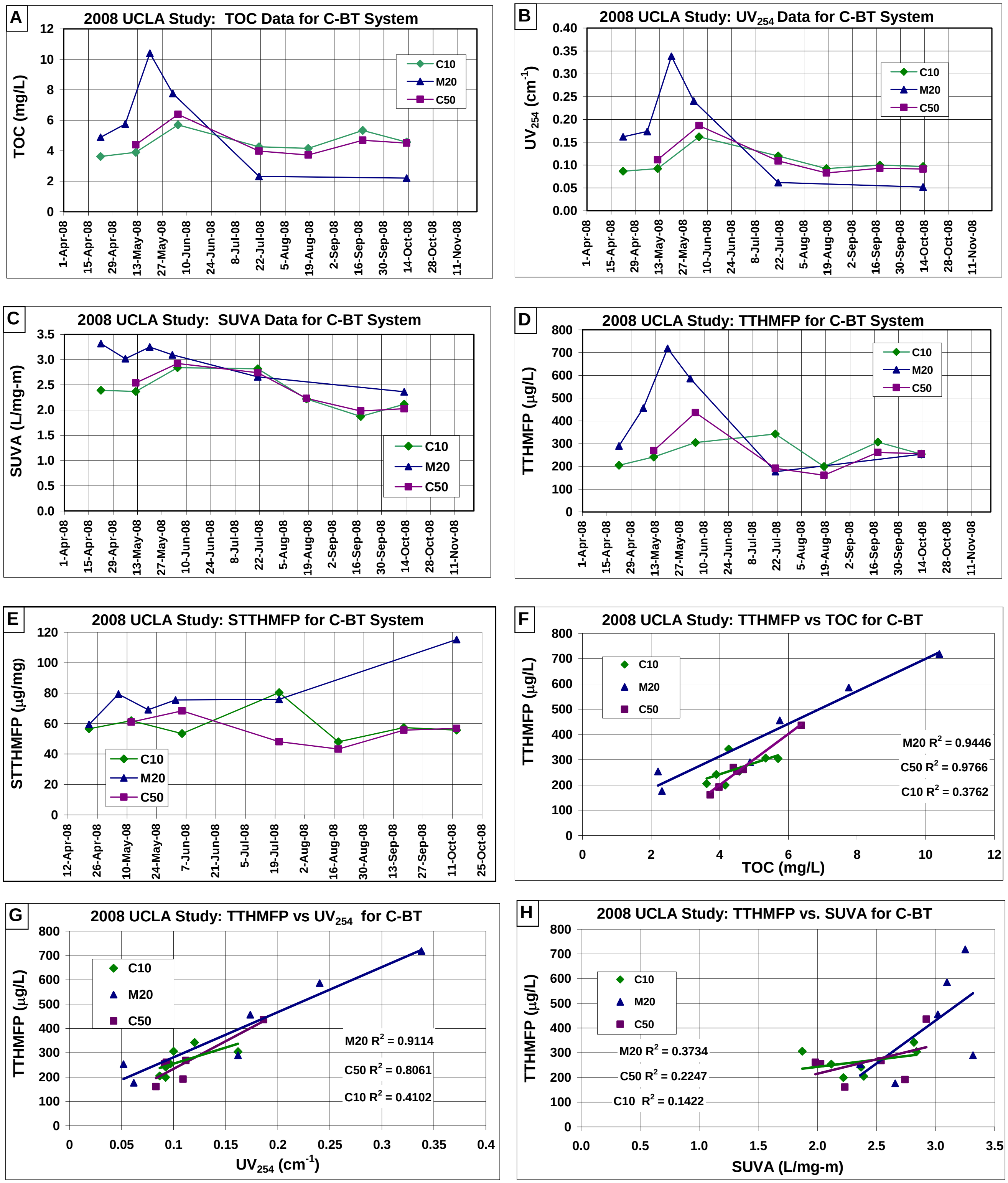


Figure 2-2(A-H). **2008 UCLA DOM Study Data: Plots of TOC, UV254, SUVA, TTHMFP and STTHMFP data collected for C-BT System sites upstream of Horsetooth Reservoir; C10 = east portal Adams Tunnel, M20 = Big Thompson River above Lake Estes, C50 = Hansen Feeder Canal upstream of Horsetooth Reservoir.**

Plots for the Big Thompson River above Lake Estes (M20), the east portal Adams Tunnel (C10), and the Hansen Feeder Canal just upstream of Horsetooth Reservoir (C50) are shown on Figure 2-2. The 2008 data set shows the typical increase in Big Thompson River TOC during spring runoff period, along with associated increases in UV_{254} and TTHMFP. Water in the Hansen Feeder Canal consists of both Big Thompson River water and water from the Adams Tunnel and, depending on the blending ratio, can take on characteristics of either source. At the time of the peak TOC in the Big Thompson River, the Adams Tunnel flow was significantly higher than the native Big Thompson River flow such that water in the Hansen Feeder Canal was more similar to the Adams Tunnel water, as can be seen in the time series plots for TOC, UV_{254}, and SUVA.

- **Specific TTHMFP and DOM reactivity with chlorine:** The 2008 data indicate that Big Thompson River DOM is more reactive to chlorine during most of the year (Figure 2-2-E) than the other sites, with more TTHM formed per mg TOC. The 2008 specific TTHMFP data also suggest that Horsetooth Reservoir and Hansen Feeder Canal DOM (Figure 2-1-E) is slightly less reactive with chlorine in the summer (i.e., less TTHM formed per mg TOC in the summer) than at other times of the year.

- **Relationships with TTHMFP:** For Horsetooth Reservoir and Adams Tunnel, bulk TOC, UV_{254}, and SUVA are not correlated to TTHMFP (Figures 2-1-F, G, H and 2-2-F, G, H) and therefore do not serve as good predictors of TTHMFP. For the Big Thompson River, TOC and UV_{254} are both strongly correlated to TTHMFP and therefore serve as good predictors of TTHMFP, while SUVA is not a good predictor of TTHMFP. The 2008 data indicate that TOC and UV_{254} are good predictors of TTHMFP for Hansen Feeder Canal water.

- **Big Thompson River Fluorescence Parameters Findings:** Fluorescence and UV parameters indicate that Big Thompson River DOM is significantly different from Adams Tunnel DOM and Horsetooth Reservoir DOM during all times of the year. Big Thompson River DOM is fresher, more aromatic, more hydrophobic, and of higher molecular weight.

- **Hansen Feeder Canal & Horsetooth Reservoir Fluorescence Parameters Findings:** Fluorescence and UV parameters indicate that Horsetooth Reservoir DOM is more oxidized, more hydrophilic, less aromatic, and of lower molecular weight than the Hansen Feeder Canal DOM. Differences between the reservoir DOM and the Hansen Feeder Canal DOM suggest that reservoir processes transform the DOM. Fluorescence data indicate that photobleaching -- not microbial activity (algae) -- is the main reservoir process responsible for the DOM transformations in the reservoir (Beggs, 2010, pg. 64).

Water Research Foundation/CU Study Results. Results of the fluorescence analysis conducted for the Water Research Foundation/CU Study are presented in Chapters 4 and 5 of Beggs (2010). A formal Water Research Foundation report that presents the results and findings for all project tasks is expected in 2012.

The data from the Water Research Foundation/CU Study are consistent with the findings of the 2008 UCLA Study. Nearly 500 fluorescence EEMS were produced and used in the data analysis, including 156 watershed samples (raw and coagulated), 101 chlorinated watershed samples, 126 coagulated and chlorinated watershed samples, and 73 pine litter leachate (fresh and biodegraded) samples. An example of an EEM showing regions that have been identified in the literature as humic-like (indicative of DOM of terrestrial origin) or protein-like (indicative of microbial DOM) is shown on Figure 2-3. Parallel factor analysis (PARAFAC) modeling was used to statistically decompose the EEMs into individual or groups of fluorescent components to provide more information about the origin and character of DOM.

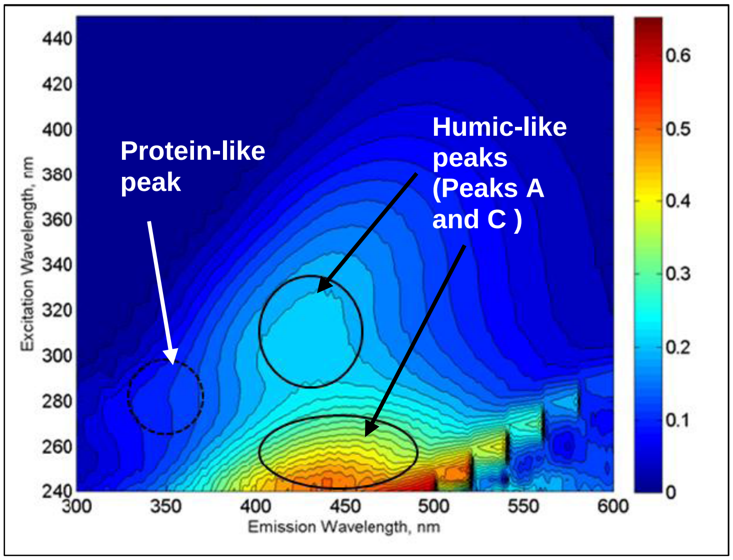


Figure 2-3. Example of a fluorescence excitation and emission matrix (EEM) with primary peaks (from Beggs, 2010).

The EEMS were together used to develop a watershed-specific six component PARAFAC model (Figure 2-4). Components 1-4 were identified as being humic-like, Component 5 was identified as polyphenolic/tyrosine (protein)-like, and Component 6 was identified as tryptophan (protein)-like. Protein-like components are indicative of microbial activity including the presence of algae (note that tyrosine and tryptophan are amino acids).

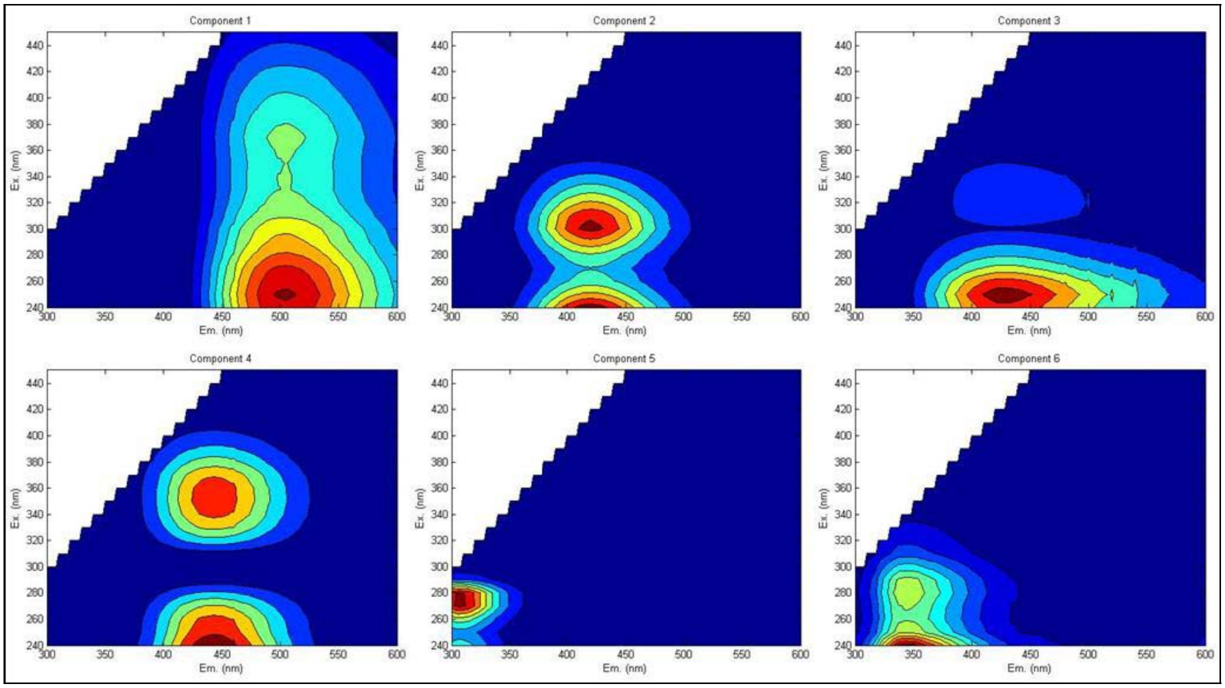


Figure 2-4. Components from the six component PARAFAC model developed for the Upper CLP, Horsetooth Reservoir, and the CBT system upstream of Horsetooth Reservoir. Components 1-4 appear to be humic-like in nature while Component 5 is polyphenolic/ tyrosine-like, and Component 6 appears to be tryptophan (protein)-like (from Beggs, 2010, page 133).

The significant findings from the Water Research Foundation/CU Study were previously summarized in Billica and Oropeza (2010). For completeness of this section, the relevant portions of that summary are repeated below.

Watershed DOM Origin

- River sites (main stem Poudre River above the North Fork, and Big Thompson River above Lake Estes) are dominated by humic-like (terrestrial) components (Beggs, 2010, pg. 137).

- Hansen Feeder Canal (at Horsetooth inlet) and the East Portal Adams Tunnel sites are dominated by humic-like components. However, compared to the river sites, the canal site and tunnel site show a larger contribution from a specific humic-like component (Component 3) that is hypothesized to be related to reservoir processes such as photobleaching and lignin degradation (Beggs, 2010, pg. 137). Water at these sites has had a residence time in western slope reservoirs, such that further degradation of lignin may have taken place compared with the river sites. [Note: Lignins are components of, and produced only by, vascular plants, accounting for 5 to 10% of the dry weight of leaves and up to 30% of the dry weight of wood. Lignins are some of the most refractory (i.e., resistant to degradation) nonhumic substances present in soils, and are some of the more important precursors to the humic substances (Essington, 2004, pg. 152).]

- Horsetooth Reservoir is also dominated by humic-like components. And, like the canal and tunnel sites, Horsetooth Reservoir shows a higher contribution from the humic-like component (Component 3) that may be related to lignin degradation or other reservoir processes such as photobleaching. Horsetooth Reservoir also has a larger contribution (compared to the river, canal, and tunnel sites) from the protein-like (tryptophan-like) component, and slightly lower contributions from the other humic-like components. This indicates a slightly more microbial, less humic DOM compared to the river, canal, and tunnel sites (Beggs, 2010, pg. 138). Differences in DOM character between the top and bottom of Horsetooth Reservoir were not observed.

- Overall, the average differences in DOM composition between site types (river, canal, tunnel, reservoir) are minor as the entire study area shows similar character, with all sites dominated by allochthonous (terrestrial) DOM represented by humic-like components (Beggs, 2010, pg. 138). The flush from spring snowmelt runoff helps to mobilize the humic-like components into the watershed where they remain relatively dominant year round.

- The fact that the DOM in the source waters of this study area does not strongly exhibit microbial characteristics (including the Horsetooth Reservoir samples) implies that watershed management activities to reduce nutrient loads and algal growth may not have a significant impact on TOC quantity and quality. However, increases in nutrient loads to Horsetooth Reservoir could potentially result in a shift to more microbial (algae) derived DOM.

Relationships between DOM Characteristics and Coagulation, Chlorine Demand and DBP Precursors

- The humic-like components appear to be the chlorine reactive fraction of the DOM as measured by chlorine demand (oxidation) and DBP formation (substitution) (Beggs, 2010, pg. 154).

- The humic-like components exhibited strong positive correlations with chlorine demand and TTHM and HAA5 concentrations. Correlations were, in general, stronger with chlorine demand and HAA5 than TTHM, suggesting that for the Fort Collins study area, HAA5 precursors are better captured by fluorescence analysis than TTHM precursors (Beggs, 2010, pg. 154). Many different types of organic compounds react with chlorine to form TTHM, but not all of them will be captured by fluorescence analysis because of low absorptivity.

- The humic-like component (Component 3) that may be related to photobleaching and/or lignin degradation was less strongly correlated to chlorine demand and TTHM and HAA5 concentrations than the other humic-like components (Beggs, 2010, pg. 147). The data suggest that reservoir processes such as photobleaching decrease DOM reactivity to chlorine.

- Coagulation is effective at removing the material associated with DBP formation, primarily the humic–like components (Beggs, 2010, pg. 154).

- The protein-like (tryptophan-like) component was reasonably well removed by coagulation but was not associated with DBP formation. The lack of correlation between this component and DBP formation suggests that while CBT Project reservoir microbial processes may result in taste and odor issues, microbial activity does not appear to relate to DBP precursor concentrations (Beggs, 2010, page 155).

2.4 Colorado WQCD High Quality Water Supply Reservoir Study and Evaluation of Horsetooth Reservoir Data

The WQCD has proposed a numeric chlorophyll-a standard to support a new Protected Water Supply Reservoirs classification. The WQCD is developing this standard based on an understanding of relationships of DBPs with nutrients, phytoplankton, chlorophyll, and organic carbon. In 2010, the WQCD conducted the High Quality Water Supply Study with the University of Colorado, Boulder (CU) to better understand these relationships in Colorado reservoirs. The study included synoptic sampling of 28 lakes/reservoirs and intensive sampling of 10 lakes/reservoirs. The intensive sampling was conducted by several utilities in Colorado, with the laboratory analysis conducted by CU. Laboratory analysis included dissolved organic carbon (DOC), TOC, ammonia, nitrite, nitrate, total nitrogen, total phosphorus, chlorophyll-a, UV_{254}, haloacetic acid formation potential (HAA5FP; formed after 24 hours under uniform formation conditions), and total trihalomethane formation potential (TTHMFP; formed after 24 hours under uniform formation conditions). The City of Fort Collins participated in this study by supporting the intensive sampling of Horsetooth Reservoir to coincide with the FCU routine monitoring program. Samples were collected at the Soldier Canyon Dam monitoring site at one meter below the surface and one meter above the reservoir bottom during one sampling event in May and two sampling events in each of the months of June, July, August, and September.

Although the sample collection and laboratory analysis for the WQCD High Quality Water Supply Study has been completed, the final report is not yet available from the WQCD. The final report will investigate correlations developed by combining the data collected from all reservoirs included in the study to support chlorophyll-a criteria development for the whole state.

Horsetooth Reservoir Data. The Horsetooth Reservoir data collected for the WQCD High Quality Water Supply Study were obtained from the WQCD for review, and Horsetooth Reservoir-specific correlations were investigated by FCU. Findings from the evaluation of the 2010 Horsetooth Reservoir data by FCU are summarized below and on the graphs shown on Figure 2-5:

- **Relationship of DOC to Chlorophyll-a** (Figure 2-5-A1 and A2): The 2010 Horsetooth Reservoir data showed that the surface DOC was highest during the late spring and early summer, influenced by the inflow of high TOC Big Thompson River water during the runoff period. The chlorophyll-a increased from spring through the summer, and peaked in July. No correlation is observed in the chlorophyll-a versus DOC plot for Horsetooth Reservoir (Figure 2-5-A2) since Horsetooth Reservoir DOC appears to be dominated by terrestrial sources of dissolved organic matter that are mobilized during the spring runoff.

- **Chlorophyll-a, DOC, and Disinfection Byproduct Formation Potential** (Figure 2-5-B1, B2, C1, C2, D1, D2, E1, and E2): For Horsetooth Reservoir, correlations between disinfection byproduct formation potential and chlorophyll-a are poor. Disinfection byproduct formation potential is more strongly correlated with DOC than with chlorophyll-a. This applies to both TTHMFP and HAA5FP. The strongest correlation was obtained between HAA5FP and the surface DOC (Figure 2-5-E2).

- **Ratio of Dissolved to Total Organic Carbon, DOC/TOC** (Figure 2-5-F1 and F2): Approximately 94% of the Horsetooth Reservoir TOC in the surface samples was in the dissolved form (range of 87% to 97%), while approximately 91% of the Horsetooth Reservoir TOC in bottom samples was in the dissolved form (range of 76% to 97% for the bottom samples).

- **Specific Ultraviolet Absorbance at 254 nm, SUVA** (Figure 2-5-G1 and G2): SUVA (= UV_{254}/DOC) is an indicator of the presence of aromatic compounds. Higher SUVA values indicate higher aromatic content which can impact the reaction of DOC with coagulants and chlorine. The 2010 Horsetooth Reservoir SUVA data indicate that the aromatic character of the surface DOC did not change from spring to fall. For the bottom DOC, the SUVA data indicate that the DOC became more aromatic from spring to fall (higher SUVA in the fall compared to the spring). Figure 2-5-G2 indicates that SUVA is not a good predictor of TTHMFP.

- **Specific TTHMFP and Specific HAA5FP** (Figure 2-5-H): Specific TTHMFP (STTHMFP = TTHMFP/DOC) and Specific HAA5FP (SHAA5FP = HAA5FP/DOC) represent the yield of TTHMFP and HAA5FP per mg of DOC. The plots of STTHMFP (Figure 2-5-H) show that it did not vary much between spring and fall, indicating that the characteristics of the DOC that impact its reactivity with chlorine did not significantly change. The most apparent changes were observed beginning in mid-summer and continuing into the fall, when the STTHMFP increased slightly compared to the previous months while the SHAA5FP decreased slightly compared to the previous months. An increase in STTHMFP indicates that it is more reactive with chlorine with respect to the formation of TTHMs, and more ug of TTHMs are formed per mg of DOC. A decrease in SHAA5FP indicates that the DOC is less reactive with chlorine with respect to the formation of HAA5, and less ug of HAA5 are formed per mg of DOC.

- **DOC versus UV_{254}** (Figure 2-5-I): UV_{254} is an indicator of humic substances and aromaticity. Figure 2-5-I shows a strong correlation between DOC and UV_{254} for Horsetooth Reservoir surface samples, and a moderate correlation between DOC and UV_{254} for Horsetooth Reservoir bottom samples.

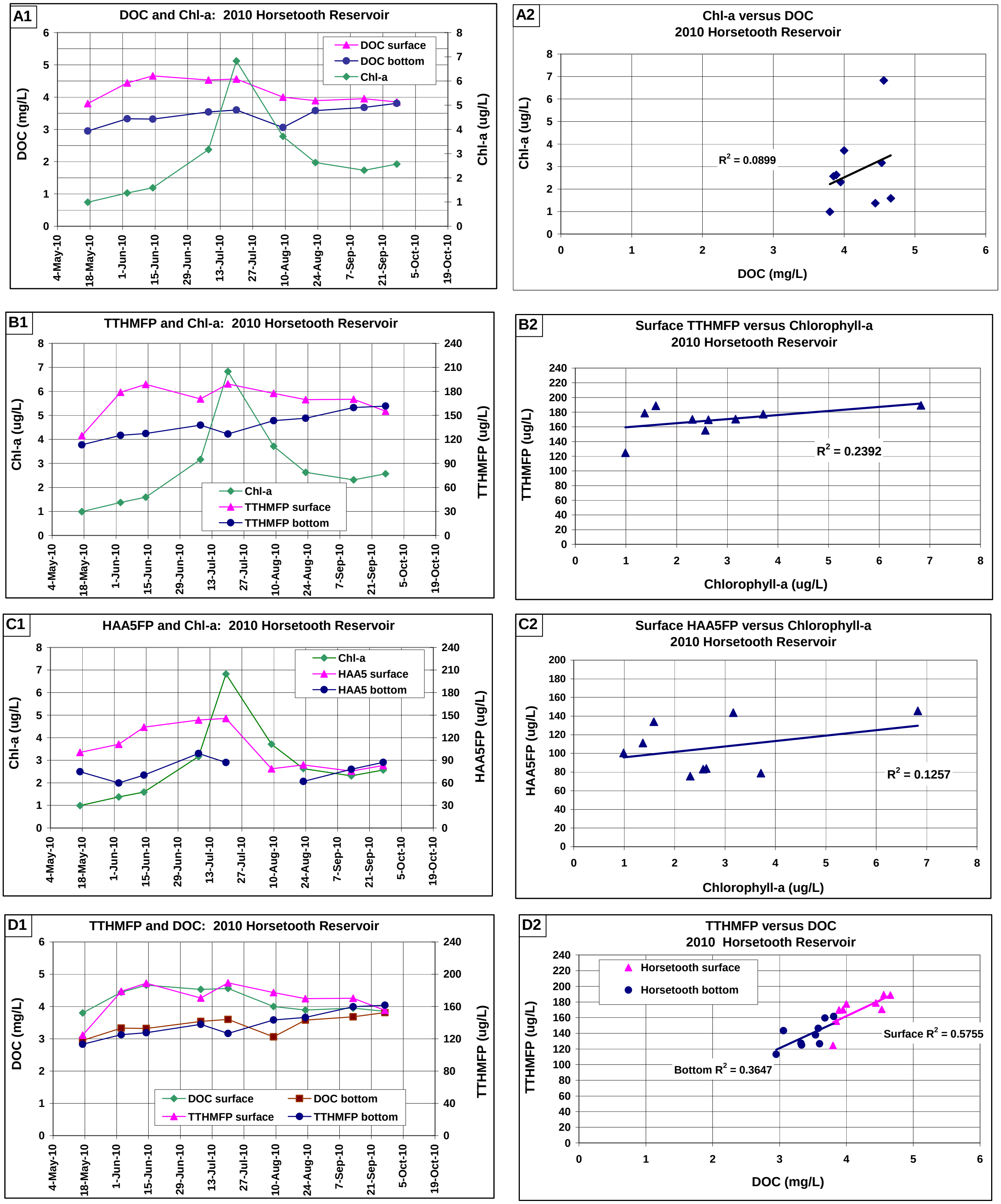


Figure 2-5 (A-I). Plots of 2010 Horsetooth Reservoir Chlorophyll-a, TOC, DOC, UV254, SUVA, TTHMFP, HAA5FP, STTHMFP, and SHAA5FP data collected for the Colorado WQCD High Quality Water Supply Reservoir Study (laboratory analysis by CU Boulder).

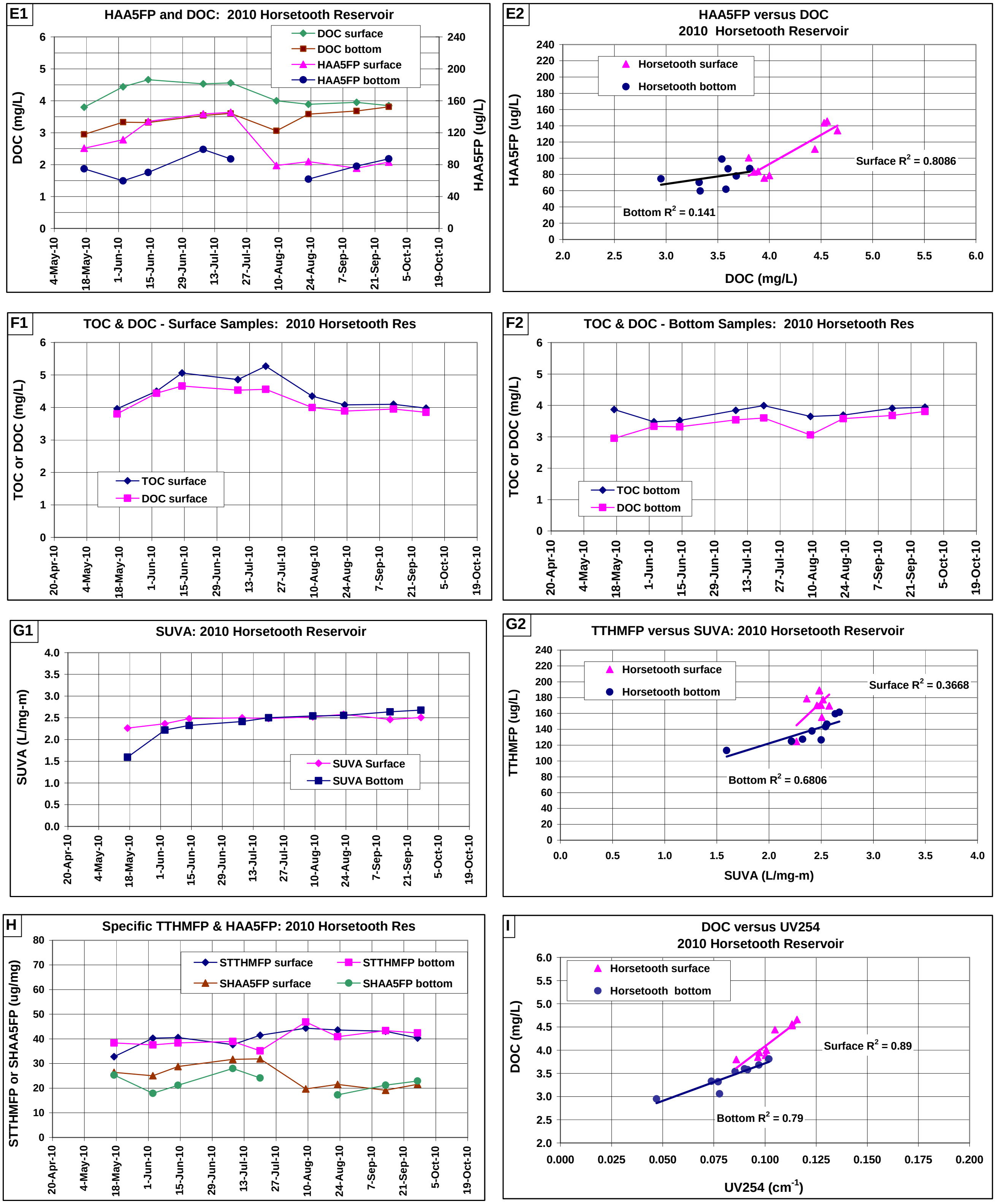


Figure 2-5 (A-I) (CONTINUED). Plots of 2010 Horsetooth Reservoir Chlorophyll-a, TOC, DOC, UV254, SUVA, TTHMFP, HAA5FP, STTHMFP, and SHAA5FP data collected for the Colorado Water Quality Control Division High Quality Water Supply Reservoir Study (laboratory analysis by CU Boulder).

2.5 Geosmin Occurrence in Horsetooth Reservoir and upstream components of the CBT Project

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 found in both raw Poudre River water and raw Horsetooth Reservoir water and is very difficult to remove. The highest geosmin concentration measured in raw Horsetooth water at the FCWTF was nearly 25 ng/L in October 2008.

FCU staff have 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 2-6). Beginning in 2009, watershed monitoring was also designed to provide for a better geosmin "early warning" system for the treatment plant. Watershed geosmin sampling has included the Horsetooth Reservoir routine sampling sites (beginning in 2008), Hansen Feeder Canal sites (beginning in 2009), Big Thompson River above the Dille Tunnel (beginning in 2009), and the east Portal Adams Tunnel (beginning in 2009). The results of the 2008 and 2009 sampling efforts are presented and assessed in Billica, Oropeza, and Elmund (2010).

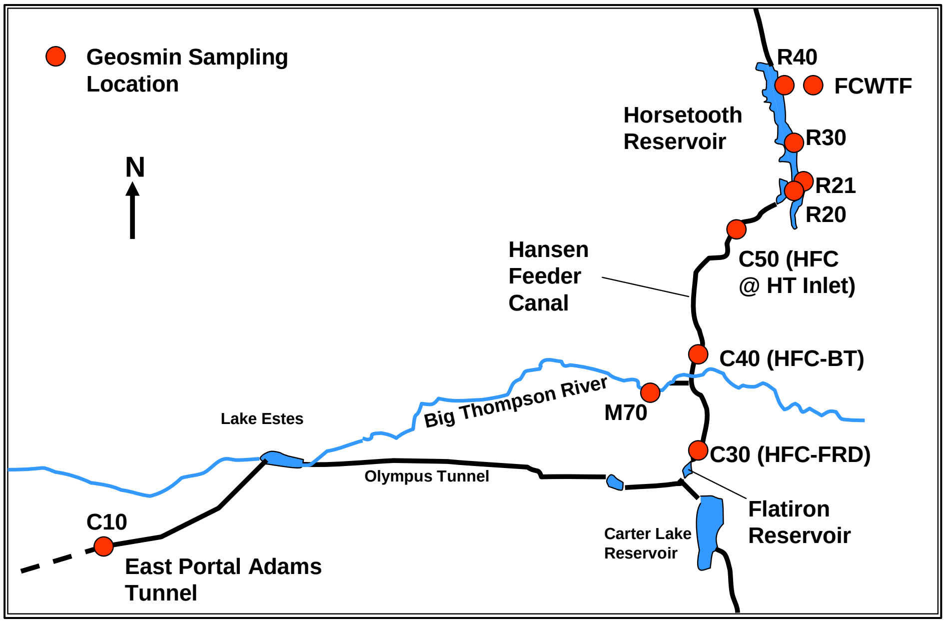


Figure 2-6. FCU geosmin monitoring locations.

Horsetooth Reservoir 2010 geosmin data are compared to the 2008 and 2009 data on Figure 2-7. In 2010, geosmin concentrations in all Horsetooth Reservoir samples were below 4 ppt, except for the Sept. 13 sample collected at Inlet Bay (R20) at 1 meter above bottom (13.9 ppt). Analysis of the 2010 data does not provide any insight as to why the geosmin concentrations in Horsetooth Reservoir were lower in 2010 compared to the previous two years.

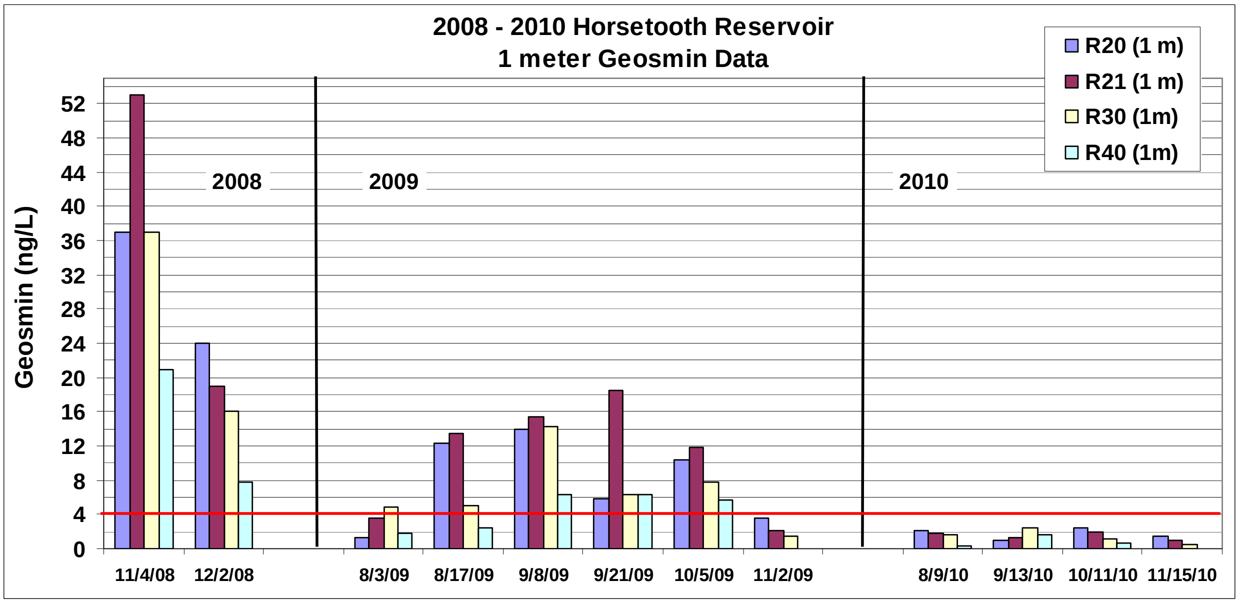
It is not readily clear whether the bulk of the geosmin occurring in Horsetooth Reservoir in 2010 was transported to the reservoir via the Hansen Feeder Canal, or if it was produced by cyanobacteria occurring within the reservoir. Concentrations in Hansen Feeder Canal waters entering Horsetooth Reservoir ranged from 1.3 to 9.0 ppt in 2010 (Figure 2-8 (A)), compared to a somewhat higher concentration range of 3 to 15 ppt in 2009.

A very rough estimate of geosmin loads from the Hansen Feeder Canal was calculated based on the flow data (flow station HFCBBSCO minus flow station HFCLOVCO; see Section 3.1) and the geosmin data shown in Figure 2-9 (using the method described in Section 4.3). The calculations indicate that in 2010, the geosmin load to Horsetooth Reservoir from the Hansen Feeder Canal was approximately 0.41 pounds during the period of August 1 through November 20 (the period of geosmin monitoring). The estimated 2009 geosmin load during the same period was 0.31 pounds. The higher estimated load during the August 1 to November 2010 time period was due to the fact that the total flow during this period was nearly two times higher than in 2009. Note that these calculated loads are not considered to be the total annual loads because there was likely detectable geosmin in the Hansen Feeder Canal water in July (and possibly earlier) based on the values measured during early August.

The estimated Hansen Feeder Canal geosmin loads can be added to the total volume of Horsetooth Reservoir to get a very rough idea of their impact on geosmin concentrations within Horsetooth Reservoir. The average reservoir volume during the August 1 through November time period was 90,484 ac-ft in 2009 and 97,261 ac-ft in 2010. If the Hansen Feeder Canal geosmin load is equally distributed throughout these reservoir volumes, the 2009 geosmin load of 0.31 pounds would result in a geosmin concentration of approximately 1.3 ng/L above the geosmin concentration that would originate from in-reservoir production alone. The 2010 geosmin load of 0.41 lbs would result in a geosmin concentration of approximately 1.5 ng/L above the geosmin concentration that would occur from in-reservoir production. Note that these calculations do not account for geosmin degradation within the reservoir and the influence of reservoir transport mechanisms that would prevent the instantaneous and equal distribution of the geosmin load throughout the entire reservoir volume. However, in 2010, the geosmin load from the Hansen Feeder Canal likely made up a significant fraction of the very low geosmin concentrations (generally ≤ 2 ng/L) that were measured within Horsetooth Reservoir.

Significant geosmin concentrations were measured in August and September 2010 at the east portal Adams Tunnel (30 ppt and 27 ppt, respectively; Figure 2-8(B)). 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.

(A)



(B)

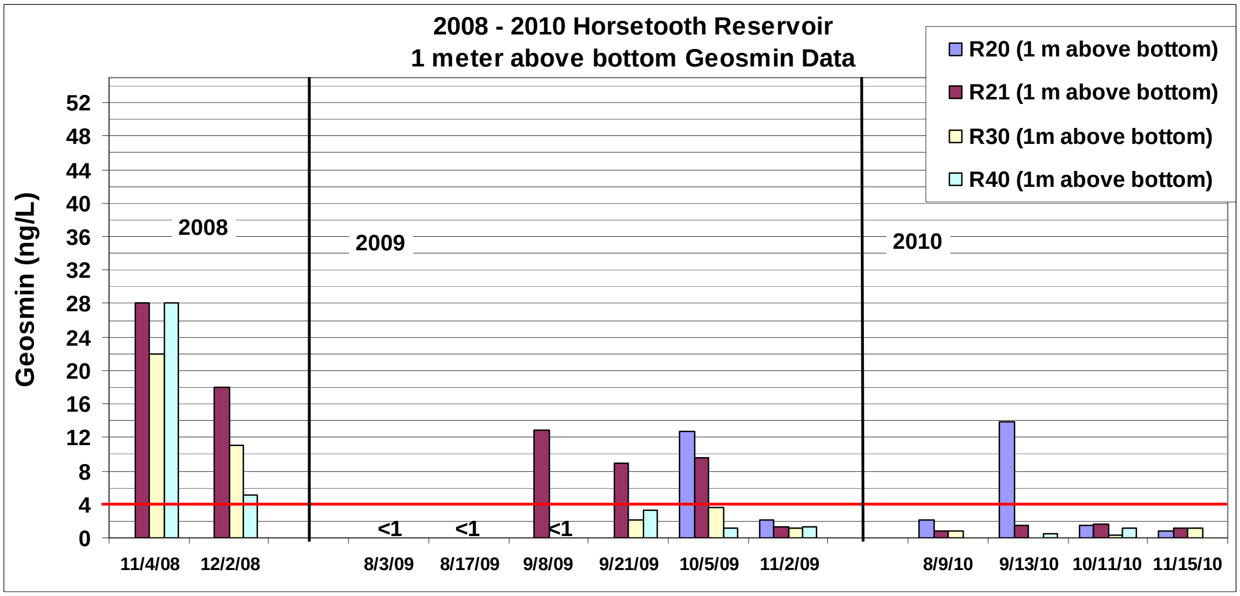
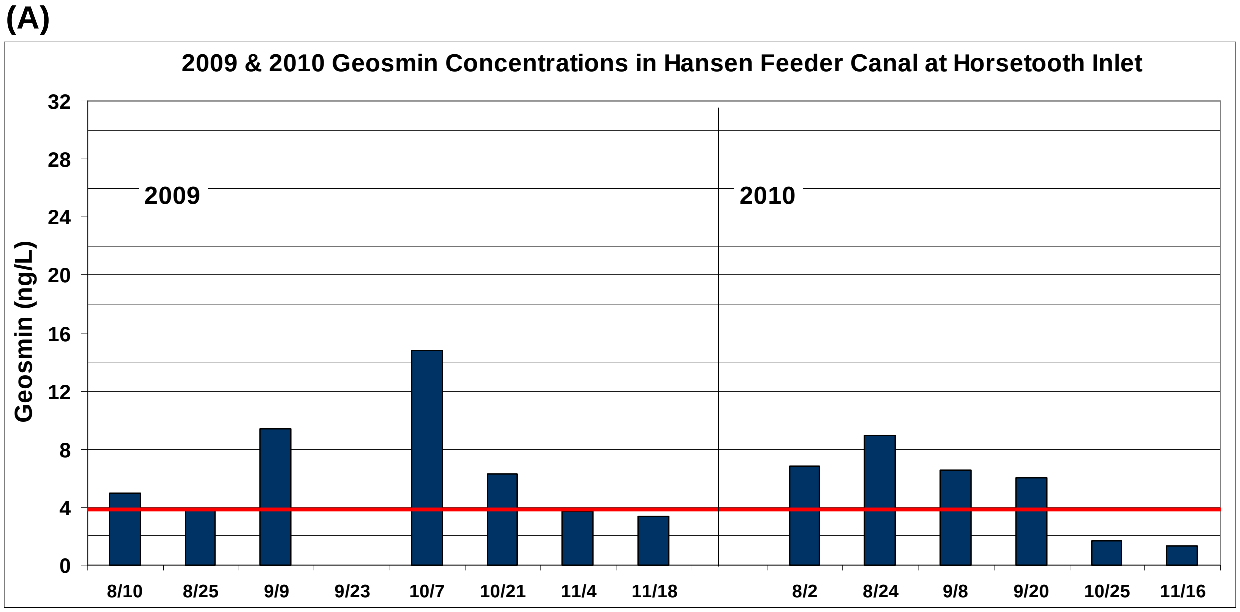


Figure 2-7. Geosmin concentrations measured within Horsetooth Reservoir in 2008 – 2010 at A) a depth of 1 meter below the surface, and B) a depth of 1 meter above the reservoir bottom.



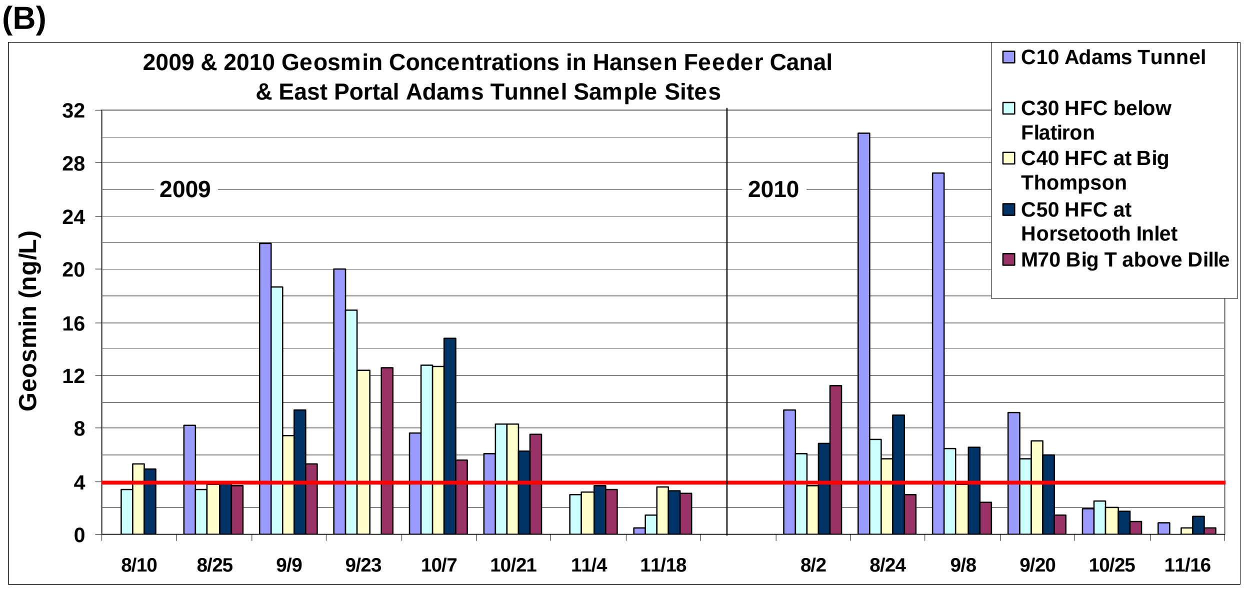
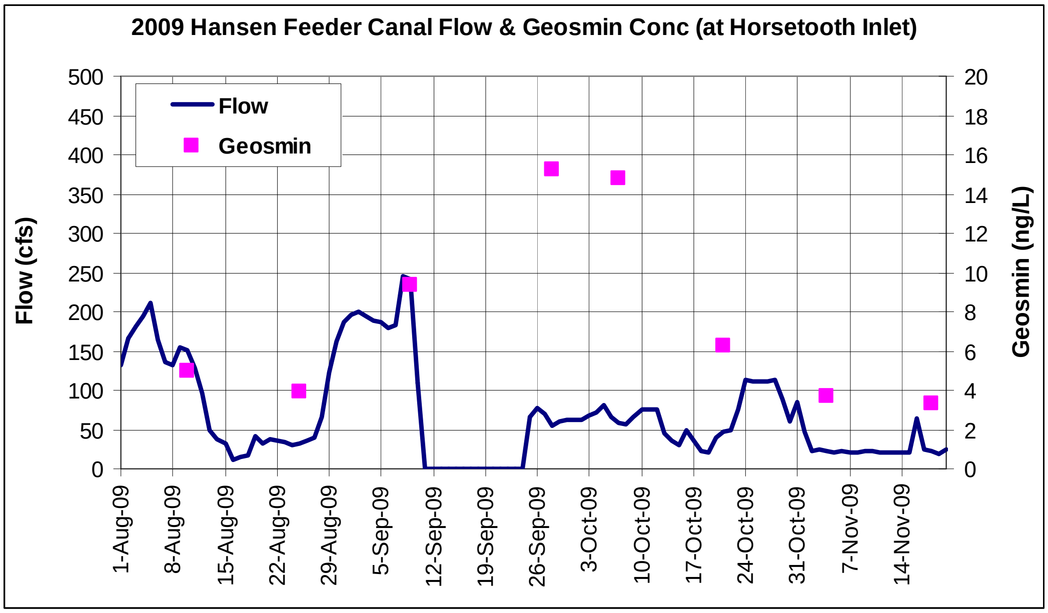


Figure 2-8. Geosmin concentrations during 2009 and 2010 in (A) Hansen Feeder Canal at Horsetooth Inlet, and (B) CBT Project sites upstream of Horsetooth Reservoir.

(A)



(B)

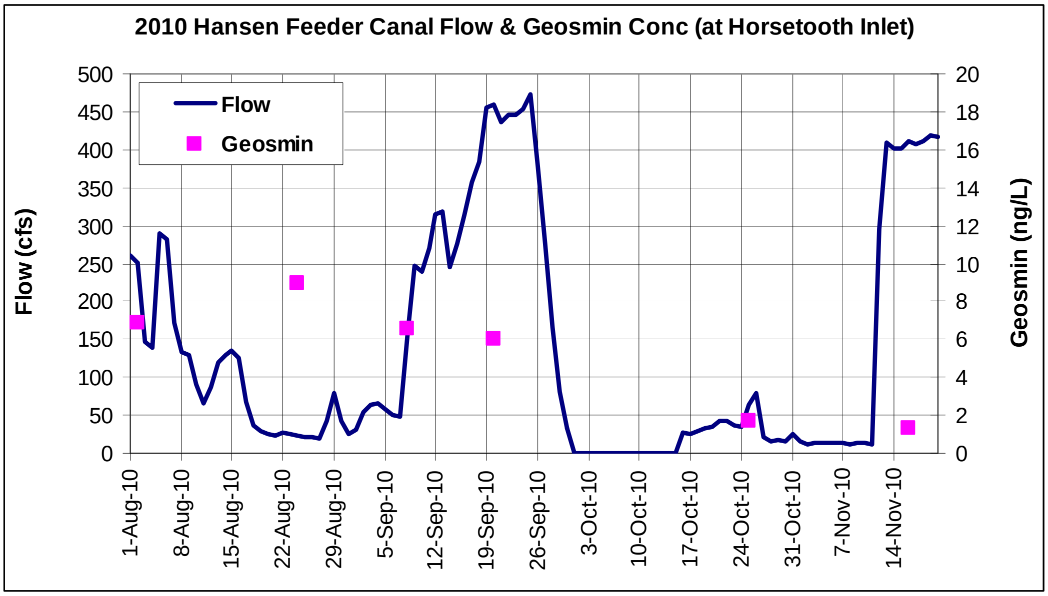


Figure 2-9. Hansen Feeder Canal (at Horsetooth Inlet) geosmin concentrations and flows used to estimate geosmin loads to Horsetooth Reservoir in A) 2009, and B) 2010.

2.6 Northern Water Collaborative Emerging Contaminant Study

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

- Personal care products (PCPs): fragrances, sunscreens, insect repellants, detergents, household chemicals
- Pharmaceuticals: prescription and non-prescription human drugs (including pain medications, antibiotics, β-blockers, anti-convulsants, etc) and veterinary medications
- Endocrine disrupting chemicals (EDCs): 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, Northern Water initiated a collaborative emerging contaminant study to determine the presence of these compounds in waters of the Colorado- Big Thompson system including Horsetooth Reservoir (Figure 2-10). 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).

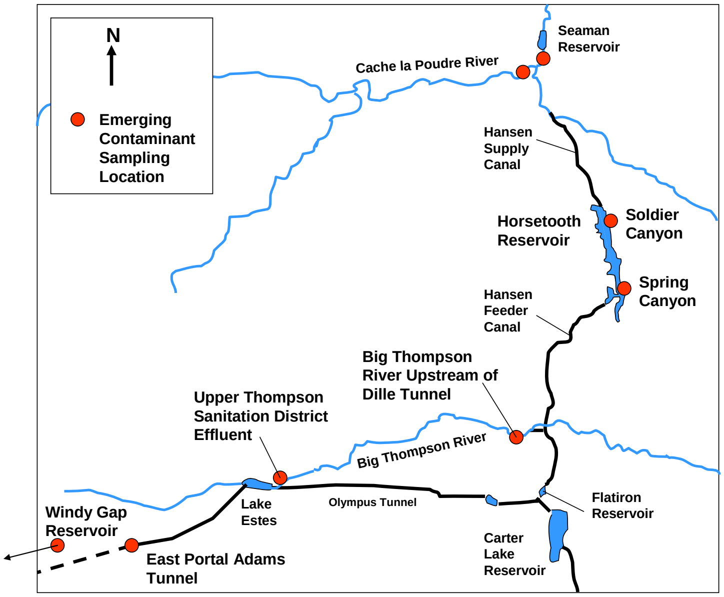


Figure 2-10. Sampling sites for Northern Water Emerging Contaminant Study

Laboratory Analysis. Samples are submitted to the Center for Environmental Mass Spectrometry Laboratory at the University of Colorado at Boulder (CU Lab) 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 (UL), 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 Lab also began conducting low-level analysis by liquid chromatography with tandem mass spectrometry (LC/MS-MS) for a subset of 22 different pharmaceuticals and personal care products, in addition to the analysis of 51 pharmaceuticals and 103 pesticides by LC/TOF-MS.

Results through August 2010. Results from the June and August 2010 sampling events are summarized on Table 2-1 and have been assessed in data reports prepared by Imma Ferrer and Michael Thurman (CU Boulder) for Northern Water. Some observations can be made about the sampling to date. As seen from the Upper Thompson Sanitation District effluent data, wastewater treatment plant effluent is a source of many pharmaceuticals and personal care products, although 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. However, only trace concentrations of carbamazepine, metoprolol, and sulfamethoxazole were detected in both the June and August sampling events. The effect of wastewater treatment plant effluent on Windy Gap and East Portal Adams Tunnel waters appears to be very low or non-existent.

Metoprolol (a beta blocker) appears to be a stable, persistent pharmaceutical. Low levels of metoprolol were measured in both the June and August 2010 sampling events in Horsetooth Reservoir at both Spring Canyon and Soldier Canyon at all three depths.

Two herbicides, 2,4-D and diuron, were detected in the June and August 2010 samples collected at both Spring Canyon and Soldier Canyon at all three depths. Both 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. Trace concentrations of diuron from all Horsetooth Reservoir sampling sites (three depths at Spring and Soldier Canyons) fell within the narrow range of 5.0 to 6.8 ng/L. 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.

Caffeine was detected in all of the Horsetooth Reservoir samples in June and August 2010 and in the August 2010 sample from the Big Thompson River above the Dille Tunnel. Caffeine is used as a chemical tracer (indicator) of contamination from domestic wastewater (treatment plant effluents and septic systems). The large amount of caffeine that is consumed and discarded (i.e., pouring out unused caffeinated beverages) in our society results in continuous loadings of caffeine to the aquatic environment. In addition to domestic wastewater, sources of caffeine in Horsetooth Reservoir may be use of beverages by fisherman and boaters on the reservoir.

2011 Sampling. In 2011, samples will be collected at the Horsetooth Reservoir sites (top, middle, and bottom) in June and August. Samples were also collected in November 2010 as part of the 2011 Water Year. These sampling dates will span the range of conditions experienced by Horsetooth Reservoir including the period of peak summer recreational use, and the period of herbicide applications. These samples will also provide additional information about what emerging contaminants are persistent (and consistently observed) in Horsetooth Reservoir.

Table 2 - 1 . Results of Northern Water Collaborative Emerging Contaminants Study - June & August 2010

All units are ng/L (parts per trillion)

		WG-DAM-1	AT-EP	UT-EFF	BT-DLU	HT-SOL-1	HT-SOL-8	HT-SOL-B	HT-SPR-1	HT-SPR-9	HT-SPR-B
Compound	**Function**	Windy Gap Dam	East Portal Adams Tunnel	Upper Thompson Sanitation District Effluent	Big Thompson River above Dille Tunnel	Horsetooth Reservoir Soldier Canyon 1 meter	Horsetooth Reservoir Soldier Canyon 8 meters	Horsetooth Reservoir Soldier Canyon bottom	Horsetooth Reservoir Spring Canyon 1 meter	Horsetooth Reservoir Spring Canyon 9 meters	Horsetooth Reservoir Spring Canyon bottom
JUNE 2010 Low Level Analysis conducted by CU Boulder:											
2,4-D	Herbicide	<5	<5	--	<5	11.5	10.8	9.1	11.7	9.1	8.8
Acetaminophen	Pain reliever	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
Atenolol	Beta blocker	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
BAM	Septic Tank indicator	<10	<10	--	<10	<10	<10	<10	<10	<10	<10
Bisphenol A	Used in plastics	<20	<20	--	<20	<20	<20	<20	<20	<20	<20
Bupropion	Antidepressant	<1	<1	--	<1	<1	<1	<1	<1	<1	<1
Caffeine	Stimulant	<5	<5	--	<5	9.9	10.8	10	12.4	13.2	8.6
Carbamazepine	Anti-epileptic	<1	<1	--	1.5	1.4	1.5	1.2	1.4	1.5	1.3
Clarithromycin	Antibiotic	2.1	<1	--	2.6	2.3	2.5	2.3	2.4	2.5	2.4
Cotinine	Nicotine metabolite	<1	<1	--	3.1	3.7	3.7	3.6	3.7	3.5	3.6
DEET	Insect repellant	<20	<20	--	<20	<20	<20	<20	<20	<20	<20
Diazinon	Insecticide	<1	<1	--	<1	<1	<1	<1	<1	<1	<1
Diltiazem	Heart/blood pressure	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
Diphenhydramine	Antihistamine	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
Diuron	Herbicide	<5	<5	--	<5	6.4	6.2	5.3	6.4	5.1	6.8
Erythromycin	Antibiotic	<10	<10	--	<10	<10	<10	<10	<10	<10	<10
Fluridone	Aquatic herbicide	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
Gemfibrozil	Cholesterol drug	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
Metoprolol	Beta blocker	<1	<1	--	2.8	1.4	1.7	1.2	1.4	2	1.3
Propanolol	Beta blocker	<1	<1	--	<1	<1	<1	<1	<1	<1	<1
Sulfamethoxazole	Antibiotic	<2	<2	--	4.4	3.2	3.6	2.9	3.4	3.5	3.2
Trimethoprim	Antibiotic	<5	<5	--	<5	<5	<5	<5	<5	<5	<5
JUNE 2010 Hormone & Phenolic Endocrine Disrupting Chemicals - analysis conducted by Underwriters Laboratories, Inc.:											
Progesterone	Hormone	0.3	0.1	--	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
no other compounds detected by UL											
AUGUST 2010 Low Level Analysis conducted by CU Boulder:											
2,4-D	Herbicide	--	13.9	20.3	5.7	13.9	13.7	9.5	15.9	12.2	8.8
Acetaminophen	Pain reliever	--	<5	<5	<5	<5	<5	<5	<5	<5	<5
Atenolol	Beta blocker	--	<5	1515	5.0	<5	<5	<5	<5	<5	<5
BAM	Septic Tank indicator	--	<10	<10	<10	<10	<10	<10	<10	<10	<10
Bisphenol A	Used in plastics	--	<20	<20	<20	<20	<20	<20	<20	<20	<20
Bupropion	Antidepressant	--	<1	756	1.9	<1	<1	<1	<1	<1	<1
Caffeine	Stimulant	--	<5	336	14	11.6	11.9	9.7	14.6	11.8	6.2
Carbamazepine	Anti-epileptic	--	<1	368	4.0	<1	<1	<1	<1	<1	<1
Clarithromycin	Antibiotic	--	<1	2,877	<1	<1	<1	<1	<1	<1	<1
Cotinine	Nicotine metabolite	--	<1	48	<1	<1	<1	<1	1.6	<1	<1
DEET	Insect repellant	--	<20	130	<20	<20	<20	<20	<20	<20	<20
Diazinon	Insecticide	--	<1	30.4	<1	<1	<1	<1	<1	<1	<1
Diltiazem	Heart/blood pressure	--	<5	494	<5	<5	<5	<5	<5	<5	<5
Diphenhydramine	Antihistamine	--	<5	2,000	<5	<5	<5	<5	<5	<5	<5
Diuron	Herbicide	--	<5	54	<5	5.7	5.6	5.5	5.7	5.0	5.0
Erythromycin	Antibiotic	--	<10	793	<10	<10	<10	<10	<10	<10	<10
Fluridone	Aquatic herbicide	--	<5	<5	<5	<5	<5	<5	<5	<5	<5
Gemfibrozil	Cholesterol drug	--	<5	2,881	9.6	<5	<5	<5	<5	<5	<5
Metoprolol	Beta blocker	--	<1	2,535	6.0	1.9	1.5	1.6	1.8	2.8	1.4
Propanolol	Beta blocker	--	<1	286	<1	<1	<1	<1	<1	<1	<1
Sulfamethoxazole	Antibiotic	--	<5	1,261	28	<5	<5	<5	<5	<5	<5
Trimethoprim	Antibiotic	--	<5	1,531	<5	<5	<5	<5	<5	<5	<5
AUGUST 2010 Hormone & Phenolic Endocrine Disrupting Chemicals - analysis conducted by Underwriters Laboratories, Inc.:											
Progesterone	Hormone	--	<0.1	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Estrone	A natural estrogen		<0.5	6.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Nonylphenol	Surfactant/detergent metabolite		<0.5	1.1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Phenylphenol	Fungicide, disinfectant		<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

🟧	Detected in both sampling events
🟨	Detected in one sampling event

2.7 Northern Water Collaborative Horsetooth Reservoir Water Quality Modeling Study

A project to develop a hydrodynamic water quality model of Horsetooth Reservoir was begun in 2010 and should be completed in late 2011. The project is being managed by Northern Water with financial contributions from the City of Greeley, the City of Fort Collins, and Soldier Canyon Filter Plant. The collaborators selected Jean Marie Boyer (Hydros Consulting Inc.) to develop the model and run several scenarios. In 2010, a significant effort was made by Northern Water to provide an accurate daily water balance for the reservoir. This is important because if an accurate daily water balance cannot be achieved, an accurate simulation of water quality parameters cannot be achieved.

The development of a hydrodynamic water quality model for Horsetooth Reservoir will help us evaluate a range of inter-related water quality issues (D.O., TOC, nutrients, and water quality fate and transport) under situations that include interflow from the Hansen Feeder Canal and seasonal thermal stratification and turnover within the reservoir. Some of these inter-relationships are shown conceptually on Figure 2-11.

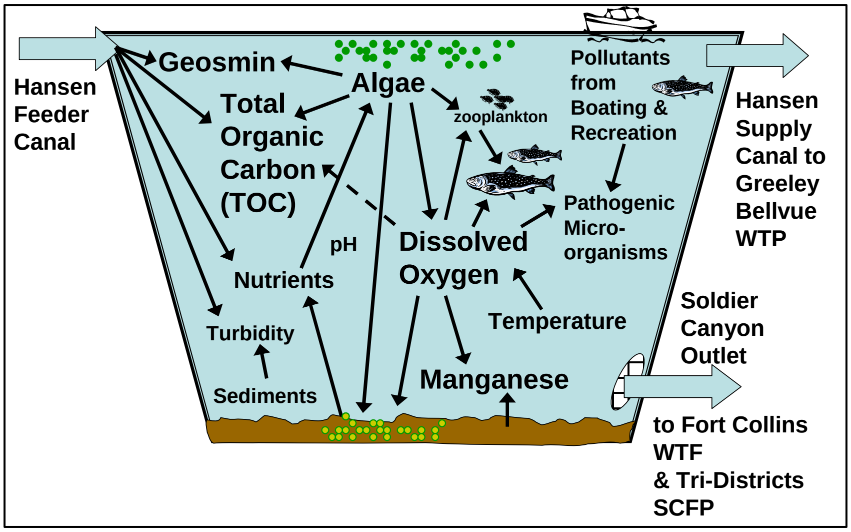


Figure 2-11. Inter-related water quality parameters in Horsetooth Reservoir.

The primary objectives of the Horsetooth Reservoir water quality model are to:

- Accurately mimic existing water quality conditions and dynamics.
- Help gain a better understanding of the general limnological processes occurring in Horsetooth Reservoir and possible reasons for low D.O. in the reservoir.
- Provide a tool to investigate the impact of reservoir hydrodynamics and operations on flow paths, water quality transport, and water age.

2.8 Wildfires and Watershed Wildfire Assessments

2010 Wildfires. Wildfires that occurred in parts of the Big Thompson and/or Horsetooth Reservoir watersheds in 2010 include the Cow Creek, Round Mountain, Reservoir Road, and Bighorn Fires. Characteristics of these fires are outlined below in Table 2-2. None of these fires has had a measureable (if any) impact on Horsetooth Reservoir water quality.

Table 2-2. Summary of wildfires that occurred in 2010 within the Big Thompson Watershed or Horsetooth Reservoir Watershed.

Fire Name	Location	Date Started/ Controlled	Cause	Acres burned	Burned area drains to Horsetooth Res?
Cow Creek	West Creek Drainage, Rocky Mtn Nat'l Park; 4 miles west of Glen Haven	June 2010/ Nov 2010	Lightning	1,200	Yes; however, in remote area that drains to North Fork Big Thompson River
Round Mountain	3 miles east of Drake, south of Hwy 34 in Big Thompson River canyon	June 25, 2010/ June 30, 2010	Human caused	76	Yes; drains to Big Thompson River upstream of Dille Tunnel
Reservoir Road	4 miles west of Loveland, near CBT System Pinewood and Flatiron Reservoirs	Sept 12, 2010/ Sept 16, 2010	Human caused	750	No; not part of drainage areas for nearby CBT reservoirs and conveyance system
Bighorn	On ridge adjacent to Bighorn Crossing Rd, Stout Wild Lane, and West Cty Rd 38E, just off southern end of Horsetooth Res	Oct 10, 2010/ Oct 10, 2010	Human caused	6	Yes; drains directly to Horsetooth Res.

Suppression of the Reservoir Road Fire (Figure 2-12) included the use of retardant slurry dropped onto the fire by air tankers. Fire retardant slurries generally consist of water, fertilizers (ammonium phosphate or ammonium sulfate), clay thickeners, and color (red dye). Although rules exist for dropping retardants near water bodies, the use of ammonium-based fire retardants has been implicated in fish kills and in the establishment of noxious weeds. A federal judge ordered the U.S. Forest Service to more thoroughly evaluate the toxic effects of ammonium-based fire retardants on plants and animals. The evaluation was presented in a draft Environmental Impact Statement (EIS) issued in May 2011; a final EIS and a decision on continuing the aerial application of fire retardants on U.S. Forest Service lands is expected by the end of 2011 (http://www.fs.fed.us/fire/retardant/index.html).

Figure 2-12. Reservoir Road Fire, Sept 14, 2010.

Cache la Poudre Wildfire Watershed Assessment. In 2010, the City of Fort Collins and the City of Greeley jointly funded the Cache la Poudre Wildfire Watershed Assessment Project conducted by J.W. Associates Inc. The local Horsetooth Reservoir watershed is a sixth-level watershed within the Cache la Poudre watershed and was therefore included in this wildfire assessment. The project included four meetings attended by key watershed stakeholders including the City of Fort Collins, City of Greeley, Tri-Districts, U.S. Forest Service, Colorado State Forest Service, Larimer County, and Northern Water.

The susceptibility of water supplies to impacts from severe wildfires was evaluated based on four main watershed characteristics: wildfire hazard, flooding/debris flow hazard, soil erosivity and the location of critical water supply infrastructure. In addition, the project identified opportunities to protect water supplies from debris flows and sediment loads resulting from high-severity wildfires. All sixth-level watersheds of the Cache la Poudre watershed were considered. Results identified a limited number of opportunities for protection in areas along roadsides and around reservoirs where hazard-fuel reduction work is planned by the State and US Forest Service, as well as areas where existing forest treatments could potentially be expanded or linked together. The full report, including a full summary of identified opportunities, is available at:

> http://www.jw-associates.org/Projects/Poudre_Main/Poudre_Main.html.

Page 97 of the report states the following with respect to opportunities related to the 11,051 acre Horsetooth Reservoir zone of concern (i.e., the Horsetooth Reservoir sixth-level watershed):

> *The Poudre Fire Authority Community Wildfire Protection Plan (CWPP) covers the entire zone of concern. The Loveland CWPP covers the southern portion of the zone of concern. The CWPPs should be reviewed for additional proposed treatments that would contribute to watershed-level protection. If the CWPPs do not address watershed issues and protection, there would be a good opportunity to inform the Fire Protection Districts, agencies, and area residents about this issue and to collaborate with them to update the CWPPs as necessary.*
>
> *Some existing treatments have been completed in Lory State Park and on Larimer County lands. There is good opportunity to partner with these agencies on future, and possibly, expanded treatments. Follow-up thinning of regenerated stands and ongoing, periodic maintenance should be conducted. Consider also developing fuel breaks along the road corridors that run through the zone of concern.*

Big Thompson Wildfire Watershed Assessment. An assessment of the Big Thompson Watershed will be conducted in 2011 by J.W. Associates Inc. using the same methodology as was used for the Cache la Poudre Wildfire Watershed Assessment. This assessment is important since the Big Thompson Watershed forms part of the total land area that drains to Horsetooth Reservoir via the CBT Project.

2.9 Mountain Pine Beetles

The mountain pine beetle (MPB), *Dendroctunus ponderosae*, is native to forests of western North America. Periodically, populations increase to result in regional outbreaks of beetle-related tree deaths. The current outbreak, which began in the late 1990's, has grown to ten times the size of the largest previously known outbreak and continues to expand through forests dominated by Lodgepole and Ponderosa pines (*Pinus contorta* and *Pinus ponderosa*). The result has been expansive swaths of dead and dying trees across the Rocky Mountain West.

Information from the US Forest Service (USFS) and Colorado State Forest Service 2010 Forest Health Aerial Survey provided by the USFS (http://www.fs.fed.us/r2/news/press-kits/2010/index.shtml) reports that the total number of infested acres in Colorado and southern Wyoming increased by 400,000 acres in 2010, bringing the total number of affected acres to 4 million since 1996. The 2010 USFS Forest Health Aerial Survey shows rapid eastward spread of the MPB into lower elevation Lodgepole and Ponderosa pine stands along the Northern Colorado Front Range. The local Horsetooth Reservoir watershed and the upstream watersheds of the CBT system (the Big Thompson Watershed and Three Lakes Watershed on the western slope) are located within areas impacted by high recent forest mortality (Figures 2-13 and 2-14).

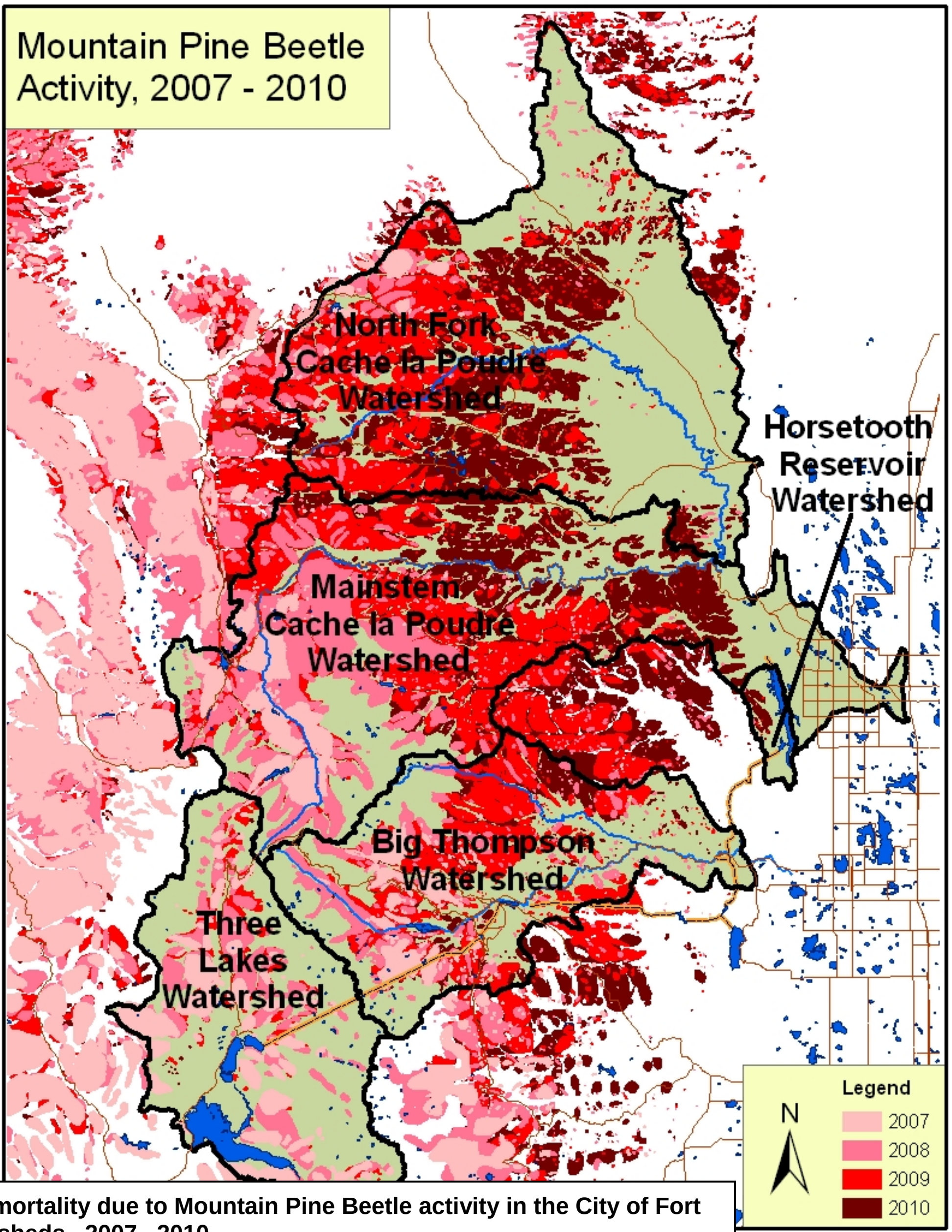


Figure 2-13. Forest mortality due to Mountain Pine Beetle activity in the City of Fort Collins source watersheds, 2007– 2010.

MPB Effects on Wildfire. During the phase of forest dieback in which affected trees retain their needles, there is a short-term elevated risk of high severity wildfire. Research continues on forest management options to improve post-outbreak forest health (McDonald and Stednick, 2003; Uunila et. al, 2006; LeMaster et al., 2007), as well as options for protecting communities and critical water supplies against the effects of wildfire (LeMaster et al., 2007; FRWWPP, 2009).

Following the loss of the red needles, the forest enters the gray phase in which the dead needles have fallen to the forest floor. The reduced amount of fine fuels in the forest canopy dramatically lowers the risk of high-severity wildfires. However, even in the absence of wildfire, the potential widespread changes in vegetative cover that occur as a result of extensive forest die-back can potentially affect water quality and quantity in the watersheds that contribute flow to Horsetooth Reservoir. Potential impacts include changes in stream flow and stream temperatures, increased sediment loads following precipitation events, as well as increases in-stream nutrient and TOC levels.

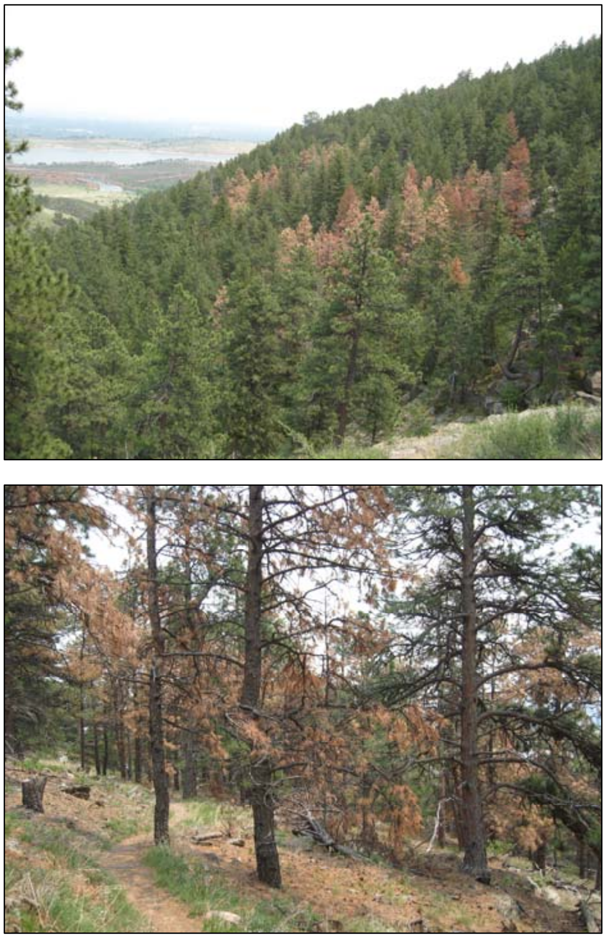


Figure 2-14. Trees impacted by bark beetles in Lory State Park west of Horsetooth Reservoir.

Larimer County actively manages the forested areas in Horsetooth Mountain Open Space just west of Horsetooth Reservoir according to their forest management plan (updated 2010). Management activities are conducted in specified treatment areas and focus on thinning trees to reduce basal area, removing poor growth, dense stands and diseased/infested trees. They do not, however, specifically target trees affected by MPB unless they happen to fall within a treatment area (personal communication, Meegan Flenniken, Larimer County Natural Resources).

MPB Effects on Water Quality and Quantity. In April 2011, the Western Water Assessment (WWA) in Boulder, CO convened a follow-up symposium to the “2010 MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality” to summarize the most recent lessons learned from completed and ongoing studies.

Some of the observed changes in water quality that were reported at the 2010 WWA symposium include instances of increases in TOC and DOC concentration in streams (Stednick, 2010; McCutchan, 2010), increases in soil (N) and stream nutrient levels (N and P) (Rhoades, 2010; Clow,2010; and McCutchan, 2010), and increases in stream temperatures where riparian areas were affected (Stednick, 2010). However, many of the anticipated changes in water quality have not been realized to the magnitude that would present problems for human uses or aquatic ecosystems (Lukas and Gordon, 2010). Similarly, there have been some observed changes in the energy and hydrologic process related to snowpack accumulation as well as the timing of snow melt runoff, but significant changes in amount of runoff have not been linked to these effects of MPB mortality (Lukas, 2011).

2.10 Invasive Mussels

Zebra and quagga mussels (*Dreissena* spp) were introduced to the United States in the early 1980’s and are considered to be among the worst aquatic nuisance species to be introduced to North America. These dreissinid mussels are prolific filter-feeders and can severely disrupt aquatic food webs by altering the quantity and distribution of phytoplankton available for higher level consumers and by out-competing native species for food and habitat. Mussel infestations can also have devastating economic and recreational impacts. Large masses of mussels can clog water conveyance structures, increase maintenance costs and discourage recreation by damaging boats, weighing down floating docks and buoys and littering shorelines with dead and decaying mussels.

In 2008, the Colorado Division of Wildlife (CDOW) initiated an invasive mussel sampling and monitoring program in water bodies of Colorado in accordance with the 2008 State Zebra and Quagga Mussel Management Plan. Under this sampling program, quagga mussel larvae (veligers) were conclusively identified in July 2008 in Lake Granby, an upper western slope reservoir of the CBT conveyance system that feeds into Horsetooth Reservoir. Other west slope CBT reservoirs that have since tested positive for zebra and quagga mussel veligers are Willow Creek Reservoir, Shadow Mountain Reservoir and Grand Lake. However, no veligers have been found, to date, in any eastern slope reservoir of the CBT project. There were no positive detections of zebra or quagga mussel veligers or adult mussels in any Colorado water in 2010 (Colorado Division of Wildlife and Colorado State Parks, 2010).

CDOW has identified Horsetooth Reservoir as a ‘high risk’ water body based on its downstream position from other ‘positive’ water bodies in the CBT system and the high level of out-of-state boating activity it receives. The ranking criteria for determining a water body’s vulnerability to invasion by zebra or quagga mussels are detailed in Anderson et al., 2008. As an at-risk water body, preventing infestations in Horsetooth Reservoir depends on two main efforts – the Larimer County mandatory boat inspection program and the CDOW Zebra/Quagga mussel sampling and monitoring program.

In 2009, CDOW initiated a boat inspection and decontamination program to control the introduction of invasive mussels into clean water bodies. In cooperation with CDOW, Larimer County began mandatory inspections for all boats on Carter and Boyd Lakes and Horsetooth Reservoir in April 2009. Statewide, watercraft inspection and decontamination stations, including the Horsetooth Reservoir station, intercepted 19 boats in 2009 and 14 boats in 2010 with attached adult zebra or quagga mussels (Colorado Division of Wildlife and Colorado State Parks, 2010). The City of Fort Collins complies with all boating inspections prior to and following each of the Horsetooth sampling events as well as the “Clean, Dry and Drain” principles promoted by CDOW to reduce the potential for mussel spread.

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 HFC or the Inlet 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 (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 (estimate) = HFCBBSCO - HFCLOVCO

HFCBBSCO and HFCLOVCO data are available on the Colorado Division of Water Resources web site for flow gaging stations in the South Platte River Basin (http://www.dwr.state.co.us/SurfaceWater/data/division.aspx?div=1). HFCLOVCO data are also available on Northern Water's website (http://www.ncwcd.org/datareports/flowdata.asp?sid=4010).

Daily inflows from the Hansen Feeder Canal are plotted on Figure 3-1 for 2005 through 2010. The graph indicates that there is nearly continuous inflow to Horsetooth Reservoir except during short periods (one to two weeks) each fall when the canal is shut down for annual maintenance. In 2010, the canal was shut down from October 1 through October 15. The total 2010 *estimated* annual inflow to Horsetooth Reservoir from the Hansen Feeder Canal was 147,600 acre-feet (ac-ft) as summarized on Table 3-1.

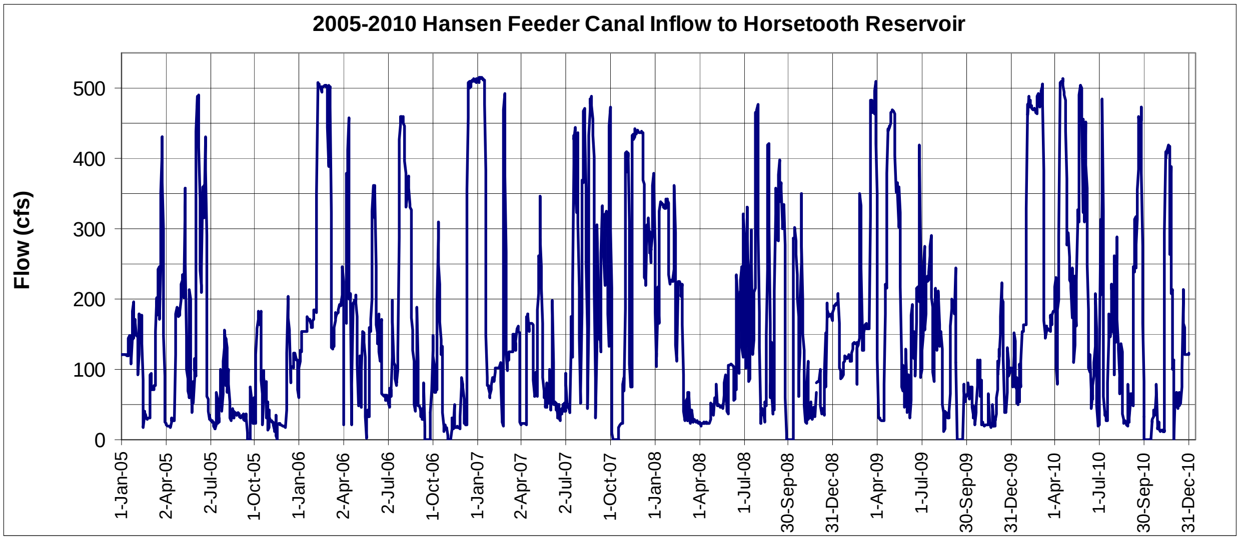


Figure 3-1. **2005 to 2010 estimated Hansen Feeder Canal Inflow to Horsetooth Reservoir (HFCBBSCO - HFCLOVCO).**

The Horsetooth Reservoir local watershed includes several small, intermittent drainages that flow into the west side of the Reservoir (including Soldier 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 ungaged and are considered insignificant (at least on an annual basis) compared to the Hansen Feeder Canal inflow.

There are two engineered outlets from Horsetooth Reservoir: the Hansen Supply Canal at Horsetooth Dam, and the Soldier Canyon Dam Outlet. The Hansen Supply Canal operates during the irrigation season and conveys water to the City of Greeley Bellvue Water Treatment Plant (WTP) and to the Poudre River and farmers on the eastern Plains. The Soldier Canyon Dam Outlet, located near the bottom of the reservoir, provides water to the FCWTF, the Tri-Districts Soldier Canyon Filter Plant (SCFP), Colorado State University research facilities, Platte River Power Authority, and Dixon Reservoir (via the Dixon Feeder Canal). Water can also be sent from the Soldier Canyon Dam Outlet to the Bellvue WTP via the Pleasant Valley Pipeline (PVP) in the winter and early spring (when the pipeline is not being used to convey Poudre River water), although quantities to date have been small (Table 3-1). The Soldier Canyon Dam Outlet provides a continuous (year round) supply of raw water to the FCWTF and the SCFP.

Evaporation and seepage are two additional outflows from the reservoir. Annual evaporation data are summarized on Table 3-1. Horsetooth Reservoir seepage data is not available and is assumed to be a minor component of the water balance.

Outflow from Horsetooth Reservoir to the FCWTF and the Tri-Districts SCFP via the Soldier Canyon Dam Outlet and to the Hansen Supply Canal are graphed on Figure 3-2 and summarized on Table 3-1 for 2005 through 2010. Note from Table 3-1 that these are the two primary sources of outflow from the reservoir. On average, the annual outflow to the Hansen Supply Canal is roughly three times the outflow at Soldier Canyon Dam even though the Hansen Supply Canal is generally off from November through April while flow to the FCWTF and SCFP at the Soldier Canyon Dam outlet occurs continuously.

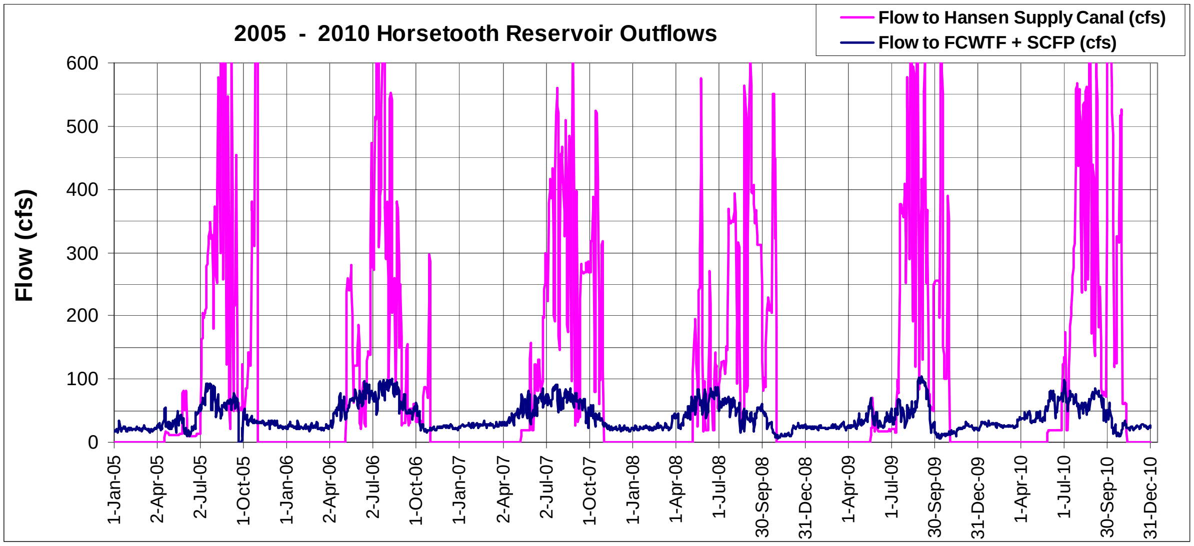


Figure 3-2. 2005 to 2010 Horsetooth Reservoir Outflows at Soldier Canyon Dam Outlet and the Hansen Supply Canal (Note: 1 cfs = 0.646 mgd).

Table 3-1. Summary of 2005 - 2010 Annual (Calendar Year) Hydrologic Data for Horsetooth Res.

	Units	**Data Source**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
INFLOWS:								
Direct Precipitation	Inches /yr	Sum of USBR Daily Operations Report data	16.2	10.9	13.6	13.3	21.8	13.9
	ac-ft/yr	Calculated, assumed reservoir surface area of 1900 acres	2,600	1,700	2,200	2,100	3,500	2,200
Hansen Feeder Canal Inflow to Horsetooth	ac-ft/yr	Sum of daily totals: HFC below Big Thompson Siphon (HFCBBSCO data) minus HFC Loveland Turnout (NCWCD data)	76,300	133,600	143,200	100,200	107,100	147,600
Total *estimated* inflow	Total ac-ft/yr	Calculated: Sum of annual inflow values	78,900	135,300	145,400	102,300	110,600	149,800
OUTFLOWS:								
Evaporation	ac-ft/yr	Sum of USBR Daily Operations Report data	4,100	3,800	4,100	4,000	3,100	4,100
Soldier Canyon Outlet to Dixon Feeder Canal Replacement Deliveries	ac-ft/yr	Sum of monthly data from NCWCD	730	680	780	600	620	730
Soldier Canyon Outlet to Dixon Feeder Canal CBT Project Deliveries	ac-ft/yr	Sum of USBR Daily Operations Report data	250	530	260	220	180	270
Soldier Canyon Outlet to Bellvue WTP via PVP	ac-ft/yr	Sum of monthly data provided by City of Greeley	Not used	Not used	730	950	540	580
Soldier Canyon Outlet to FCWTF + SCFP	ac-ft/yr	Sum of daily flow data from FCWTF and Tri-Districts SCFP	25,100	32,800	31,200	27,500	24,100	30,300
Flow to Hansen Supply Canal	ac-ft/yr	Sum of USBR Daily Operations Report data	74,300	72,300	85,200	79,900	74,000	87,100
Total *estimated* outflow	Total ac-ft/yr	Calculated: Sum of annual outflow values	104,480	110,110	122,270	113,170	102,540	123,080
VOLUME & HYDRAULIC RESIDENCE TIME:								
Volume, Annual average	ac-ft	Average of daily values from USBR Daily Operations Report	111,700	92,500	100,100	103,000	100,480	108,740
Estimated Hydraulic Residence Time	years	Calculated: [average annual reservoir volume] / [total estimated annual outflow]	1.1	0.84	0.82	0.91	0.98	0.88

Note: 1 ac-ft = 43,560 ft^3 = 325,851 gal

Table 3-2. Summary of 2006 - 2010 WATER YEAR (WY) Hydrologic Data for Horsetooth Reservoir

	Units	Data Source		WY 2006	WY 2007	WY 2008	WY 2009	WY 2010
INFLOWS:								
Direct Precipitation	Inches /yr	Sum of USBR Daily Operations Report data		8.98	15.74	15.26	19.18	16.1
	ac-ft/yr	Calculated, assumed reservoir surface area of 1900 acres		1,422	2,492	2,416	3,037	2,549
Hansen Feeder Canal Inflow to Horsetooth	ac-ft/yr	Sum of daily totals: HFC below Big Thompson Siphon (HFCBBSCO data) minus HFC Loveland Turnout (NCWCD data)		118,352	127,641	124,821	114,497	140,574
Total *estimated* inflow	Total ac-ft/yr	Calculated: Sum of annual inflow values		119,800	130,100	127,200	117,500	143,100
OUTFLOWS:								
Evaporation	ac-ft/yr	Sum of USBR Daily Ops Report data		3,772	4,036	3,928	3,232	4,041
Soldier Canyon Outlet to Dixon Feeder Canal Replacement Deliveries	ac-ft/yr	Sum of monthly data from NCWCD		711	674	769	576	684
Soldier Canyon Outlet to Dixon Feeder Canal CBT Project Deliveries	ac-ft/yr	Sum of USBR Daily Operations Report data		481	312	209	198	264
Soldier Canyon Outlet to Bellvue WTP via PVP	ac-ft/yr	Sum of monthly data provided by City of Greeley		Not used	730	950	540	580
Soldier Canyon Outlet to FCWTF + SCFP	ac-ft/yr	Sum of daily flow data from FCWTF and Tri-Districts SCFP		33,850	30,535	28,902	24,700	29,023
Flow to Hansen Supply Canal	ac-ft/yr	Sum of USBR Daily Operations Report data		85,477	72,185	82,307	71,654	76,107
Total *estimated* outflow	Total ac-ft/yr	Calculated: Sum of annual outflow values		124,300	108,500	117,100	100,900	110,700
VOLUME & HYDRAULIC RESIDENCE TIME:								
Volume, Annual average	ac-ft	Average of daily values from USBR Daily Operations Report		93,180	98,539	103,926	101,614	106,741
Estimated Hydraulic Residence Time	years	Calculated: [average annual reservoir volume] / [total estimated annual outflow]		0.75	0.91	0.89	1.0	0.96

Note: Water Year begins Oct. 1 of previous year and ends on following Sept 30 (e.g., WY 2010 starts Oct 1, 2009 and ends Sept. 30, 2010).

3.2 Water Levels, Volumes, and Estimated Hydraulic Residence Time

Horsetooth Reservoir water surface elevations annually fluctuate 35 to 50 feet in response to water entering the reservoir from the Hansen Feeder Canal and water being released from the reservoir at the Soldier Canyon Dam Outlet and to the Hansen Supply Canal. Water levels and reservoir volumes are lowest in the late fall after the end of the irrigation season and rise over the winter during the reservoir filling period (Figures 3-3 and 3-4). Water levels and volumes are highest in the late spring or early summer before water is released to meet irrigation demands on the eastern Plains. The water surface elevation at full capacity is 5,430 feet.

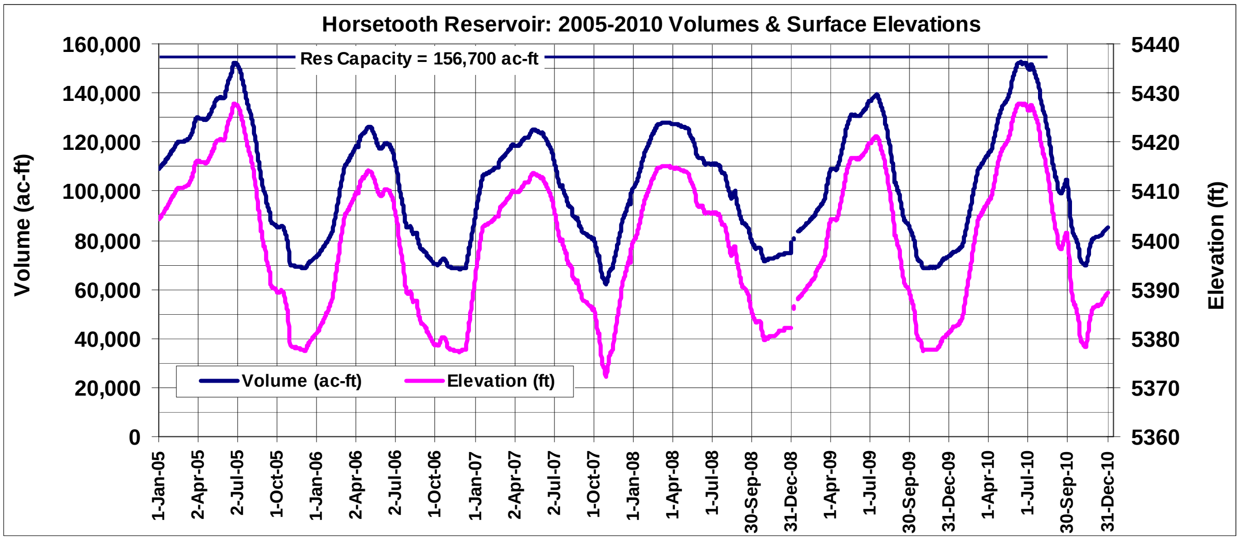


Figure 3-3. **2005 to 2010 Daily Horsetooth Reservoir volumes and water surface elevations (from USBR Daily Operations Report).**

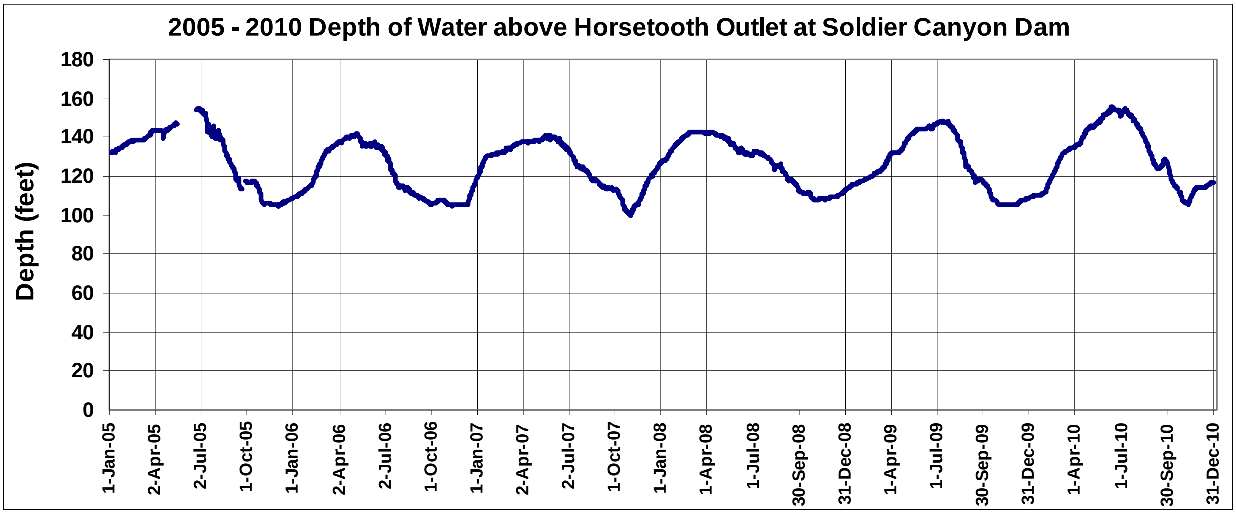


Figure 3-4. **2005 to 2010 Depth of Water above Horsetooth Reservoir Soldier Canyon Dam Outlet (from FCWTF database).**

The estimated annual hydraulic residence time was calculated as the average reservoir volume over the year divided by the total annual outflow (Table 3-1). The estimated hydraulic residence time for calendar year 2010 is 0.88 years, and ranged from 0.82 to 1.1 years for the six year period of 2005 through 2010.

4.0 HANSEN FEEDER CANAL (HORSETOOTH INLET) WATER QUALITY

This section summarizes Hansen Feeder Canal water quality data collected by FCU including the continuous monitoring sonde data and the grab sample data. Hansen Feeder Canal flows are used with weekly measurements of TOC to calculate TOC mass loads to the reservoir.

4.1 Continuous Monitoring (Sonde) Data

The City of Fort Collins operates and maintains a multi-parameter YSI probe (sonde) with continuous monitoring at the C50 Hansen Feeder Canal site. The C50 sonde continuously measures water temperature, dissolved oxygen, and specific conductance, and records six values each day at times 00:00, 04:00, 08:00, 12:00, 16:00, and 20:00.

Plots of the 2010 sonde temperature, dissolved oxygen, and specific conductance data are found on Figures 4-1, 4-2, and 4-3, respectively. The temperature and dissolved oxygen plots show diurnal fluctuations as well as seasonal changes in the data. The 2010 temperature data (Figure 41) show an increasing trend in values until late summer, followed by a decreasing trend to the end of the year. In 2010, the maximum water temperature measured in the Hansen Feeder Canal was 21.2°C on July 31. The temperature fluctuations observed during the second half of the year are related to the operation of the CBT system. For example, the jump in temperature seen at the beginning of December coincides with a change in source flows to the Hansen Feeder Canal. From mid-October to the end of November, the majority of flows were being diverted to the Hansen Feeder Canal at the Dille Tunnel; beginning on December 1, flows to the Hansen Feeder Canal came from Flatiron Reservoir.

The 2010 dissolved oxygen data (Figure 4-2) show a decreasing trend in concentrations until late summer, followed by an increasing trend to the end of the year. Among other things, dissolved oxygen concentrations are inversely related to water temperature (i.e., saturation decreases with increasing temperature), and the decreases and increases in D.O. concentrations generally follow the increases and decreases in temperature. On a daily basis, the minimum dissolved oxygen values occur in the early morning. The minimum dissolved oxygen concentrations were in the range of 7.0 to 7.3 mg/L during August.

The 2010 specific conductance sonde data (Figure 4-3) show a decrease in specific conductance during the spring as a result of dilution of flows in the Big Thompson River water by snowmelt waters. Big Thompson River water typically makes up a significant portion of flow in the Hansen Feeder Canal during the spring runoff. From May 9 to June 26, 2010, Adams Tunnel water made up less than 10% of the water flowing into Lake Estes. As a result, greater than 90% of the water flowing in the east slope CBT system during this time was Big Thompson River water. Minimum specific conductance values occurred in Hansen Feeder Canal water in mid-June, coincident with the peak of the Big Thompson River spring runoff. The specific conductance then slowly increased over the next several months. The jump in values seen at the beginning of December coincides with a change in source flows to the Hansen Feeder Canal as described above for the temperature data.

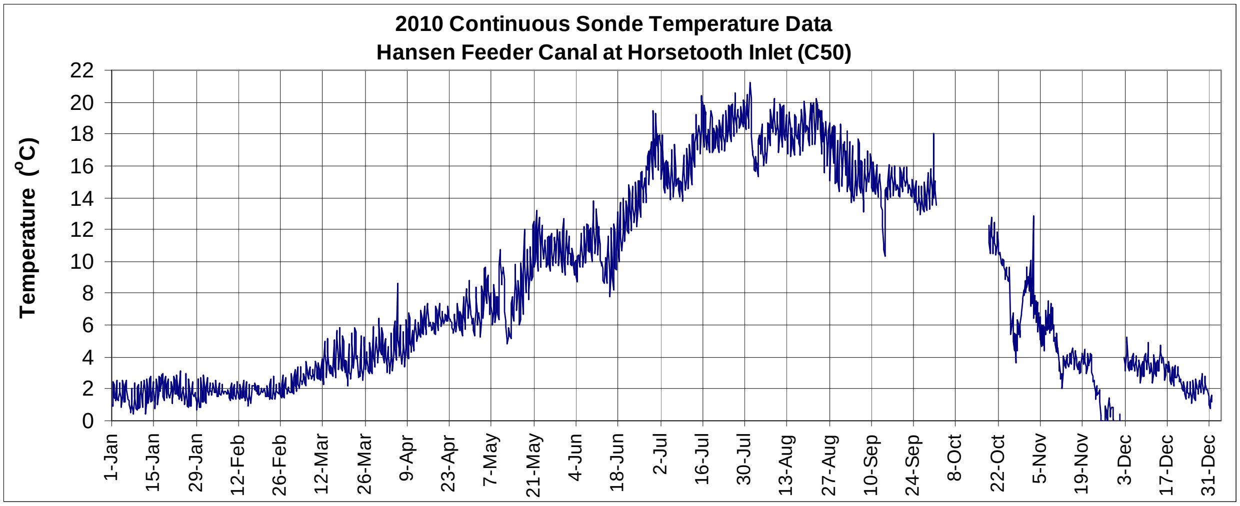


Figure 4-1. 2010 Hansen Feeder Canal continuous sonde temperature data.

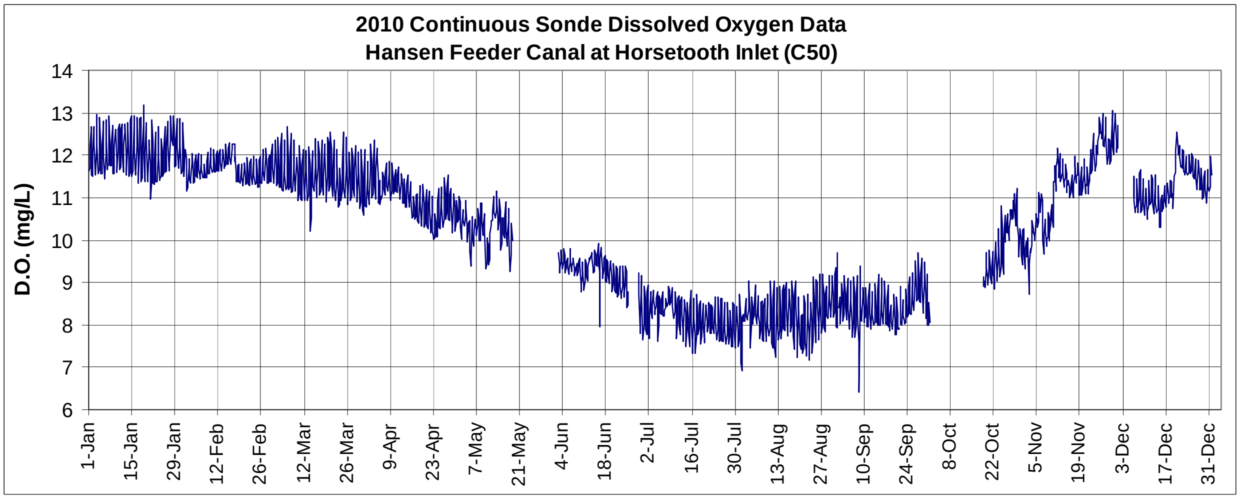


Figure 4-2. 2010 Hansen Feeder Canal continuous sonde dissolved oxygen data.

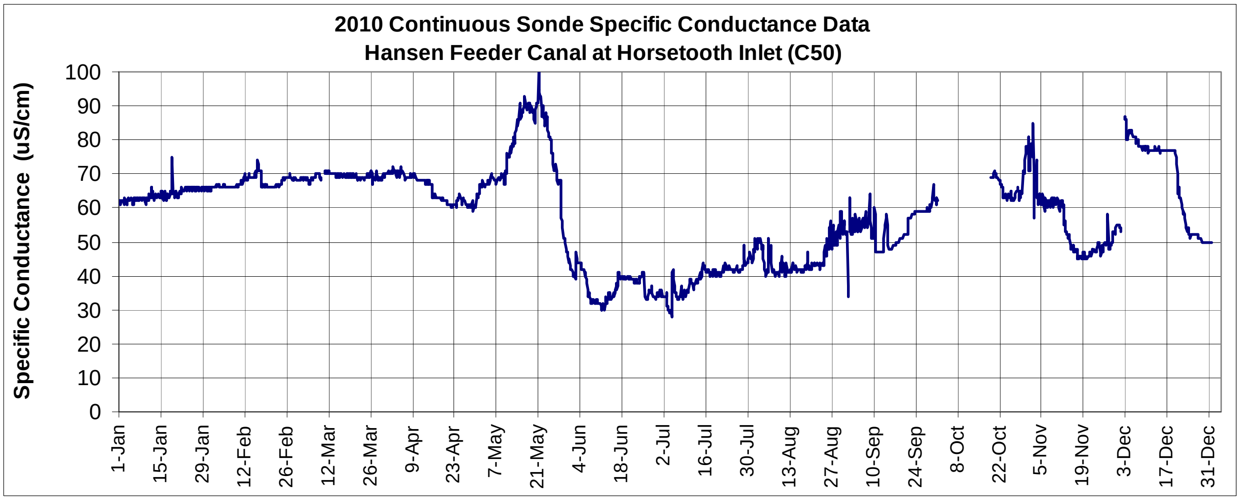


Figure 4-3. 2010 Hansen Feeder Canal continuous sonde specific conductance data.

4.2 Grab Sample Data

Table 1-3 listed the parameters that are analyzed in grab samples collected from the Hansen Feeder Canal inflow to Horsetooth Reservoir. These parameters were summarized and presented in the 2009 FCU Horsetooth Reservoir Water Quality Monitoring Program Report for the five-year period 2005 through 2009. For this 2010 Report, only general parameters, TOC, and phytoplankton data will be presented.

4.2.1 General Parameters: Specific conductance, TDS, alkalinity, pH, turbidity

Total dissolved solids (TDS) and specific conductance are generally lowest in June and July after the snowmelt period (Figure 4-5). A visual inspection of Figure 4-5 indicates that on average, both the TDS and specific conductance were higher in 2010 than in the previous five years. The 2010 sonde specific conductance data is compared on Figure 4-6 to the grab sample lab data. The two data sets follow the same general patterns, although the 2010 grab sample lab data are consistently higher than the 2010 sonde data.

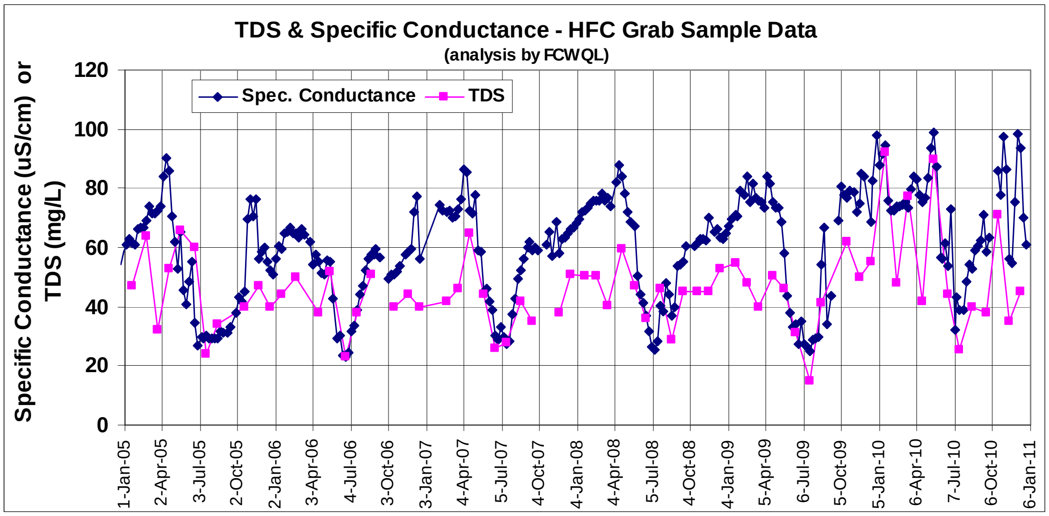


Figure 4-4. Hansen Feeder Canal grab sample TDS and specific conductance data.

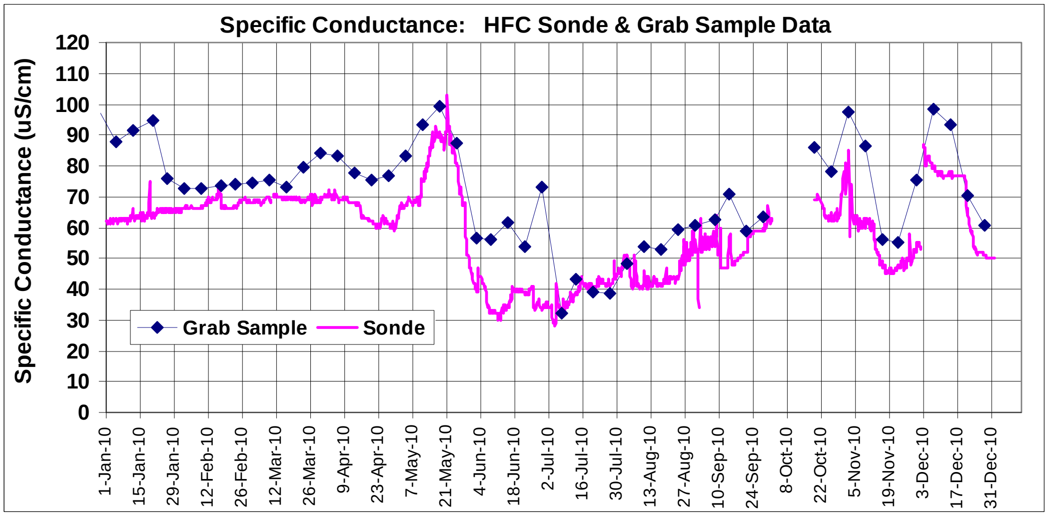


Figure 4-5. Comparison of Hansen Feeder Canal grab sample and sonde specific conductance data.

Alkalinity and pH exhibit the typical pattern with values lowest in June and July (Figure 4-7). Alkalinity drops during the snowmelt runoff period from values of approximately 30 mg/L as $CaCO_3$ down to values of approximately 10 mg/L as $CaCO_3$; this is similar to what is observed on the Poudre River during the spring snowmelt runoff period.

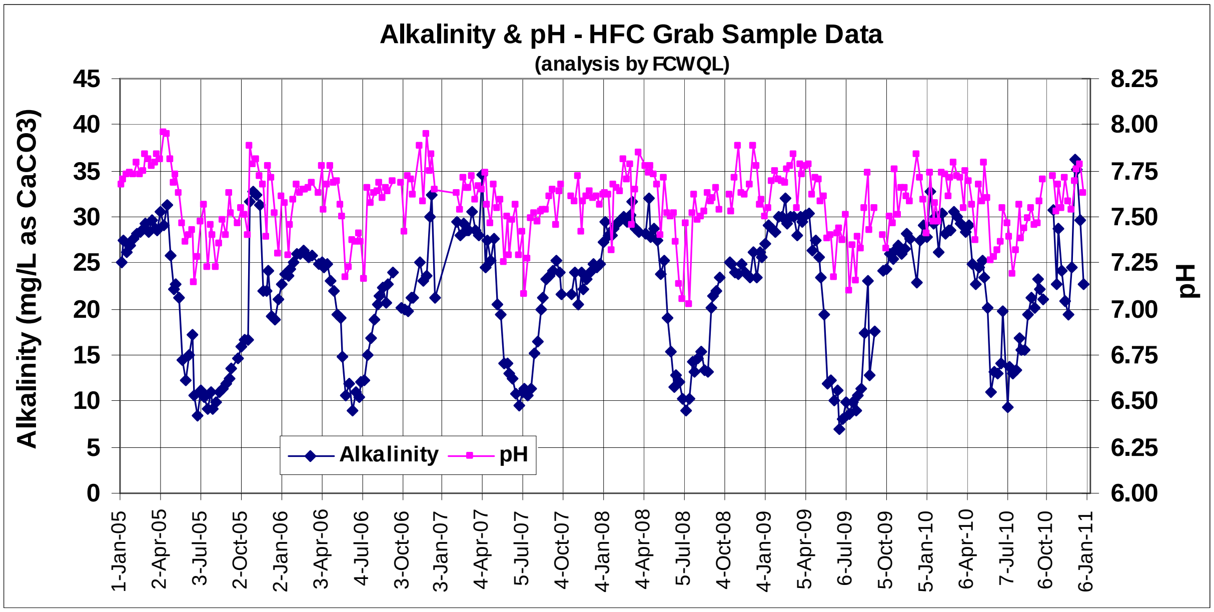


Figure 4-6. Hansen Feeder Canal grab sample alkalinity and pH data.

Turbidity is generally lowest from January through March (Figure 4-7), with an increase in May to July depending on the amount of Big Thompson River water that enters the canal during the spring runoff period. The turbidity was high in the Hansen Feeder Canal during the 2010 spring runoff period since a significant fraction of the flow was from the Big Thompson River.

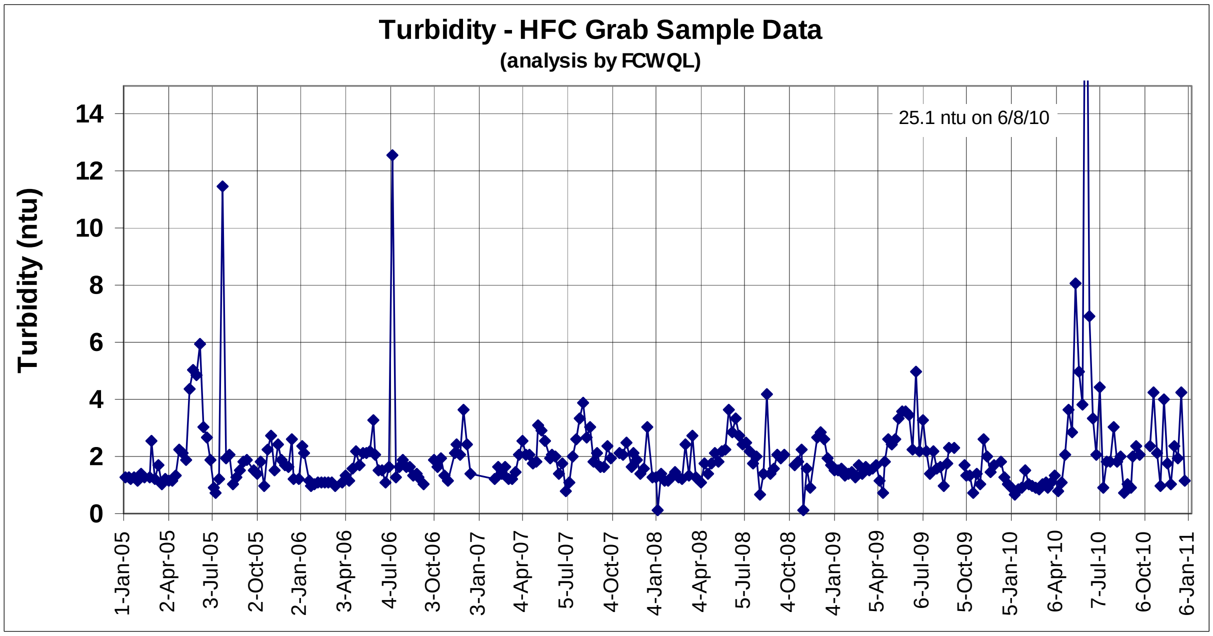


Figure 4-7. Hansen Feeder Canal grab sample turbidity data.

4.2.2 Total Organic Carbon (TOC)

The Hansen Feeder Canal is the primary source of water to Horsetooth Reservoir and also a significant source of TOC. The results of weekly TOC sampling conducted by the FCWQL are shown on Figure 4-8 for the six year period of 2005 to 2010.

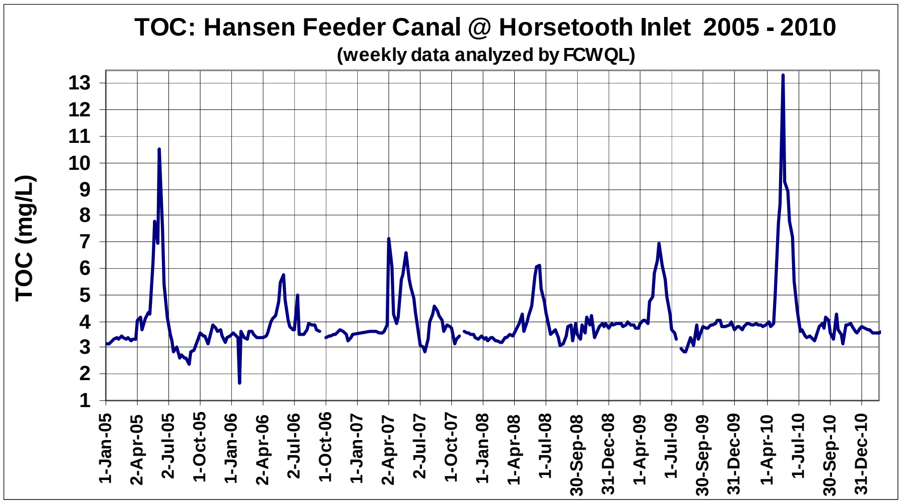


Figure 4-8. Hansen Feeder Canal TOC concentrations.

Water in the Hansen Feeder Canal is a mix of water from the west slope (via the Adams Tunnel) and the Big Thompson River, and takes on characteristics of both sources. During most of the year, the TOC concentration in Hansen Feeder Canal water is within the range of 3 to 4 mg/L, very similar to concentrations in water from the Adams Tunnel (Figure 4-9) since 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 (with its runoff-related high TOC concentrations) comprises a significant fraction of the total flow in the Hansen Feeder Canal. In May and June 2010, high TOC Big Thompson River waters made up most (>90%) of the Hansen Feeder Canal flow (Figure 4-10), resulting in very high TOC concentrations.

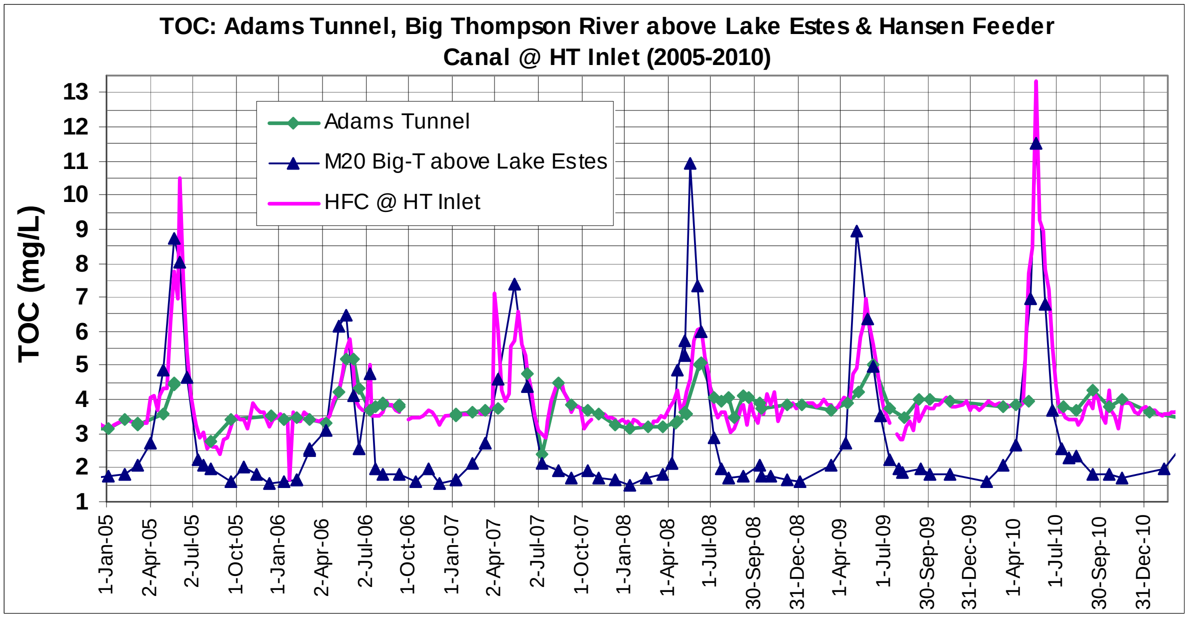
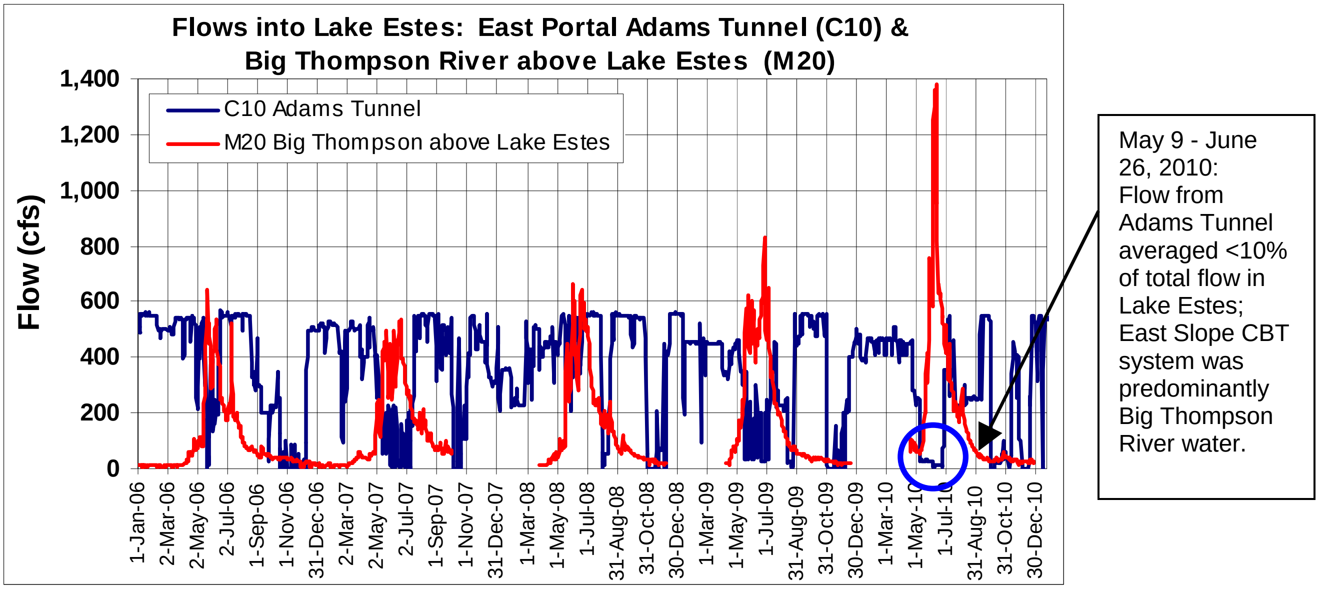


Figure 4-9. TOC concentrations in water from the Adams Tunnel, the Big Thompson River above Lake Estes, and the Hansen Feeder Canal upstream of Horsetooth Reservoir.



May 9 - June 26, 2010: Flow from Adams Tunnel averaged <10% of total flow in Lake Estes; East Slope CBT system was predominantly Big Thompson River water.

Figure 4-10. Flows at East Portal Adams Tunnel and Big Thompson River above Lake Estes

4.2.3 Phytoplankton

Phytoplankton are microscopic, free-floating algae and cyanobacteria that can be carried in the CBT canals from reservoir to reservoir. The 2010 phytoplankton data for the Hansen Feeder Canal (at the Horsetooth Inlet) indicate that the densities (cells/mL) were very low compared to values measured within Horsetooth Reservoir (see Section 5.2.5) except for the November sample. During the November sampling event, all water going to Horsetooth Reservoir was entering the Hansen Feeder Canal via the Dille Tunnel since the canal below Flatiron Reservoir was off for maintenance. This may have impacted the phytoplankton density observed for the November 16, 2010 sample.

Green algae were the most abundant algae group during all sampling events (Figure 4-11). *Chlorella minutissima* was the dominant green algae, while the dominant blue-green algae included *Aphanothece smithii* and the genus *Aphanocapsa*.. During the November sampling event, approximately 4% of the total count was made up of geosmin producing species including *Lyngbya* sp., *Planktothrix agardhii, and Pseudanabaena catenata.*

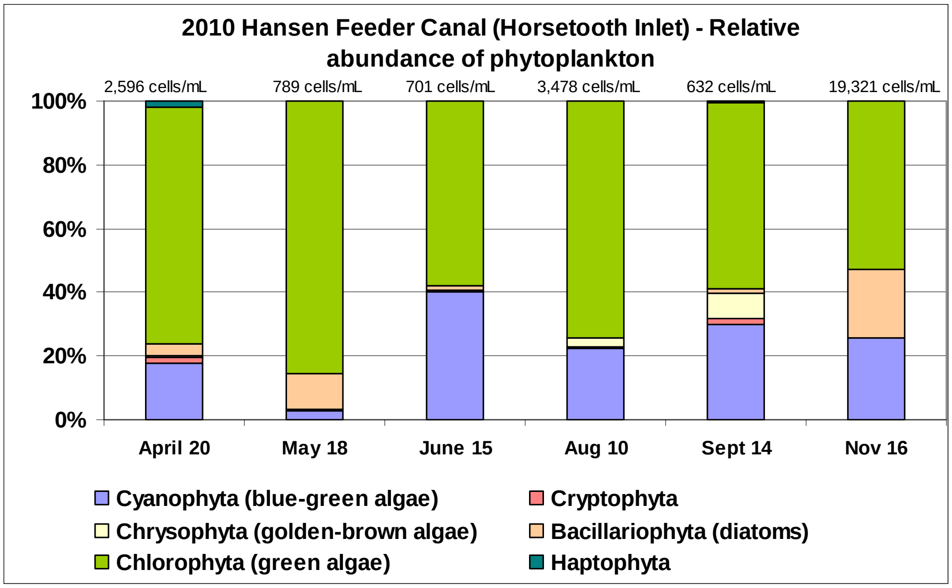


Figure 4-11. **Relative abundance (based on # cells/mL) of phytoplankton groups found in the 2010 samples from the Hansen Feeder Canal (Horsetooth Inlet).**

4.3 Flow Weighted Concentrations and Mass Loads of TOC to Horsetooth Reservoir

Annual flow weighted concentrations and mass loads of TOC entering Horsetooth Reservoir from the Hansen Feeder Canal were calculated using daily flow data for the Hansen Feeder Canal (see Section 3.1) and weekly (or near weekly) TOC 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 previous sampling day (Day_{i-1}) and 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):

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

Similar calculations are conducted to estimate monthly mass loads. The annual flow weighted concentrations were calculated from:

$$\text{Annual Flow Weighted Concentration} = \frac{\sum_{d=1}^{365} (Q_d \times C_d)}{\sum_{d=1}^{365} Q_d}$$

The annual TOC mass loads and annual flow weighted TOC concentrations are summarized on Table 4-1.

Table 4-1. Hansen Feeder Canal at Horsetooth Inlet (C50): 2005 - 2010 Annual *Calendar Year* TOC Summary Statistics and Mass Loads to Horsetooth Reservoir

	2005	2006	2007	2008	2009	2010
Estimated Total Annual Canal Inflow (ac-ft/yr)	76,300	133,600	143,200	100,200	107,100	147,600
Total Organic Carbon:						
Number of Samples	51	47	46	51	49	50
Mean Conc. (mg/L)	3.8	3.7	4.1	3.8	4.0	4.6
Standard Error (mg/L)	0.21	0.091	0.14	0.10	0.12	0.28
Median Conc. (mg/L)	3.4	3.6	3.6	3.7	3.9	3.8
Flow Weighted Mean Conc. (mg/L)	4.5	3.7	3.8	3.7	4.1	4.9
Estimated Annual Load (kg/yr)	428,200	602,700	676,000	460,900	542,400	882,300
Estimated Annual Load (ton/yr)	472	664	745	508	598	973

The estimated 2010 annual mass TOC load to Horsetooth Reservoir was significantly greater than previous years (Figure 4-12). The high average TOC concentration during May 2010 combined with relatively high Hansen Feeder Canal inflows in May (Figure 4-13) resulted in a May 2010 TOC load of 250 tons, or 26% of the total 2010 TOC load.

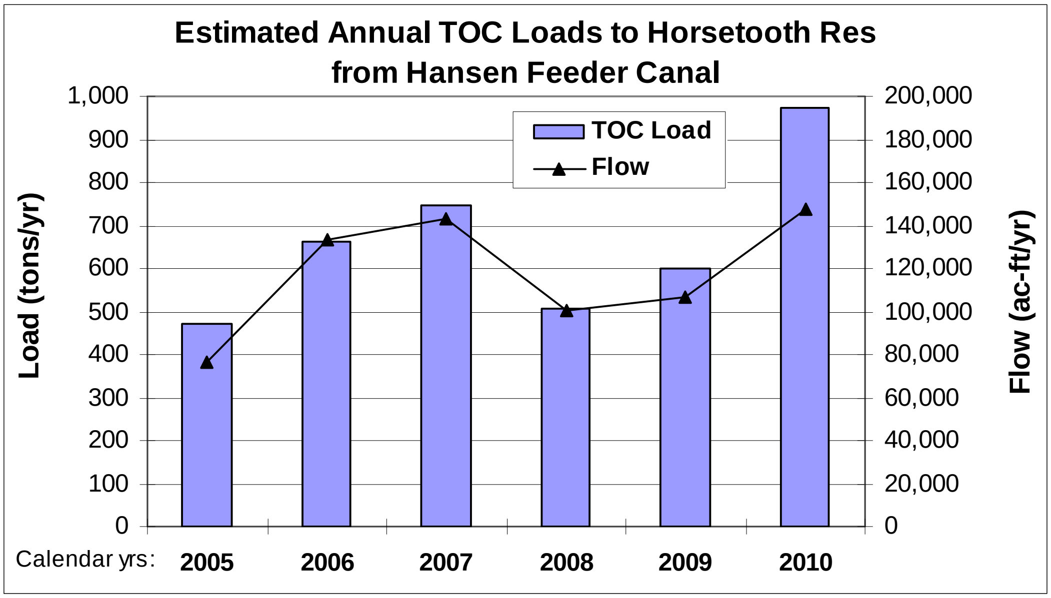
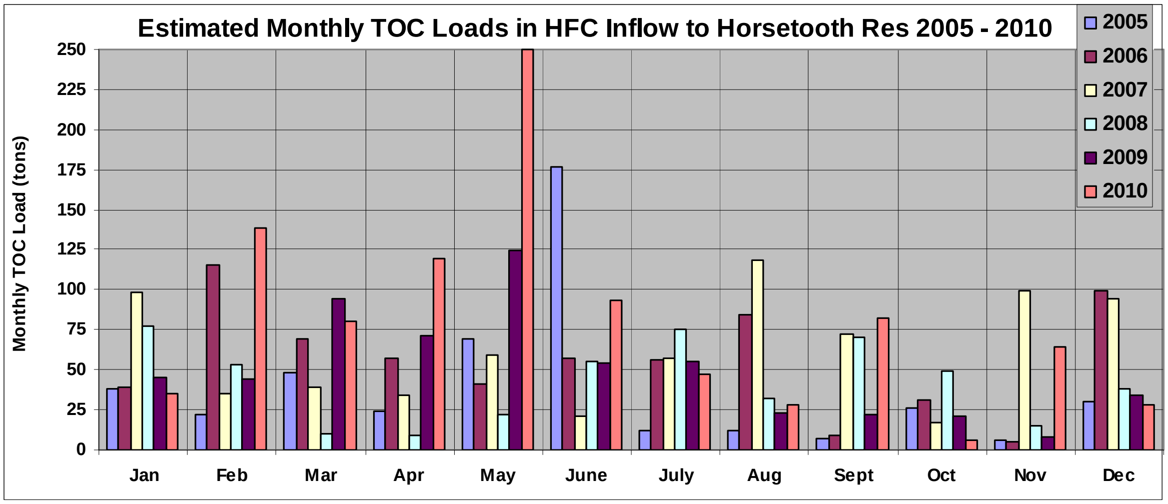
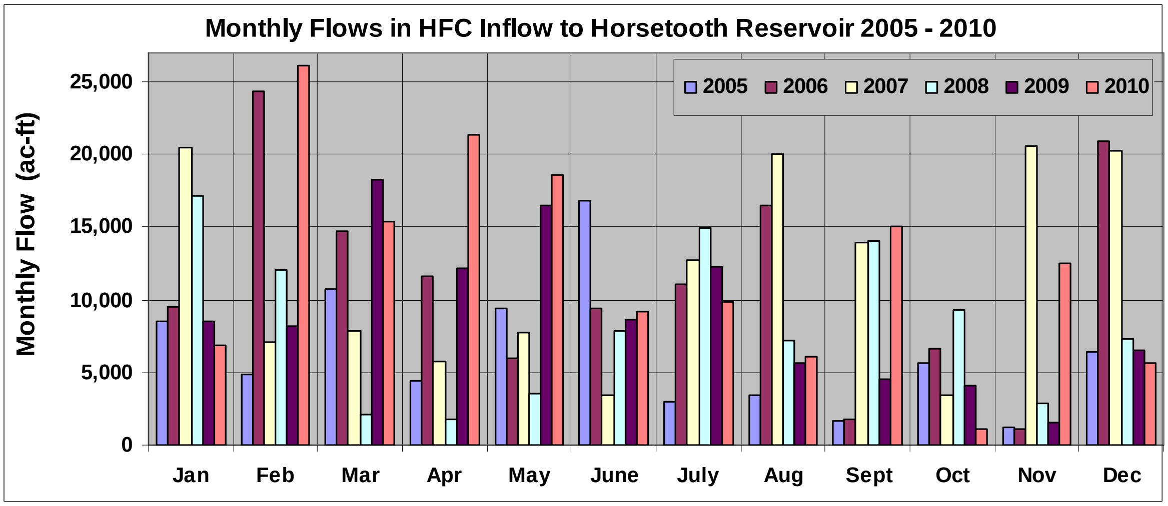


Figure 4-12 Hansen Feeder Canal annual TOC loads to Horsetooth Reservoir, calendar years 2005 to 2010.

(a) Calculated monthly TOC loads (1 ton = 907 kg).



(b) Monthly Hansen Feeder Canal flows.



(c) Monthly average TOC concentrations.

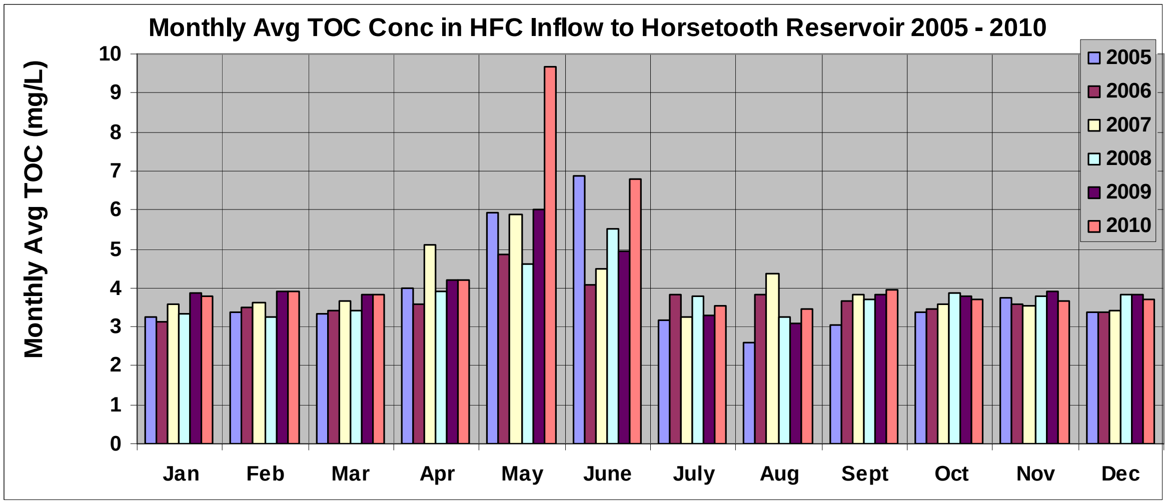


Figure 4-13. Hansen Feeder Canal Inflow to Horsetooth Reservoir: Comparison of (a) calculated monthly TOC loads, (b) monthly Hansen Feeder Canal flows, and (c) monthly average TOC concentrations.

5.0 HORSETOOTH RESERVOIR WATER QUALITY

This section summarizes Horsetooth Reservoir water quality data collected by the FCU, including sonde profile data and the grab sample data. In 2010, there were seven routine Horsetooth Reservoir sampling events: April 19, May 17, June 14, August 9, September 13, October 11, and November 15.

5.1 Sonde Profiles for Temperature, Dissolved Oxygen, and Specific Conductance

The 2010 temperature, dissolved oxygen (D.O.), and specific conductance profiles for Horsetooth Reservoir are shown on Figures 5-1, 5-2, and 5-3, respectively. Note that for the Soldier Canyon site (R40), the plots include the additional profiles obtained by FCU for the Colorado WQCD High Quality Water Supply Reservoir Study (see Section 2.4).

The temperature profiles show the typical development of thermal stratification beginning in the spring and progressing through the summer and early fall. The presence of the epilimnion (the well-mixed upper layer characterized by uniform temperatures), the metalimnion (the middle layer where the temperature drops sharply), and the hypolimnion (the bottom layer) was evident by the June 14 sampling event.

Fall turnover (complete mixing of the vertical profile) does not uniformly occur in the reservoir, with turnover in the pool behind Soldier Canyon Dam occurring earlier than turnover in the pools behind Spring Canyon and Dixon Canyon Dams. Turnover in the pool behind Soldier Canyon Dam is influenced by the withdrawal of hypolimnetic waters at the Soldier Canyon Outlet. Continuous dissolved oxygen data collected for raw Horsetooth Reservoir water at the FCWTF (representative of conditions at the bottom of Soldier Canyon Dam) indicate that reservoir turnover in the pool behind Soldier Canyon Dam occurred on October 25(Figure 5-4). The temperature, dissolved oxygen, and specific conductance profiles for Spring Canyon and Dixon Canyon indicate that complete mixing in these parts of the reservoir occurred sometime after the November 15 sampling event.

Similar to previous years, the dissolved oxygen profiles (Figure 5-2) show depletion in both the metalimnion and the hypolimnion. The low dissolved oxygen levels at the middle of the reservoir (metalimnion) are important from an aquatic life perspective and have resulted in Horsetooth Reservoir being placed on Colorado’s 2010 M&E List (see Section 1.5.1) because of occurrences of dissolved oxygen concentrations in the metalimnion that are less than the Aquatic Life Standard of 6 mg/L. From a water treatment perspective, it is the dissolved oxygen at the bottom of the reservoir (hypolimnion) that is of interest because low dissolved oxygen levels can result in the release of manganese and iron from the bottom sediments to the water column near the FCWTF intake. Dissolved oxygen at the bottom of the reservoir steadily decreases from spring, through the summer and into the fall until reservoir turnover occurs as is shown on Figure 5-4 for Soldier Canyon.

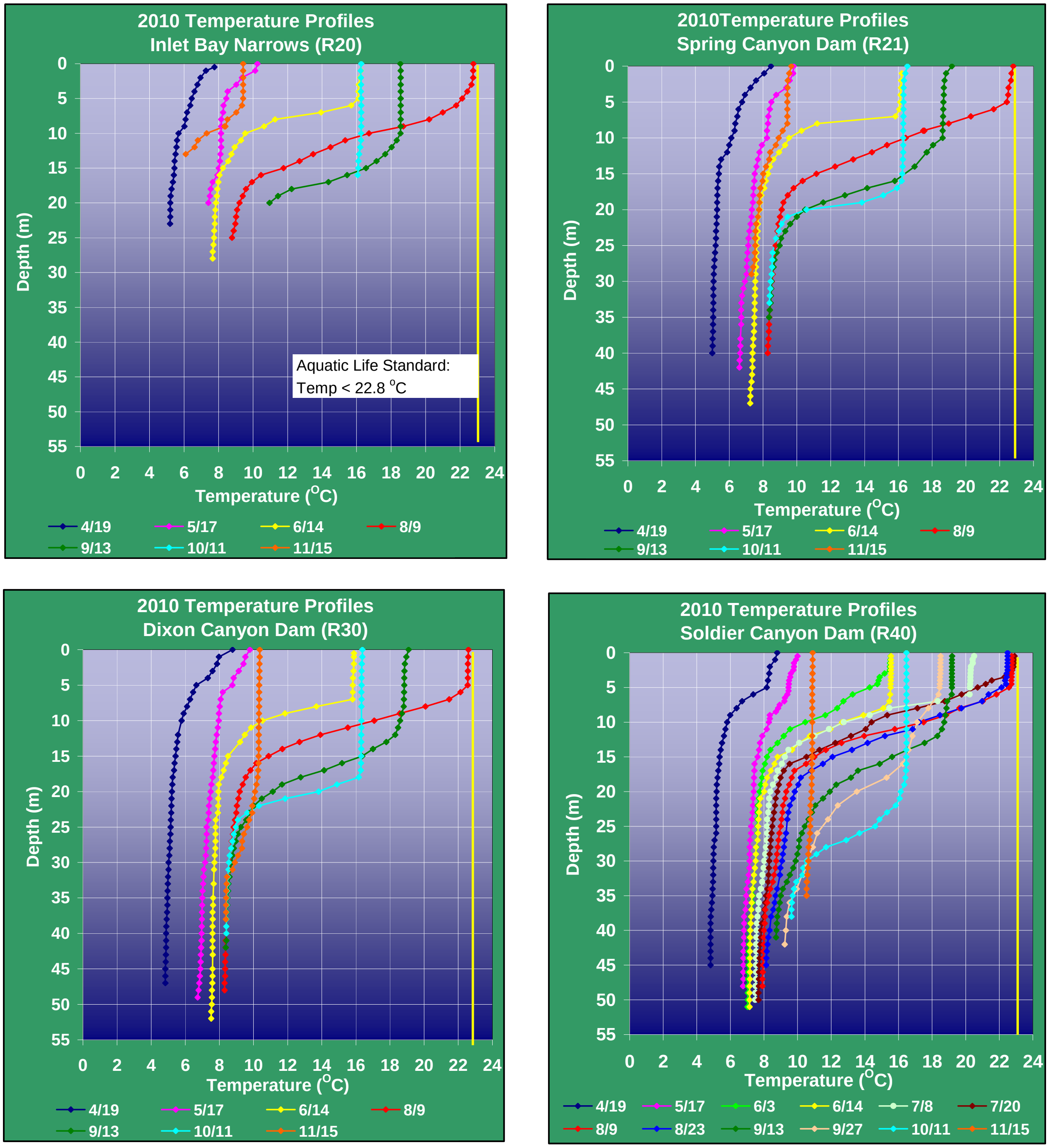


Figure 5-1. 2010 Temperature profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40).

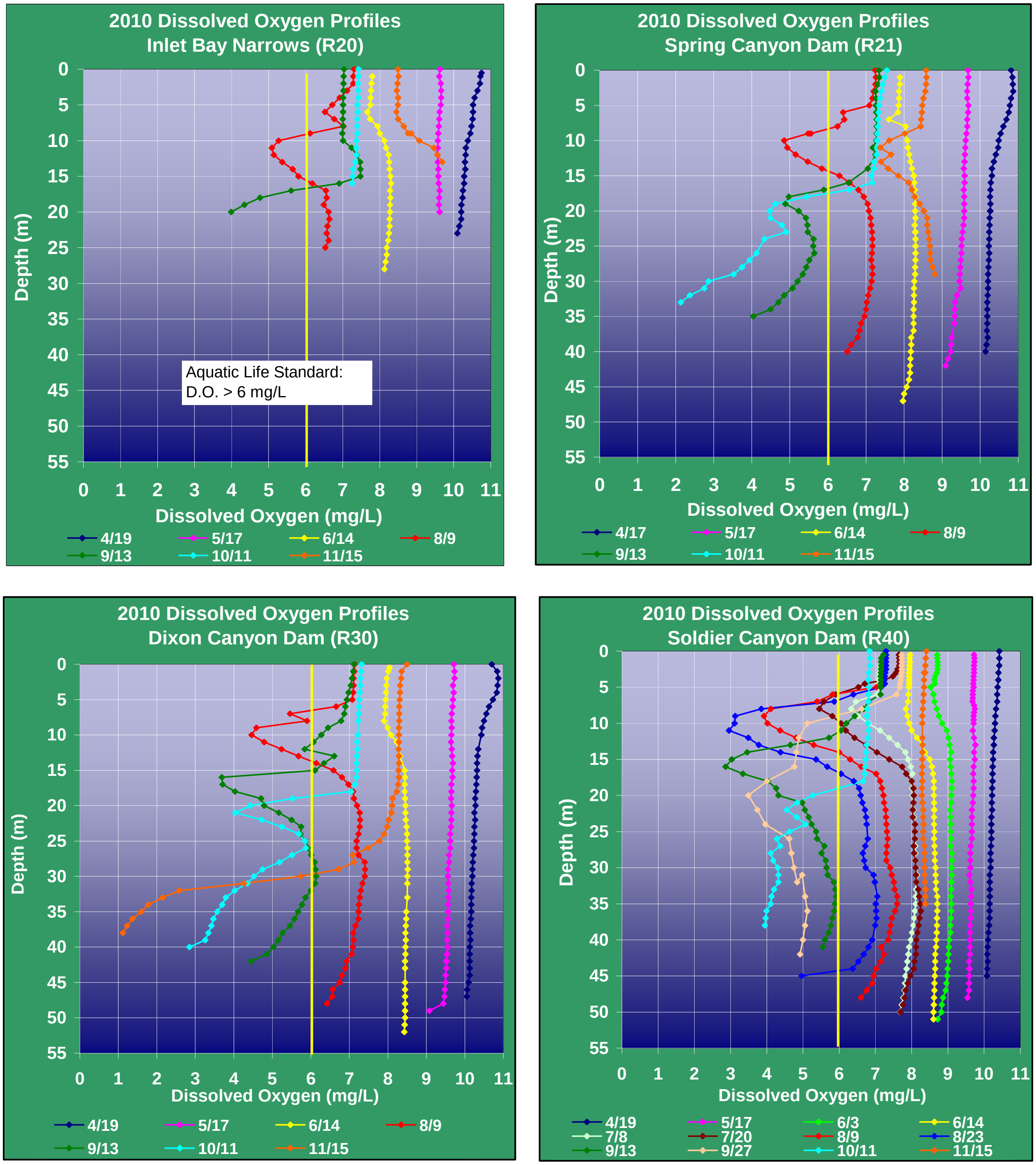


Figure 5-2. 2010 Dissolved oxygen profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40); Aquatic Life Standard: D.O. > 6 mg/L.

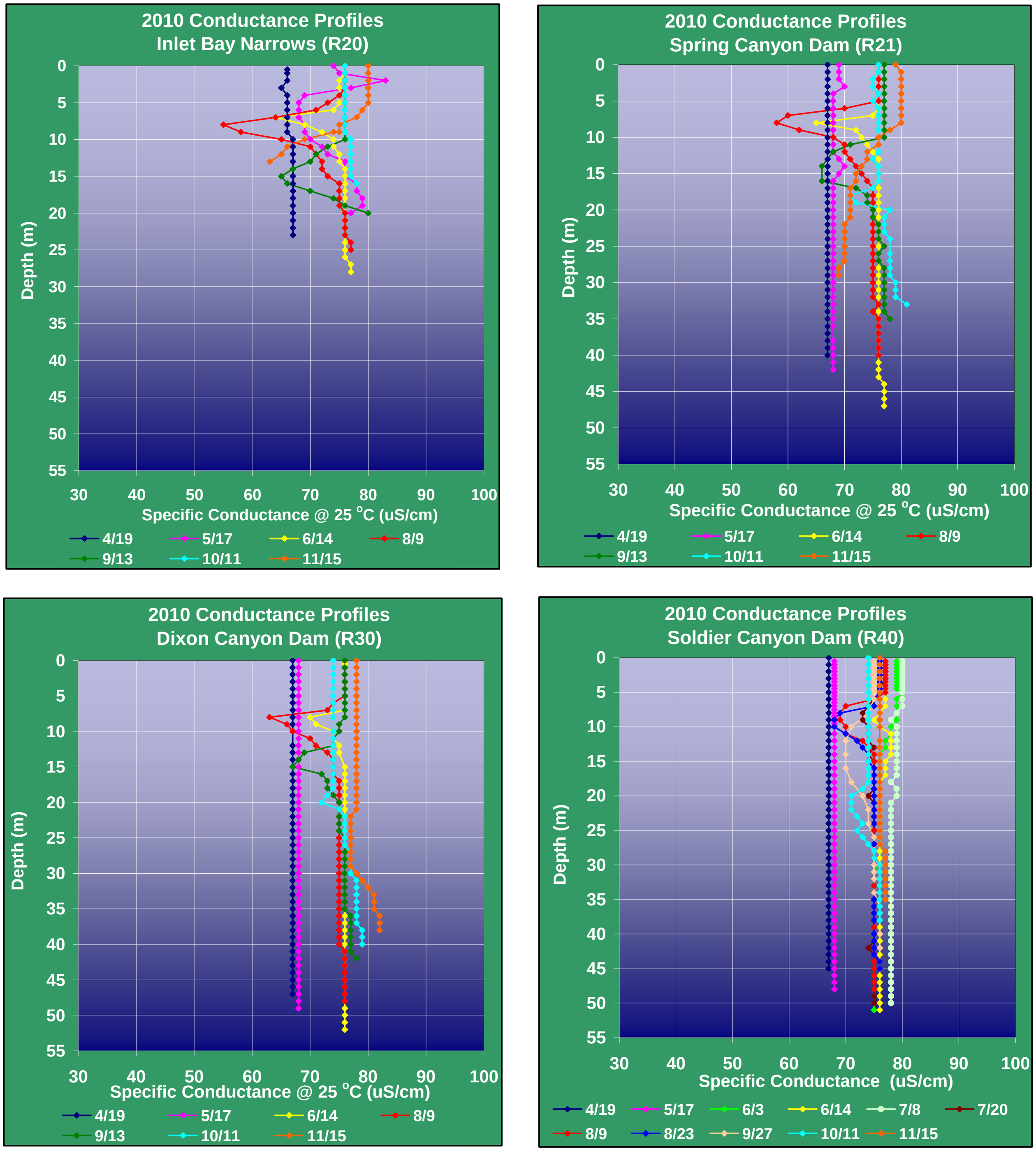


Figure 5-3. 2010 Specific conductance profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40).

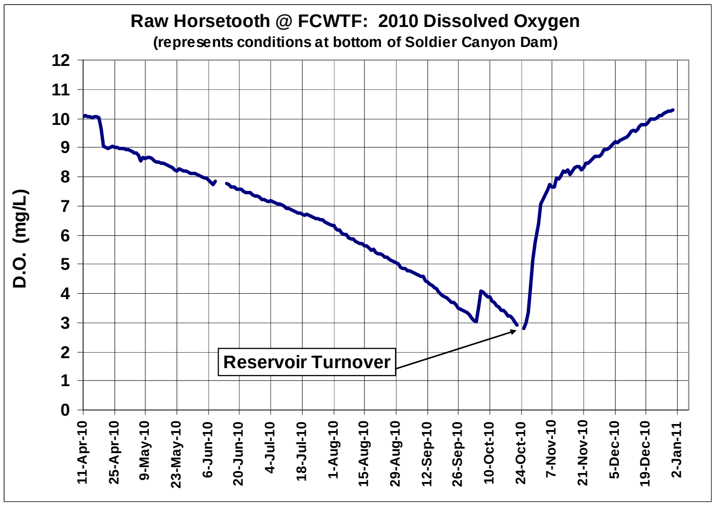


Figure 5-4. 2010 Continuous D.O. data for Horsetooth Reservoir water at FCWTF raw water sample station.

The 2005-2010 dissolved oxygen data from the reservoir top (1 meter) and bottom (1 meter above bottom) at Spring Canyon, Dixon Canyon, and Soldier Canyon are plotted together on Figure 5-5. Dissolved oxygen depletion at the reservoir bottom is 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.

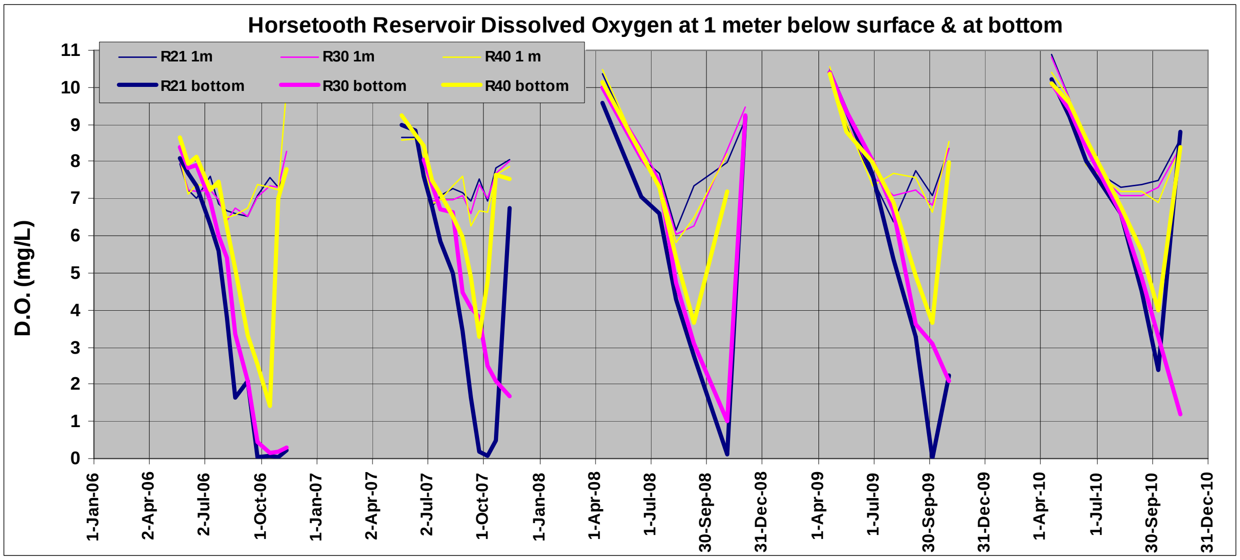


Figure 5-5. Dissolved oxygen at 1 meter and at the reservoir bottom at Spring Canyon (R21), Dixon Canyon (R30), and Soldier Canyon (R40).

Temperature differences between the Hansen Feeder Canal inflow and the Horsetooth Reservoir surface waters impact the flow of Hansen Feeder Canal water through the reservoir. Because of temperature-induced density differences, cooler Hansen Feeder Canal water plunges below the reservoir surface until it reaches a level where the inflow and ambient reservoir water temperatures (densities) are the same. Hansen Feeder Canal inflow then moves through the reservoir as an interflow until it is dissipated. The occurrence of a minimum in specific conductance at the same depth range where the Hansen Feeder Canal water is predicted to exist based on water temperatures is further evidence for the occurrence of interflow. The specific conductance of Hansen Feeder Canal water is significantly less than that of the ambient Horsetooth Reservoir water during the summer and can therefore be used as a tracer of the interflow process. Figure 5-6 is a conceptual diagram of interflow using temperature and specific conductance profile data from August 9, 2010.

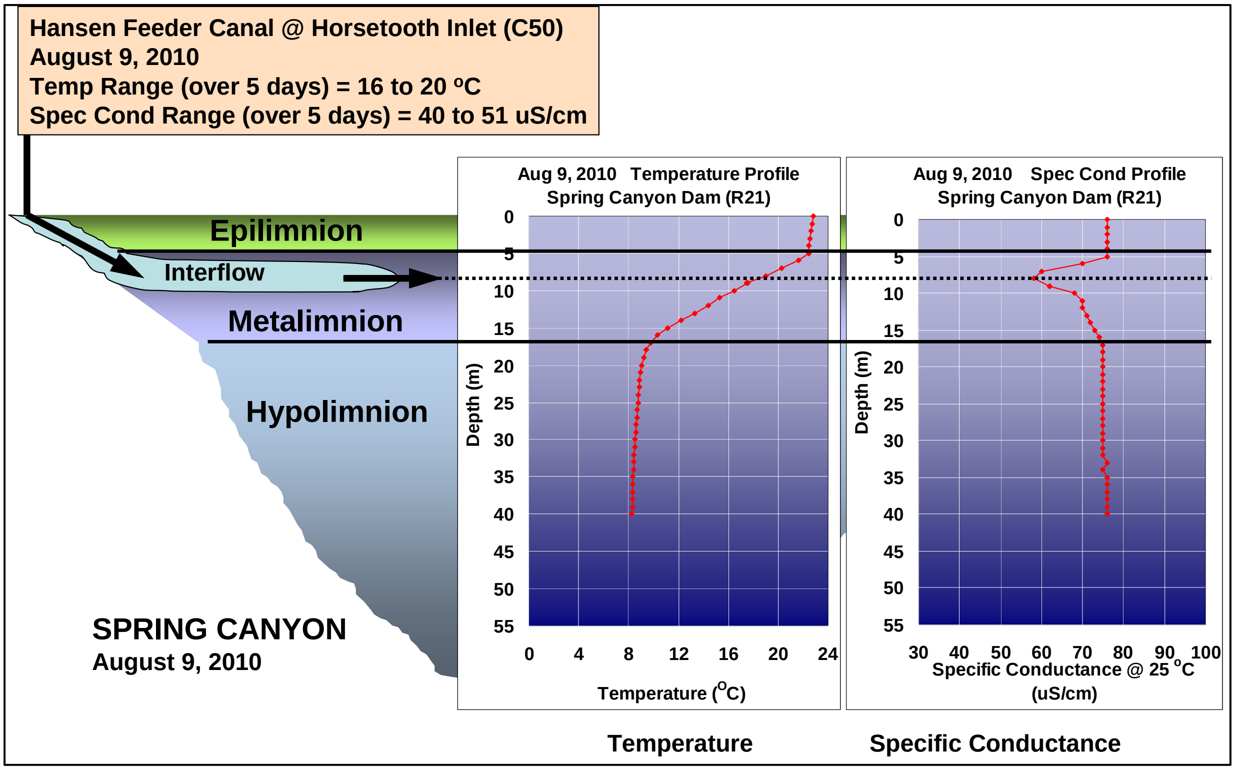


Figure 5-6. **Occurrence of interflow: conceptual diagram of interflow at Spring Canyon using Aug 9, 2010 temperature and specific conductance data.**

The specific conductance profiles collected at Inlet Bay, Spring Canyon, Dixon Canyon, and Soldier Canyon can be compared to evaluate the degree to which the Hansen Feeder Canal interflow is maintained or dissipated along the length of the reservoir. Figure 5-3 shows the presence of a specific conductance minima in the metalimnion of all of the profiles collected on June 14, 2009, August 9, 2009, and September 13, 2009, indicating the occurrence of interflow all the way to Soldier Canyon. The hydrodynamic water quality model currently being developed for Horsetooth Reservoir (see Section 2.7) is expected to provide a better understanding of the flow patterns and fate of Hansen Feeder Canal water in Horsetooth Reservoir.

5.2 Grab Sample Data

Table 1-3 listed the parameters that are analyzed in grab samples collected from Horsetooth Reservoir. All parameters were summarized and presented in the 2009 FCU Horsetooth Reservoir Water Quality Monitoring Program Report for the five-year period 2005 through 2009. For this 2010 Report, only secchi depth, TOC, nutrient, chlorophyll-a, and phytoplankton data will be presented.

5.2.1 Secchi Depth

The clarity or transparency of Horsetooth Reservoir as measured by secchi depth varies due to the presence of turbidity particles (organic or inorganic) and algae. The 2005 - 2010 secchi depth data collected by the City of Fort Collins for Horsetooth Reservoir are plotted on Figure 5-7. Secchi disk readings of 2 m to 4 m (or Trophic-State Index (TSI) values between 50 and 40) fall into the mesotrophic range, while secchi disk readings of 0.5 m to 2 m (or 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): TSI = 60 – 14.41 ln(SD in meters). The mean secchi disk measurements for Horsetooth Reservoir fall into the mesotrophic range.

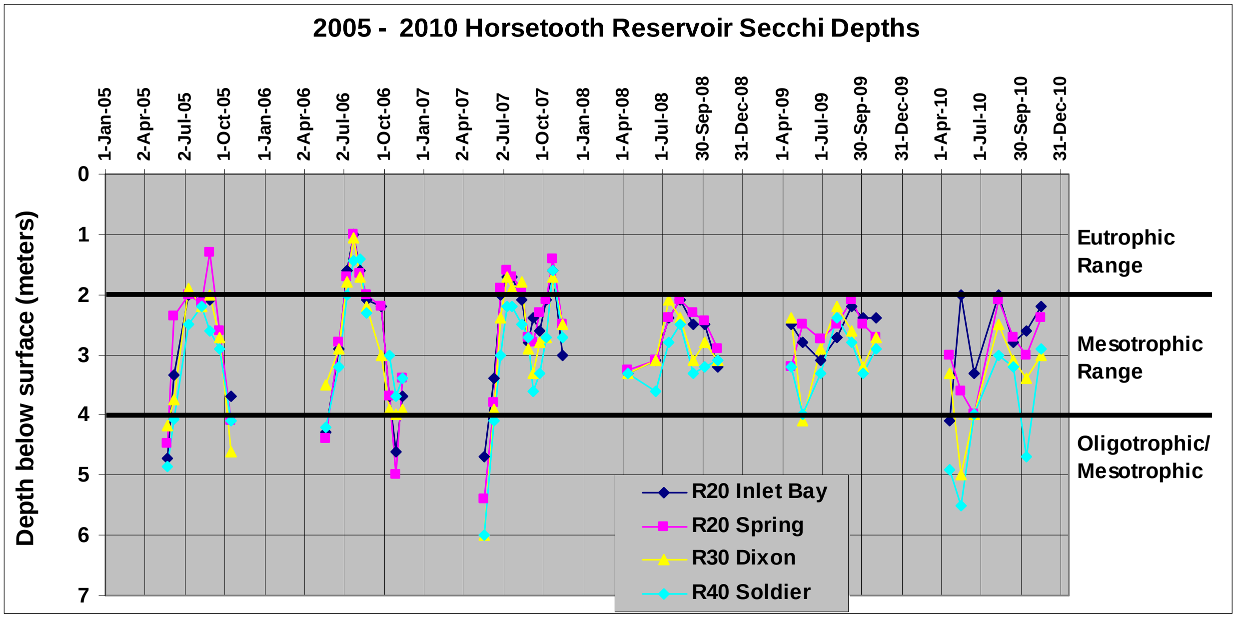


Figure 5-7. 2005 to 2010 Horsetooth Reservoir secchi depths.

5.2.2 Total Organic Carbon (TOC)

TOC at FCWTF raw Horsetooth Reservoir Sample Station. A plot of weekly TOC data collected from 2005 through 2010 at the FCWTF raw Horsetooth sample station is shown on Figure 5-8. The data show a significant increase in TOC at the FCWTF during 2010 due to the significant TOC load that occurred from the Hansen Feeder Canal during the 2010 spring runoff period (see Section 4.3). The TOC peaked on October 12, 2010 at 4.2 mg/L, compared to the 2005-2009 five-year average TOC of 3.2 mg/L. Concentrations then began decreasing, but were still significantly above the normal range at the end of 2010. Depending on the inflow conditions and TOC loads during 2011, the TOC levels are expected to continue to drop back down to more normal levels after the slug of high TOC water makes its way through the reservoir.

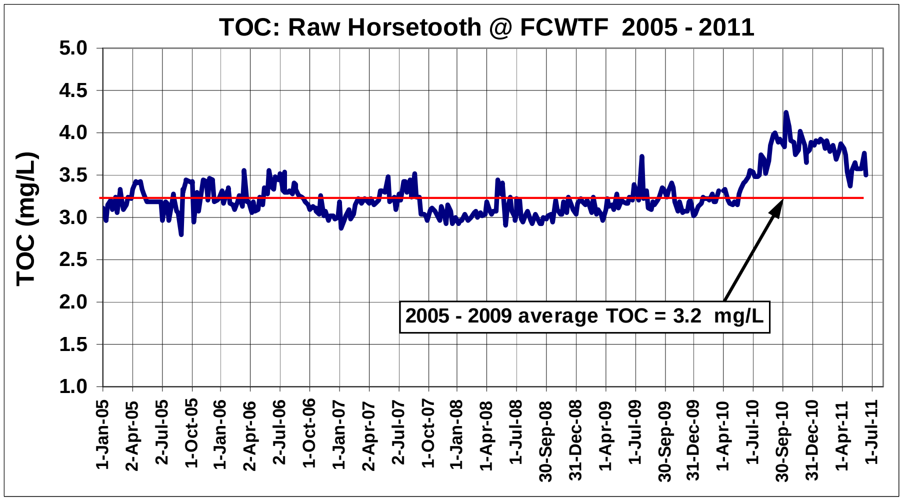


Figure 5-8. TOC at the FCWTF raw Horsetooth Reservoir sample station from 2005 through 2010.

TOC Data for Reservoir Sites. TOC data collected within the reservoir allow for an evaluation of TOC differences with reservoir depth and with reservoir length. Figures 5-9 (a) and (b) are plots of TOC at various depths at Spring Canyon Dam and Soldier Canyon Dam, respectively (note range of y-axis). The 5 to 15 meter sample is a composite of samples taken at depths of 5, 10, and 15 meters, and in mid- to late-summer generally represents the metalimnion. Visual inspection of the figures indicates that the TOC between depths of 1 and 15 meters (1-meter and the 5-15 meter composite) is generally higher than the TOC at the reservoir bottom throughout the summer, and that TOC at 1 meter generally peaks in June or July. The figures indicate that late-season increases in bottom TOC occasionally occur at both Spring and Soldier Canyons.

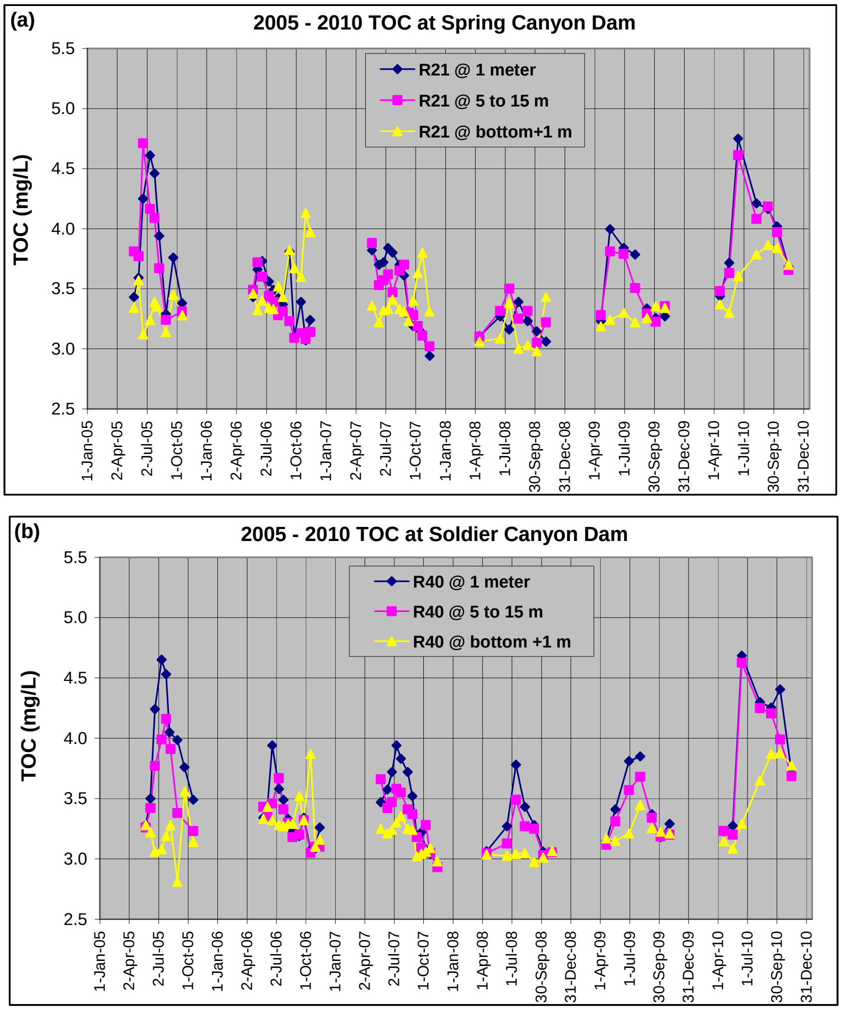


Figure 5-9. 2005-2010 TOC at (a) Spring Canyon, and (b) Soldier Canyon (note y-axis scales).

Figure 5-10 compares TOC data from R20 (Inlet Bay), R21 (Spring Canyon) and R40 (Soldier Canyon) at 1 meter below the surface. The 1 meter data do not indicate a general TOC gradient from upstream (R20) to downstream (R40). Note, however, that significant TOC differences occurred from upstream to downstream in May 2010 with the highest TOC occurring at the upstream (R20 Inlet Bay) end. Higher TOC at the upstream end of Horsetooth Reservoir would be expected during the spring due to increases in TOC in the Hansen Feeder Canal during the spring runoff (see Section 4.2.2).

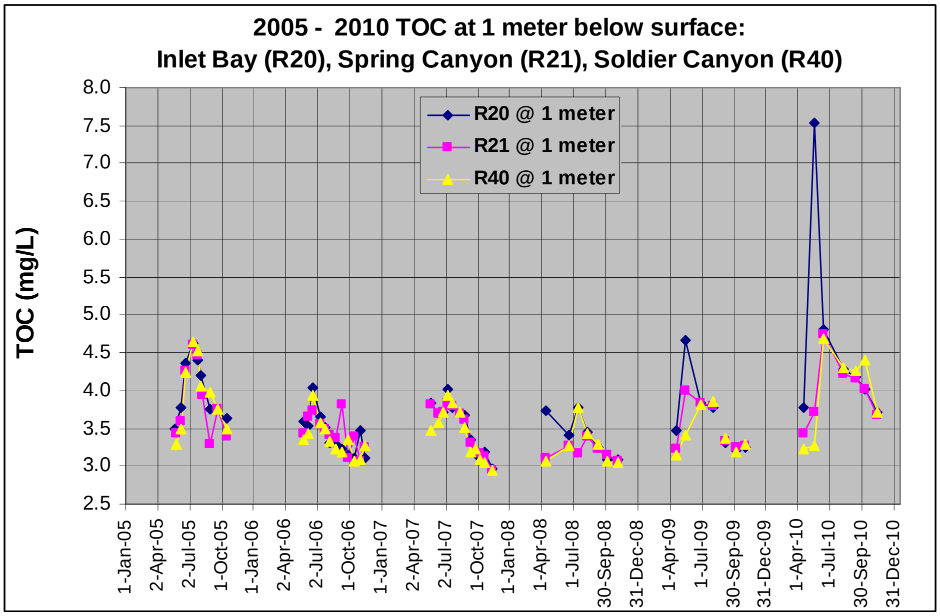


Figure 5-10. 2005 - 2010 Horsetooth Reservoir TOC at 1 meter below surface.

Figure 5-11 compares 2005-2010 TOC data from R21 (Spring Canyon) and R40 (Soldier Canyon) at 1 meter above the reservoir bottom. The TOC data from the reservoir bottom indicate that the TOC at the bottom of Spring Canyon is occasionally higher than the TOC at the bottom of Soldier Canyon. The increase in bottom TOC that occurred during 2010 was due to the significant TOC load that occurred from the Hansen Feeder Canal during the 2010 spring runoff period. This same increase is shown on the plot of TOC at the FCWTF (Figure 5-8) since raw Horsetooth water comes from the bottom of the reservoir.

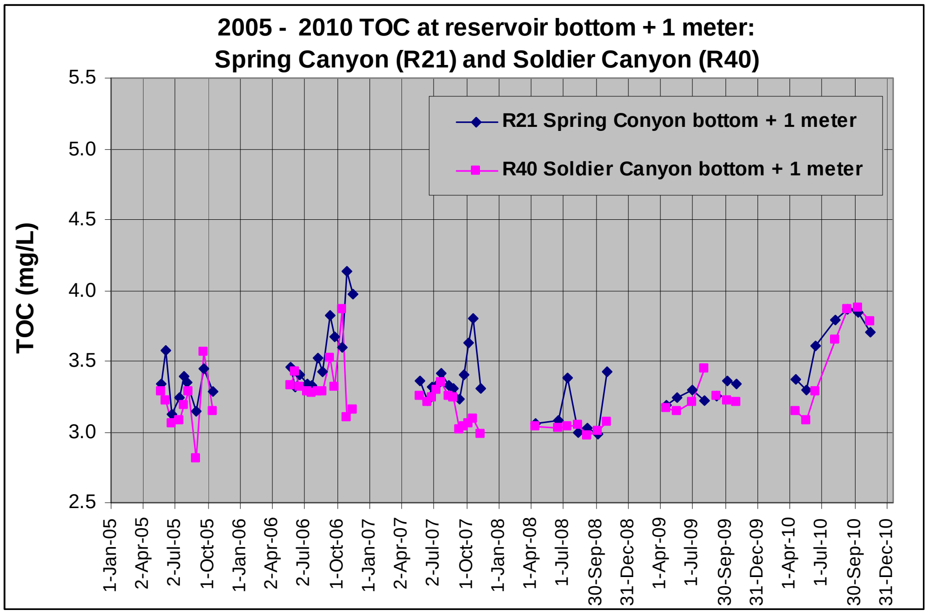


Figure 5-11. 2005-2010 TOC at Horsetooth Reservoir bottom (bottom + 1 meter).

Comparison of TOC concentrations for Horsetooth Reservoir inflow water and Horsetooth Reservoir outflow water. Annual flow-weighted TOC concentrations for the Hansen Feeder Canal at the Horsetooth inlet (see Section 4.3, Table 4-1) are compared to the annual average TOC concentrations at the FCWTF (calculated from weekly data) on Figure 5-12 for calendar years 2005 through 2010. The data indicate that in-reservoir processes result in a *net* decrease in TOC concentrations between the reservoir inflow and the reservoir outflow. TOC concentrations of the reservoir outflow were 13 to 28 percent lower than the TOC concentrations of the reservoir inflow.

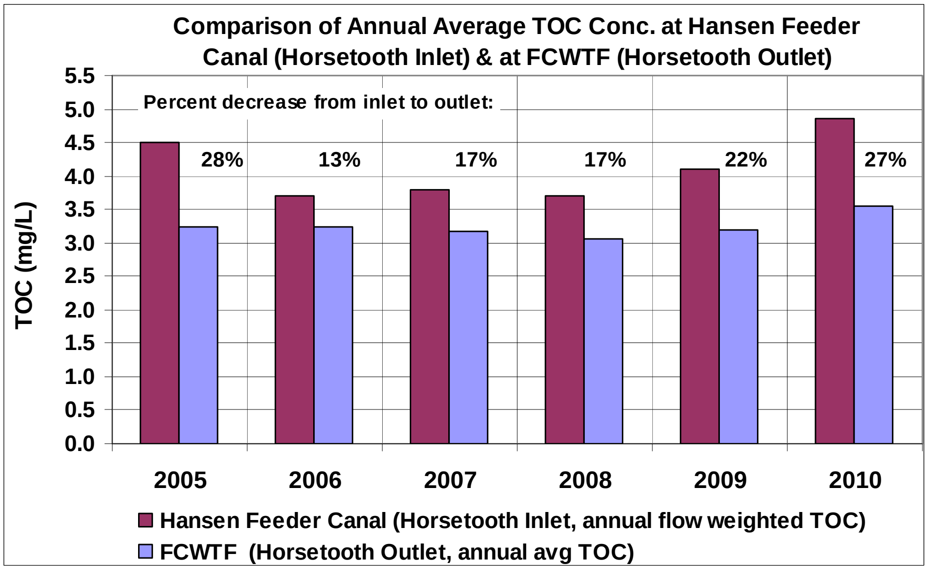


Figure 5-12. Comparison of annual flow-weighted TOC measured at the Hansen Feeder Canal (inflow to Horsetooth Reservoir) and the annual average TOC measured at the FCWTF.

5.2.3 Nutrients

Phosphorus and nitrogen are major nutrients that support algal growth in water. The solutions to water quality problems related to algae require an understanding of the sources and concentrations of these nutrients. Potential drinking water quality and treatment problems associated with algae include:

- Production of taste and odor compounds (such as geosmin)
- An increase in TOC that could lead to an increase in the production of disinfection byproducts
- Production of toxins by cyanobacteria
- Filter clogging issues at the water treatment plants
- Production of organic matter that settles to the reservoir bottom, undergoes microbial degradation that depletes oxygen levels, and results in the release of manganese and nutrients from the bottom sediments.

Phosphorus. Total phosphorus (TP) and ortho-phosphate (PO_4^{-3}) are the two forms of phosphorous measured as part of the FCU Horsetooth Reservoir Water Quality Monitoring Program. Sources of phosphorus to Horsetooth Reservoir include Hansen Feeder Canal inflows and direct inflows from the local adjacent watershed. Within the watersheds, anthropogenic sources of phosphorus include wastewater treatment plant effluent, failing individual sewage disposal systems (ISDSs), and runoff from agricultural lands.

TP includes dissolved, particulate, adsorbed, organic, and inorganic forms of phosphorus. It is considered the best value to use in quantifying phosphorus in a body of water because of the dynamic nature of the phosphorus cycle and the ability of phosphorus to be transformed and move from one form to another. TP concentrations at depths of one meter below the surface and one meter above the bottom are plotted on Figure 5-13. The TP levels at the reservoir bottom increase through the summer and into the fall as phosphorus is transported to the hypolimnion with the sedimentation of inorganic particles and organic matter, and as phosphorus is released to the water column from the sediments when oxygen levels are depleted. TP levels at the bottom of the reservoir were significantly lower in Fall 2010 than is previous years.

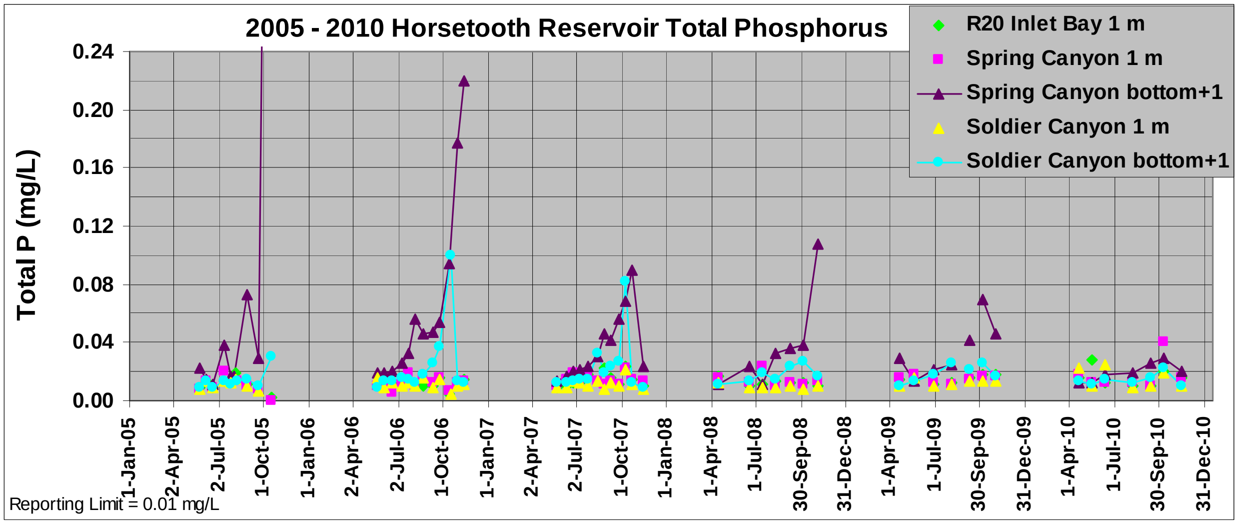


Figure 5-13. 2005-2010 Total P at Inlet Bay top (R20), Spring Canyon top and bottom (R21), and Soldier Canyon top and bottom (R40).

Ortho-phosphate (inorganic soluble phosphorus) is the form of phosphorus that is available for uptake by algae. Ortho-phosphate concentrations in the 1 meter samples are low (Figure 5-14) since it is readily taken up by algae as it becomes available. At the bottom of the reservoir, ortho-phosphate concentrations increase into the fall (prior to turnover) as oxygen levels decrease and phosphorus is released from the sediments.

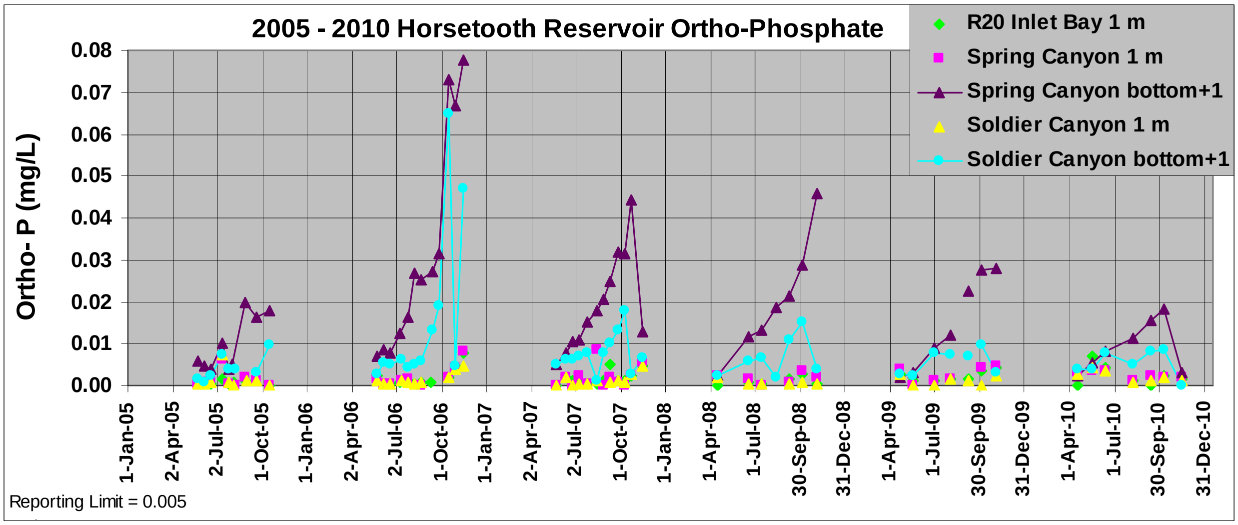


Figure 5-14. 2005-2010 Ortho-Phosphate at Inlet Bay top (R20), Spring Canyon top and bottom (R21), and Soldier Canyon top and bottom (R40).

Nitrogen. Ammonia and nitrate are the primary forms of nitrogen available to algae. The forms of nitrogen measured for this monitoring program include ammonia (present primarily as the ammonium ion, NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), and Total Kjeldahl Nitrogen (TKN). TKN is ammonia plus organic nitrogen and represents the total amount of oxidizable nitrogen. From these analyses, total nitrogen (TN) can be calculated from the sum of the concentrations of nitrate, nitrite and TKN.

Sources of nitrogen to Horsetooth Reservoir include Hansen Feeder Canal inflows, direct inflows from the local adjacent watershed, biological nitrogen fixation by some cyanobacteria, and precipitation falling directly onto the reservoir surface. Within the watersheds, anthropogenic sources of nitrogen include wastewater treatment plant effluent, failing individual sewage disposal systems, and runoff from agricultural lands.

Within the reservoir, ammonia is released during the decomposition of organic matter. In the presence of oxygen, ammonia is converted to nitrate in a process called nitrification. When anoxic conditions exist at the reservoir bottom, nitrification ceases and ammonia will accumulate. Other processes that can occur under anoxic conditions include the conversion of nitrate to ammonia through ammonification, the bacterial reduction of nitrate ions to N_2 (denitrification), and the release of ammonia from bottom sediments.

At the reservoir surface, ammonia and nitrate concentrations during the summer can be depleted or nearly depleted due to algal uptake. This can be seen on Figures 5-15 and 5-16, plots of nitrate and ammonia at the surface and bottom of Spring Canyon (R21) and Soldier Canyon (R40), respectively. Depletion of nitrogen near the reservoir surface can result in blooms of cyanobacteria because their ability to fix free nitrogen gives them a competitive advantage compared to other phytoplankton. Nitrate concentrations are higher at the reservoir bottom than at the surface (Figures 5-15 and 5-16). Nitrate concentrations at the reservoir bottom increase over the summer and peak in the early fall as nitrogen is transported to the hypolimnion with the settling of organic matter, ammonia is released during decomposition of the organic matter, and the ammonia is oxidized to nitrate (nitrification). As conditions become anoxic at the reservoir bottom, nitrification ceases, nitrate ammonification and/or denitrification occur, and nitrate concentrations drop while ammonia accumulates. Nitrate concentrations at the reservoir bottom also decrease in late fall due to reservoir mixing (turnover).

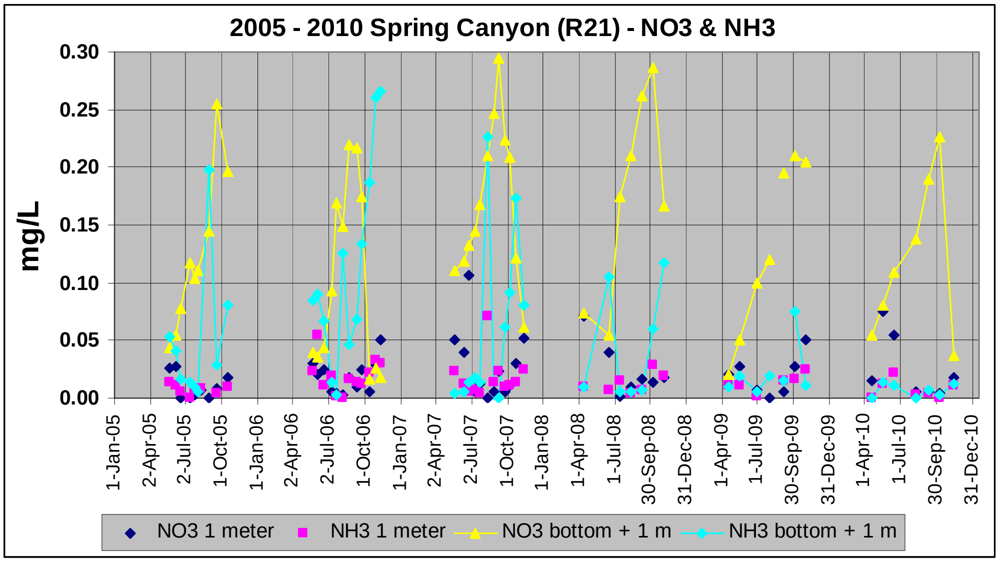


Figure 5-15. 2005 – 2010 nitrate and ammonia concentrations at Spring Canyon.

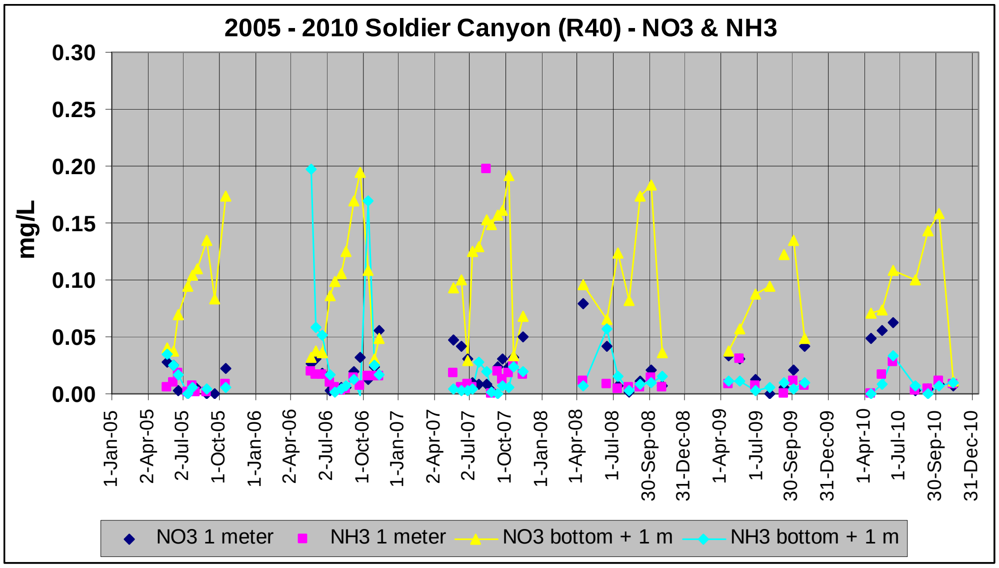
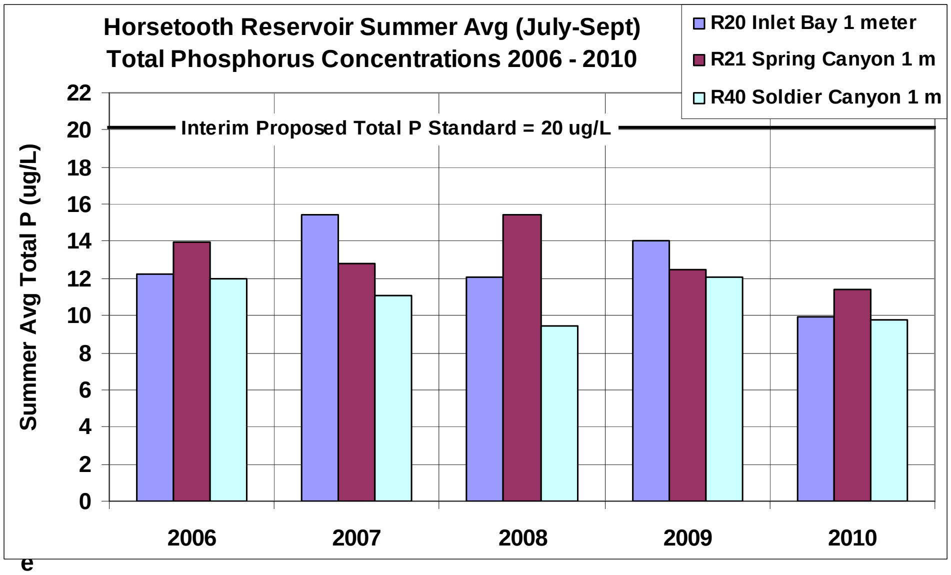


Figure 5-16. 2005 – 2010 nitrate and ammonia concentrations at Soldier Canyon.

Comparison of Data to Proposed Nutrient Standards. For cold water lakes and reservoirs greater than 25 acres, the proposed interim total P standard is 20 ug/L while the proposed interim total N standard is 410 ug/L (in both cases, summer averages (July, August, September), with an allowable exceedance frequency of 1-in-5 years).

Summer average (July, August, and September) total P and total N values for the 1 meter samples collected in Horsetooth Reservoir are plotted on Figure 5-17 and Figure 5-18, respectively, for 2006 – 2010. None of the summer averages are greater than the respective proposed interim standards. However, note that in 2009 and 2010, the summer average was calculated from one sampling event in each of August and September and may not accurately reflect actual conditions. Beginning in 2011, the Fort Collins routine sampling program will also include the month of July.



e

Figure 5-17. Summer average (July, Aug, Sept) total phosphorus concentrations at 1 meter below surface, 2006-2010.

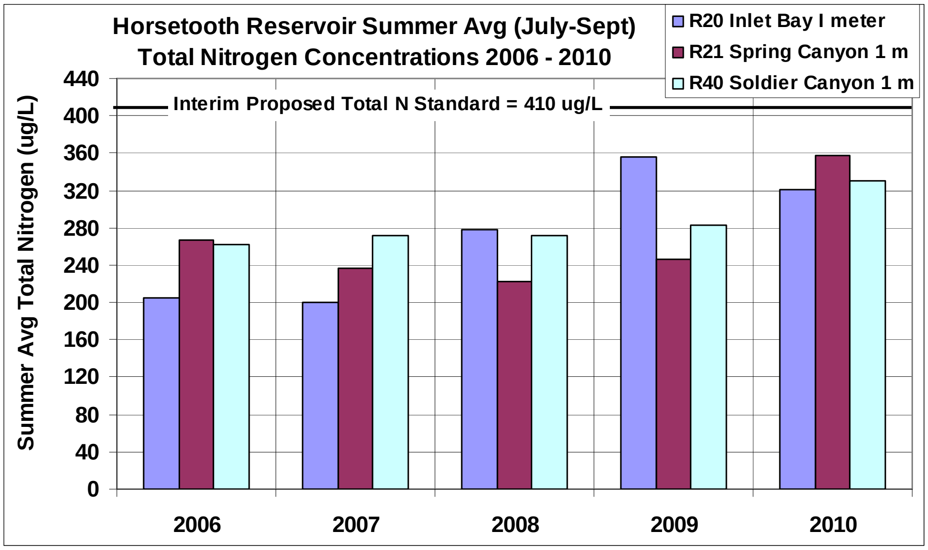


Figure 5-18. Summer average (July, Aug, Sept) total nitrogen concentrations at 1 meter below surface, 2006-2010.

5.2.4 Chlorophyll-a

Chlorophyll-a concentrations measured at one meter below the surface during the 2005-2010 time period are plotted on Figure 5-19. The graph indicates the trophic states corresponding to chlorophyll-a concentrations. Chlorophyll-a concentrations between 2.6 and 7.3 ug/L (or Trophic-State Index values between 40 and 50) fall into the mesotrophic range. The Trophic-State Index (TSI) is calculated based on chlorophyll-a data according to the equation (Carlson, 1977): TSI = 30.6 + 9.81 ln[Chlor-a in ug/L]. The 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 ug/L) and summer and fall samples sometimes approaching the eutrophic range (chlorophyll-a > 7.3 ug/L). The November 2011 samples for Spring Canyon and Inlet Bay were in the eutrophic range.

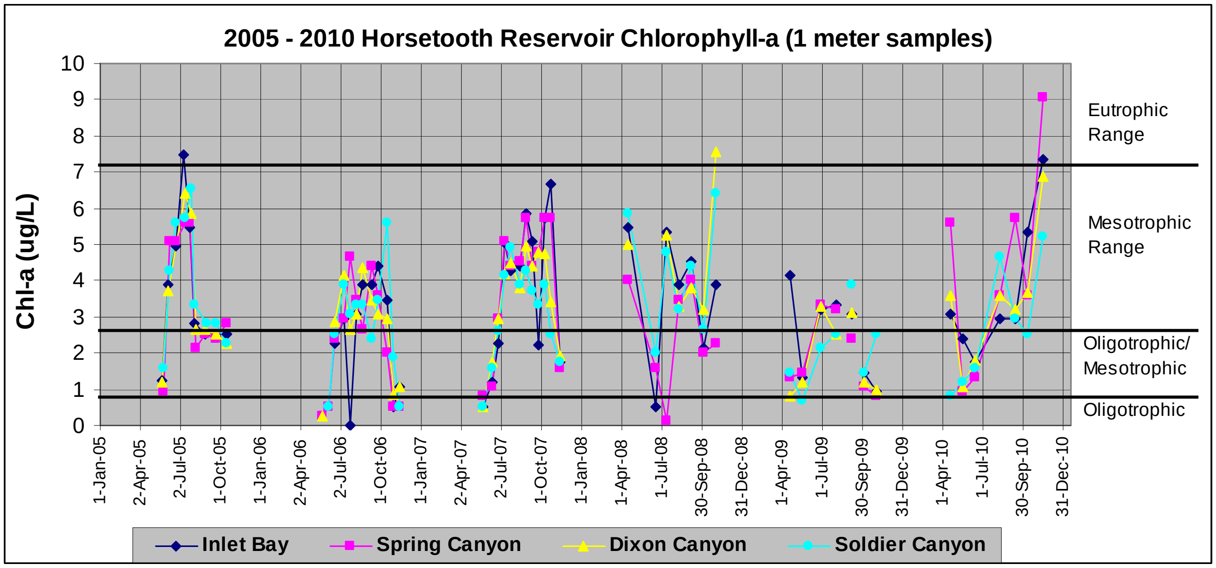


Figure 5-19. 2005-2010 Horsetooth Reservoir chlorophyll-a samples (1 meter samples)

Comparison of Data to Proposed PWSR Chlorophyll-a Standard. The PWSR chlorophyll-a standard currently proposed by the WQCD is a summer average (July, August, and September) value of 5 ug/L in the mixed (top) layer of the reservoir with an allowable exceedance frequency of 1-in-5 years. Note, however, that this is considered to be a preliminary (placeholder) value since the WQCD is currently completing data analysis to support a final proposed standard.

Summer average (July, August, and September) chlorophyll-a values for the 1 meter samples collected in Horsetooth Reservoir are plotted on Figure 5-20 from 2006 – 2010. None of the summer averages are greater than the proposed standard of 5 ug/L. Note that in 2009 and 2010, the summer average was calculated from one sampling event in each of August and September and may not fully represent the actual conditions. Beginning in 2011, routine sampling will also include the month of July. Note also that for Horsetooth Reservoir, the peak annual chlorophyll-a concentrations do not always occur in the summer months. Figure 5-19 shows that high chlorophyll-a concentrations can occur in October or November.

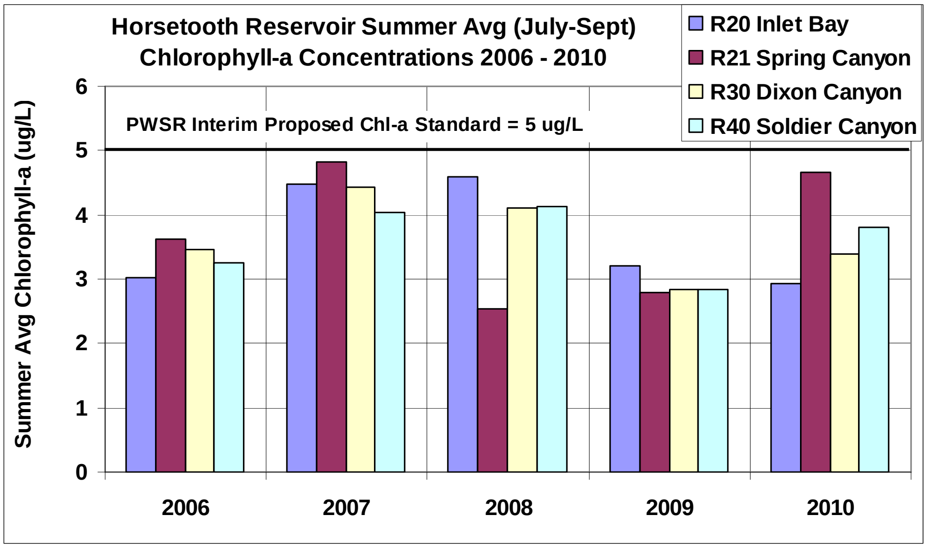


Figure 5-20. Summer average (July, Aug, Sept) chlorophyll-a concentrations, 2006-2010.

5.2.5 Phytoplankton

Beginning in 2009, phytoplankton identification and enumeration has been conducted by Richard Dufford, with identification to the *species* level (when possible). The 2010 total phytoplankton density (total cells per mL) is plotted on Figure 5-21 for the Hansen Feeder Canal inflow and the 1 meter samples collected within the reservoir. The phytoplankton density in the inflow from the Hansen Feeder Canal was very low and would therefore have little or no direct influence on phytoplankton counts within Horsetooth Reservoir. Within the reservoir, there was a significant increase in total phytoplankton density beginning in August, with the highest density observed in the Spring Canyon sample on August 9 (108,424 cells/mL). This is significantly higher than the highest density observed in 2009 (39,348 cells/mL in the August 3, 2009 1-meter sample collected at Inlet Bay).

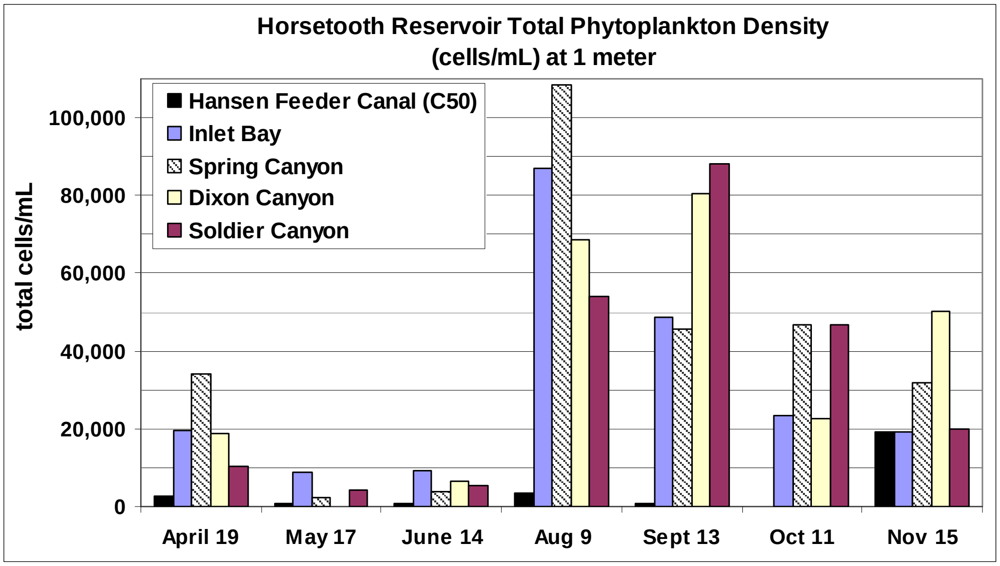


Figure 5-21. 2010 Horsetooth Reservoir total phytoplankton density (cells/mL)

The percent relative abundance of the various algal groups is shown on Figure 5-22 for the Horsetooth Reservoir samples collected at 1 meter below surface. The dominant contributor to the total algal density (number of cells per mL) in the April through June samples was the Chlorophytes (green algae). The dominant green algae species during this time was *Chlorella minutissima*. A shift in algal populations occurred in August with the cyanobacteria (blue-green algae) making up the highest percentage of the total algal density. In August, the dominant blue-green algae species was *Merismopedia tenuissima*, while in September through November the dominant blue-green algae species was *Aphanothece smithii*. Other blue-green algae species that were in abundance in the August through November 2010 samples include *Aphanocapsa delicatissima*, *Aphanothece clathrata* and *Synechococcus capitatu*. Dominant species identified from the Cryptophyta group include *Cryptomonas borealis, Komma caudate,* and *Plagioselmis nannoplanctica*. *Chrysochromulina parva* was the only species indentified in the Haptophyta group.

Geosmin producing species of blue-green algae comprised a very small fraction of the total phytoplankton count in 2010, generally one percent or less (down to zero) of the total density. Geosmin-producing species present in the 2010 samples included *Anabaena lemmermannii, Anabaena sp., Aphanizomenon gracile*, *Pseudanabaena catenata*, and *Synechococcus sp.*

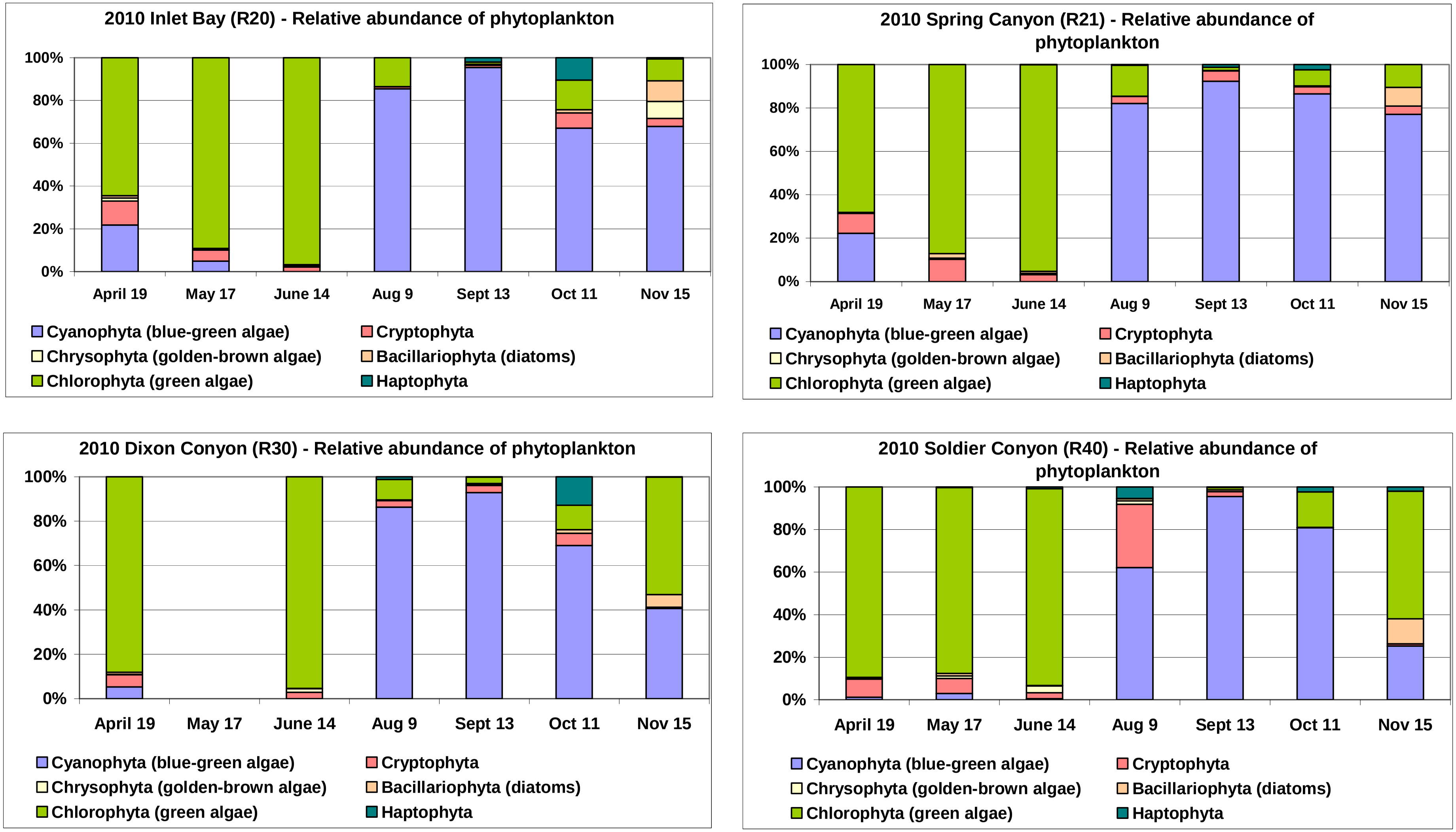


Figure 5-22. Relative abundance (based on # cells/mL) of phytoplankton groups found in the 2010 1-meter samples from Horsetooth Reservoir.

6.0 SUMMARY

The 2010 Horsetooth Reservoir Water Quality Monitoring Program Report documents information and data collected by FCU through 2010 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. Specifically, the 2010 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.

Regulatory Issues

- Horsetooth Reservoir was moved from the 303(d) List to the Monitoring and Evaluation (M&E) List in 2010 for low dissolved oxygen in the metalimnion.

- Horsetooth Reservoir remains on the 303(d) List for Aquatic Life Use due to the presence of mercury in fish tissue.

- Horsetooth Reservoir was placed on the 2010 M&E List for aquatic life chronic standard exceedances of copper and arsenic.

- The Colorado Water Quality Control Division (WQCD) has proposed interim numeric standards for total phosphorus and total nitrogen for the mixed (top) layer of lakes and reservoirs. For cold water lakes and reservoirs greater than 25 acres, the proposed interim total P standard is 20 ug/L while the proposed interim total N standard is 410 ug/L (in both cases, the current proposal is for summer averages (July, August, September), with an allowable exceedance frequency of 1-in-5 years). The rulemaking hearing to consider the adoption of the proposed nutrient standards is scheduled for March 2012.

- WQCD is in the process of developing a chlorophyll-a standard to support a new Protected Water Supply Reservoirs sub-classification to the existing Water Supply use classification. The proposed interim standard is 5 ug/L. This is considered to be a preliminary (placeholder) value since the WQCD is currently completing data analysis to support a final proposed standard.

- WQCD conducted a study in 2010 to better understand the relationship between disinfection byproducts (DBPs) and nutrients, phytoplankton, chlorophyll-a, and organic carbon in Colorado reservoirs to support chlorophyll-a criteria development for Protected Water Supply Reservoirs. Fort Collins Utilities participated in this study by conducting intensive sampling of Horsetooth Reservoir. The final report for this study from the WQCD is not yet available.

Special Studies and Events

- **UCLA and Water Research Foundation (CU Boulder) Dissolved Organic Matter (DOM) Studies.** The UCLA DOM Study and the related Water Research Foundation (CU Boulder) DOM Study both generated a significant amount of technical data. Much of the data and findings from the studies were presented in Beggs (2010). The Water Research Foundation project final report should be available by the end of 2011. The most significant findings presented in Beggs (2010) related to Horsetooth Reservoir and the associated components of the CBT system are summarized below:

    - The East Portal Adams Tunnel, the Big Thompson River above Lake Estes, and the Hansen Feeder Canal (at Horsetooth inlet) are all dominated by humic-like components.

    - Horsetooth Reservoir is also dominated by humic-like components. However, Horsetooth Reservoir has a larger contribution (compared to the river, canal, and tunnel sites) from a protein-like (tryptophan-like) component, and slightly lower contributions from some humic-like components. This indicates a slightly more microbial, less humic DOM compared to the river, canal, and tunnel sites. Differences in DOM character between the top and bottom of Horsetooth Reservoir were not observed.

    - Overall, the average differences in DOM composition between site types (river, canal, tunnel, reservoir) are minor, as the entire study area shows similar character, with all sites dominated by allochthonous (terrestrial) DOM represented by humic-like components. The flush from spring snowmelt runoff helps to mobilize the humic-like components into the watershed where they remain relatively dominant year round.

    - The fact that DOM in the source waters of the study area does not strongly exhibit microbial characteristics (including Horsetooth Reservoir samples) implies that watershed management activities to reduce nutrient loads and algal growth may not have a significant impact on TOC quantity and quality. However, increases in nutrient loads to Horsetooth Reservoir could potentially result in a shift to more microbial (algae) derived DOM.

    - Coagulation is effective at removing the material associated with disinfection byproduct formation, primarily the humic–like components.

    - The protein-like (tryptophan-like) component found in Horsetooth Reservoir DOM was reasonably well removed by coagulation but was not associated with DBP formation. The lack of correlation between this component and DBP formation suggests that while CBT Project reservoir microbial processes may result in taste and odor issues, microbial activity does not appear to relate to DBP precursor concentrations.

- **2010 WQCD High Quality Water Supply Study**. Data collected for Horsetooth Reservoir as part of the 2010 WQCD High Quality Water Supply Study indicate the following (data analysis and assessment conducted by FCU):

  - ➢ No correlation was observed between chlorophyll-a and DOC for Horsetooth Reservoir; this result was expected since the UCLA and CU DOM studies indicated that Horsetooth Reservoir DOC is dominated by terrestrial sources of dissolved organic matter that are mobilized during the spring runoff.

  - ➢ Correlations between Horsetooth Reservoir chlorophyll-a and disinfection byproduct formation potential are poor, indicating that algae are not significant sources of DBP precursors. This finding was also observed by Beggs (2010) in the Water Research Foundation (CU Boulder) DOM Study.

  - ➢ Approximately 94% of the Horsetooth Reservoir TOC in the surface samples was in the dissolved form (range of 87% to 97%).

  - ➢ Characteristics of the DOC that impact its reactivity with chlorine did not change significantly between spring and fall.

- **Geosmin Occurrence in Horsetooth Reservoir and upstream components of the CBT Project.** Findings from the 2010 geosmin monitoring program indicate the following:

  - ➢ 2010 geosmin concentrations in all Horsetooth Reservoir samples were below 4 ppt, except for the Sept. 13 sample collected at Inlet Bay (R20) at 1 meter above bottom (13.9 ppt).

  - ➢ Concentrations in Hansen Feeder Canal waters entering Horsetooth Reservoir ranged from 1.3 to 9.0 ppt in 2010, compared to a somewhat higher concentration range of 3 to 15 ppt in 2009.

  - ➢ Significant geosmin concentrations were measured in the August and September 2010 samples from the east portal Adams Tunnel (30 ppt and 27 ppt, respectively). Geosmin is subject to both volatilization and biodegradation that impact its fate in aquatic systems. These are the likely mechanisms that result in a reduction in geosmin concentrations as this Adams Tunnel water is transported downstream through the east slope CBT system.

- **Northern Water Collaborative Emerging Contaminant Study.** In 2008, Northern Water initiated a collaborative emerging contaminant study to determine the presence of these compounds in waters of the Colorado- Big Thompson system including Horsetooth Reservoir. Data from samples collected of the Upper Thompson Sanitation District effluent show that wastewater treatment plant effluent is a source of many pharmaceuticals and personal care products in the Big Thompson River. However, many of these compounds do not appear to be persistent in the aquatic environment since they do not consistently occur in the 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.

Within Horsetooth Reservoir, only a small number of compounds are consistently detected. Metoprolol (a beta blocker) appears to be a stable, persistent pharmaceutical. Low levels of metoprolol were measured in both the June and August 2010 sampling events in Horsetooth Reservoir at both Spring Canyon and Soldier Canyon at all three depths. Two herbicides, 2,4-D and diuron, were detected in the June and August 2010 samples collected at both Spring Canyon and Soldier Canyon at all three depths. Caffeine was detected in the Spring Canyon and Soldier Canyon samples (all depths) in June and August 2010. Concentrations of all compounds are in the parts per trillion (ng/L) range, and the significance of the occurrence of trace levels of emerging contaminants is unknown.

- **Northern Water Collaborative Horsetooth Reservoir Water Quality Modeling Study.** A project to develop a hydrodynamic water quality model of Horsetooth Reservoir was begun in 2010 and should be completed in late 2011. The project is being managed by Northern Water with financial contributions from the City of Greeley, the City of Fort Collins, and Soldier Canyon Filter Plant. The collaborators selected Jean Marie Boyer (Hydros Consulting Inc.) to develop the data input files for the model (CE-QUAL-W2) and run several scenarios. In 2010, a significant effort was made by Northern Water to provide an accurate daily water balance for the reservoir. This is important because if an accurate daily water balance cannot be achieved, an accurate simulation of water quality parameters cannot be achieved.

- **Wildfires and Watershed Wildfire Assessments.** Wildfires that occurred in parts of the Big Thompson and/or Horsetooth Reservoir watersheds in 2010 include the Cow Creek, Round Mountain, Reservoir Road, and Bighorn Fires. None of these fires has had a measureable (if any) impact on Horsetooth Reservoir water quality.

  In 2010, the City of Fort Collins and the City of Greeley jointly funded the Cache la Poudre Wildfire Watershed Assessment Project conducted by J.W. Associates Inc. The local Horsetooth Reservoir watershed is a sixth-level watershed within the Cache la Poudre watershed and was therefore included in this wildfire assessment. The project included four meetings attended by key watershed stakeholders including the City of Fort Collins, City of Greeley, Tri-Districts, U.S. Forest Service, Colorado State Forest Service, Larimer County, and Northern Water.

  With respect to the local Horsetooth Reservoir watershed, the final report indicated that some existing treatments have been completed in Lory State Park and on Larimer County lands. There may be opportunities to partner with these agencies on future, and possibly, expanded treatments. In addition, Community Wildfire Protection Plans (CWPP) cover the entire local watershed (the Poudre Fire Authority CWPP and the Loveland CWPP). The CWPPs should be reviewed for additional proposed treatments that would contribute to watershed-level protection.

  An assessment of the Big Thompson Watershed will be conducted in 2011 by J.W. Associates Inc. using the same methodology as was used for the Cache la Poudre Wildfire Watershed Assessment.

Horsetooth Reservoir Hydrology

- The estimated hydraulic residence time for calendar year 2010 was 0.88 years. The calendar year hydraulic residence time has ranged from 0.82 to 1.1 years over the six year period of 2005 through 2010, with an average of 0.92 years.

- Estimated 2010 inflow to Horsetooth Reservoir from the Hansen Feeder Canal totaled 147,600 ac-ft.

- 2010 annual outflow to the Hansen Supply Canal (87,100 ac-ft) was roughly 2.7 times the 2010 annual outflow at Soldier Canyon Dam (31,900 ac-ft).

- 2010 Horsetooth Reservoir water surface elevations fluctuated 49.7 feet between the maximum and minimum water levels.

- 2010 Horsetooth Reservoir annual (calendar year) average volume was 108,740 ac-ft.

Hansen Feeder Canal Water Quality

- 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 estimated annual mass load of TOC from the Hansen Feeder Canal to Horsetooth Reservoir was significantly higher in 2010 than in previous years. The high average TOC concentration during May 2010 combined with relatively high Hansen Feeder Canal inflows in May resulted in a May 2010 TOC load of 250 tons, or 26% of the annual 2010 TOC load.

Horsetooth Reservoir Water Quality

- **Sampling Events.** In 2010, there were seven routine Horsetooth Reservoir sampling events: April 19, May 17, June 14, August 9, September 13, October 11, and November 15. There were also five special sampling events at the Soldier Canyon Dam site (June 3, July 8, July 20, Aug 23, and Sept 27) associated with the Colorado WQCD High Quality Water Supply Study.

- **Temperature Profiles.** The 2010 temperature profiles show the typical development of thermal stratification beginning in the spring and progressing through the summer and early fall. The presence of the epilimnion (the well-mixed upper layer characterized by uniform temperatures), the metalimnion (the middle layer where the temperature drops sharply), and the hypolimnion (the bottom layer) was clearly evident by the June 14 sampling event.

- **Dissolved Oxygen Profiles.** Similar to previous years, the dissolved oxygen profiles show depletion in both the metalimnion and hypolimnion. Dissolved oxygen depletion at the reservoir bottom is 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.

- **Interflow.** Temperature differences between the Hansen Feeder Canal inflow and the Horsetooth Reservoir surface waters impact the flow of Hansen Feeder Canal water through the reservoir. Because of temperature-induced density differences, cooler Hansen Feeder Canal water plunges below the reservoir surface until it reaches a level where the inflow and ambient reservoir water temperatures (densities) are the same. Hansen Feeder Canal inflow then moves through the reservoir as an interflow until it is dissipated.

- **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, Spring Canyon, Dixon Canyon, and Soldier Canyon all show the presence of a specific conductance minima in the metalimnion on June 14, 2010, August 10, 2010, and September 13, 2010, indicating the occurrence of interflow all the way to Soldier Canyon.

- **Total Organic Carbon (TOC).** A significant increase in TOC concentrations occurred within the reservoir and at the FCWTF during 2010 due to the significant TOC load from the Hansen Feeder Canal during the 2010 spring runoff period. The TOC of raw Horsetooth Reservoir water at the FCWTF peaked on October 12, 2010 at 4.2 mg/L. Concentrations at the FCWTF then began decreasing, but at the end of 2010 they were still significantly above the five-year (2005 to 2009) average TOC concentration of 3.2 mg/L.

- **Comparison of Nutrient Data to Proposed Standards.** Summer average (July, August, and September) total phosphorus and total nitrogen values for the 1 meter samples collected in Horsetooth Reservoir were compared to the proposed interim nutrient standards over the period of 2006 to 2010 (total P standard of 20 ug/L, total N standard of 410 ug/L). None of the summer averages were greater than the respective proposed interim standards. However, note that in 2009 and 2010, the summer average was calculated from one sampling event in each of August and September and may not accurately reflect actual conditions. Beginning in 2011, the Fort Collins routine sampling program will also include the month of July.

- **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 ug/L) and summer and fall samples sometimes approaching the eutrophic range (chlorophyll-a > 7.3 ug/L). The November 2011 samples for Spring Canyon and Inlet Bay were in the eutrophic range. Summer average (July, August, and September) chlorophyll-a values for the 1 meter samples collected in Horsetooth Reservoir for 2006 – 2010 were compared to the proposed interim chlorophyll-a standard for Protected Water Supply Reservoirs. None of the summer averages were greater than the proposed interim standard of 5 ug/L.

- **Phytoplankton.** The dominant contributor to the total algal density (number of cells per mL) in the April through June samples was the Chlorophytes (green algae). The dominant green algae species during this time was *Chlorella minutissima*. A shift in algal populations occurred in August with the cyanobacteria (blue-green algae) making up the highest percentage of the total algal density. This shift in algal populations was accompanied by a significant increase in total phytoplankton density, with the peak density observed in the Spring Canyon sample on August 9 (108,424 cells/mL). The dominant blue-green algae species included *Merismopedia tenuissima*, *Aphanothece smithii, Aphanocapsa delicatissima, Aphanothece clathrata* and *Synechococcus capitatu*. None of these species produce geosmin. Geosmin producing species of blue-green algae comprised a very small fraction of the total phytoplankton count in 2010, generally one percent or less (down to zero) of the total density.

Issues of Concern

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

- Low dissolved oxygen concentrations in the metalimnion and hypolimnion.
- Recurring episodes of geosmin, both within the reservoir and in upstream components of the CBT Project.
- Changes in TOC concentrations or characteristics that may increase the formation of disinfection byproducts during water treatment.
- Potential impacts from proposed water supply projects.
- Impacts related to bark beetles (mountain pine beetle), including the increased risk of high severity wildfires.
- Potential for the spread of invasive mussels to Horsetooth Reservoir.

7.0 REFERENCES

Anderson, C., Briuon, D., Claudio, R., Culver, M. and M. Frisher. 2008. Zebra/Quagga Mussel Early Detection and Rapid Response; Blue Ribbon Panel Recommendations for the Colorado Division of Wildlife.

Beggs, Katherine H., 2010. Characterizing Temporal and Spatial Variability of Watershed Dissolved Organic Matter and Disinfection Byproduct Formation with Fluorescence Spectroscopy. Ph.D. Dissertation. Department of Civil and Environmental Engineering, University of Colorado, Boulder, Colorado.

Billica, J. and J. Oropeza, 2010. 2009 Horsetooth Reservoir Water Quality Monitoring Program Annual Report, Internal Water Production Report, September 13, 2010, 89 pages plus appendices.

Billica, J., J. Oropeza, and K. Elmund, 2010. Monitoring to Determine Geosmin Sources and Concentrations in a Northern Colorado Reservoir, In: Proceedings of the National Water Quality Monitoring Council and NALMS 2010 National Monitoring Conference (April 25-29, 2010, Denver).

Billica, J. and J. Oropeza, 2009. City of Fort Collins Utilities Horsetooth Reservoir Monitoring Program, Internal Water Production Report, December 2009, 99 pages plus appendices.

Clow, D., 2010. United States Geological Survey. *Effects of mountain pine beetle on water quality in the Upper Colorado River Basin.* Presentation to "MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality", hosted by Western Water Assessment, Boulder, CO. April 8, 2010. http://wwa.colorado.edu/ecology/beetle/mpb-water-apr2010.html.

Colorado Division of Wildlife and Colorado State Parks, January 2010. *State Aquatic Nuisance Species (ANS) Program Summary for Colorado Legislators per SB 08-226.* http://www.colorado.gov

Colorado Division of Wildlife and Colorado State Parks, January 2011. *State Aquatic Nuisance Species (ANS) Program Summary for Colorado Legislators per SB 08-226.* http://www.colorado.gov

Essington, Michael. E., 2004. *Soil and Water Chemistry: An Integrative Approach.* CRC Press LLC, Boca Raton, Florida.

Front Range Wildfire Watershed Protection Planning (FRWWPP) - Data Refinement Work Group, 2009. Protecting Critical Watersheds in Colorado from Wildfire: A technical approach to watershed assessment and prioritization.

Le Master, Dennis C., Guofan Shao, and Jacob Donnay, 2007. Protecting Front Range Forest Watersheds from High-Severity Wildfires. An assessment by the Pinchot Institute for Conservation, funded by the Front Range Fuels Treatment Partnership.

Lukas, J. and E. Gordon, 2010. *Impacts of the mountain pine beetle infestation on the hydrologic cycle and water quality: A symposium report and summary of the latest science.* Feature article from Intermountain West Climate Summary, May 2010. Vol. 6, Issue 4. Product of the Western Water Assessment.

MacDonald, Lee H. and John D. Stednick, 2003. Forests and Water: A State-of-the-Art Review for Colorado. Colorado Water Resources Research Institute Completion Report No. 196. Colorado State University, Fort Collins, CO.

McCutchan, J., 2010. University of Colorado-Boulder. *Effects of the mountain pine beetle on water quality in Colorado mountain streams.* Presentation to "MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality", hosted by Western Water Assessment, Boulder, CO. April 8, 2010. http://wwa.colorado.edu/ecology/beetle/mpb-water-apr2010.html.

Rhoades, C., 2010. USFS Rocky Mountain Research Station. *Forest and watershed responses to beetle-related management.* Presentation to "MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality", hosted by Western Water Assessment, Boulder, CO. April 8, 2010. http://wwa.colorado.edu/ecology/beetle/mpb-water-apr2010.html.

Stednick, J., 2010. Colorado State University. *Water resource reponses in beetle-killed catchments in north-central Colorado.* Presentation to "MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality", hosted by Western Water Assessment, Boulder, CO. April 8, 2010. http://wwa.colorado.edu/ecology/beetle/mpb-water-apr2010.html.

Uunila, L., B. Guy, and R. Pike. 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: Key questions and current knowledge. Extended Abstract. *BC Journal of Ecosystems and Management.* 7(2):37–39. URL: *http://www.forrex.org/publications/jem/ISS35/vol7_no2_art4.pdf*