City of Fort Collins Utilities

2009 Horsetooth Reservoir Water Quality Monitoring Program Report

City of Fort Collins Water Resources & Treatment Services

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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 2009 Horsetooth Reservoir Water Quality Monitoring Program Report (2009 Report) documents data and information collected and assessed by FCU during the period of 2005 through 2009 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. The 2009 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 Horestooth 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 2009 included seven routine sampling events.

Review of data for the 2009 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 2009 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 2009 dissolved oxygen profiles show depletion in both the metalimnion (middle depth of the reservoir) and hypolimnion (bottom depths) as the season progresses. Low dissolved oxygen levels at the reservoir bottom in the fall can result in the release of manganese from the sediments. However, the 2009 September and October dissolved manganese concentrations at the bottom of Soldier Canyon were below the FCWTF treated water target of 5 ug/L. Calcium concentrations in Horsetooth Reservoir are below 12 mg/L, a threshold used to identify water bodies at very low risk for invasion by zebra and quagga mussels.

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 conducted a special study in 2009 to assess the spatial and temporal occurrence of the taste and odor compound geosmin. FCU is collaborating with other entities on special studies that include: characterizing the naturally occurring total organic carbon (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); and conducting hydrodynamic water quality modeling of Horsetooth Reservoir.

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.

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.

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1.0 BACKGROUND

1.1 Monitoring Program Goals and Scope of the 2009 Report

The 2009 Report is the first annual report to be produced as part of the City of Fort Collins Utilities (FCU) Horsetooth Reservoir Water Quality Monitoring Program. This report summarizes Horsetooth Reservoir and Hansen Feeder Canal water quality data collected by FCU in 2009 and provides a comparison with water quality data collected and assessed by FCU during the 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 nutrients and 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. Trend analysis was not conducted for the 2009 Report since it was recently conducted for Horsetooth Reservoir data collected through 2008 and reported in Billica and Oropeza (2009).

The details of the FCU Horsetooth Reservoir Water Quality Monitoring Program have been previously documented (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 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).

Three Lakes Watershed. The Three Lakes Watershed (Figure 1-2) is situated on the western slope of the Continental Divide and encompasses several tributaries within the headwaters of the Colorado River (including North Fork Colorado River, North Inlet, East Inlet, Columbine Creek, Roaring Fork, Arapaho Creek, and Stillwater Creek). The Colorado River tributaries are the primary sources of water to the western slope CBT "Three Lakes" reservoir system, which includes Grand Lake, Shadow Mountain Reservoir, and Granby Reservoir (or Lake Granby).

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.

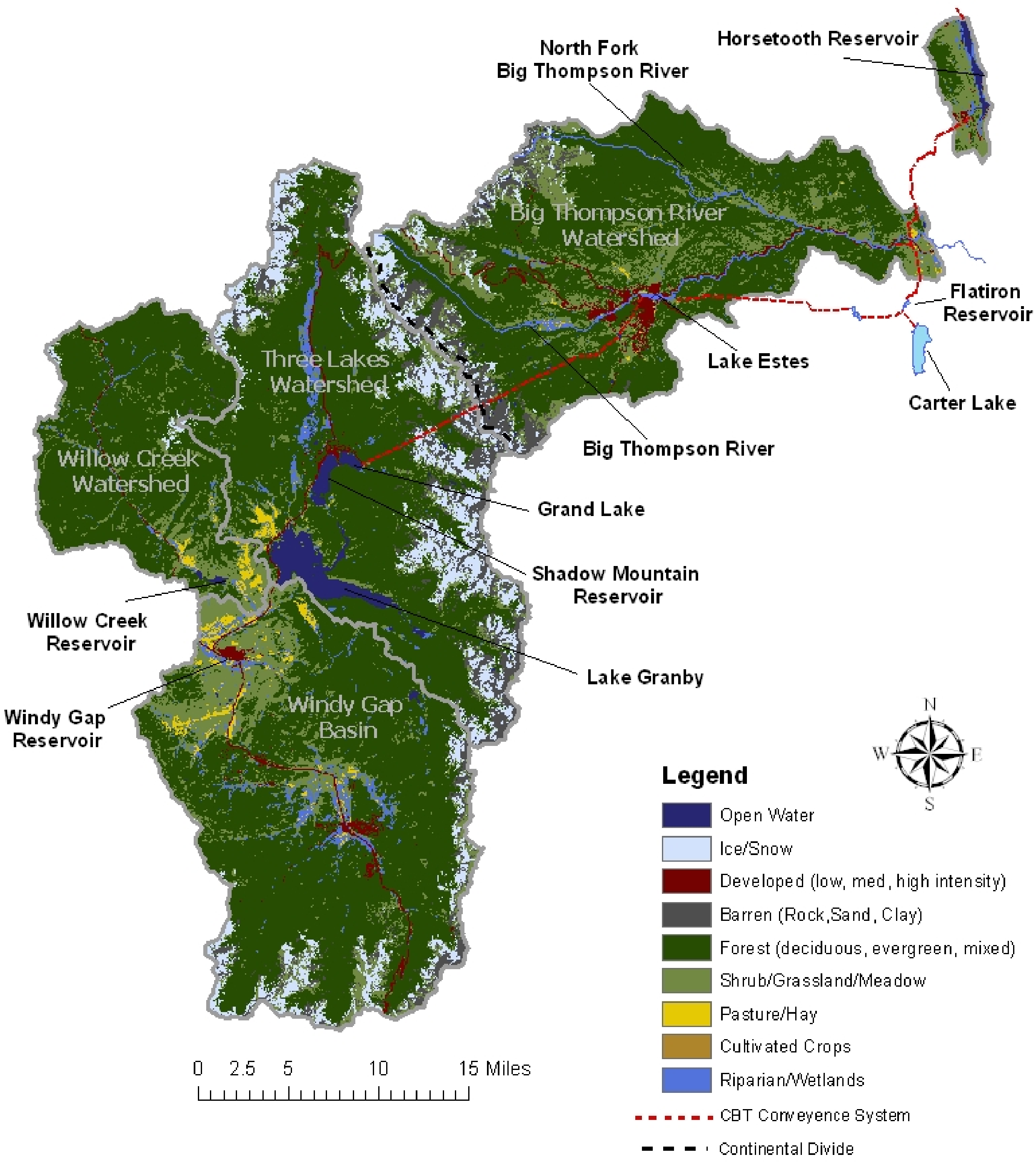
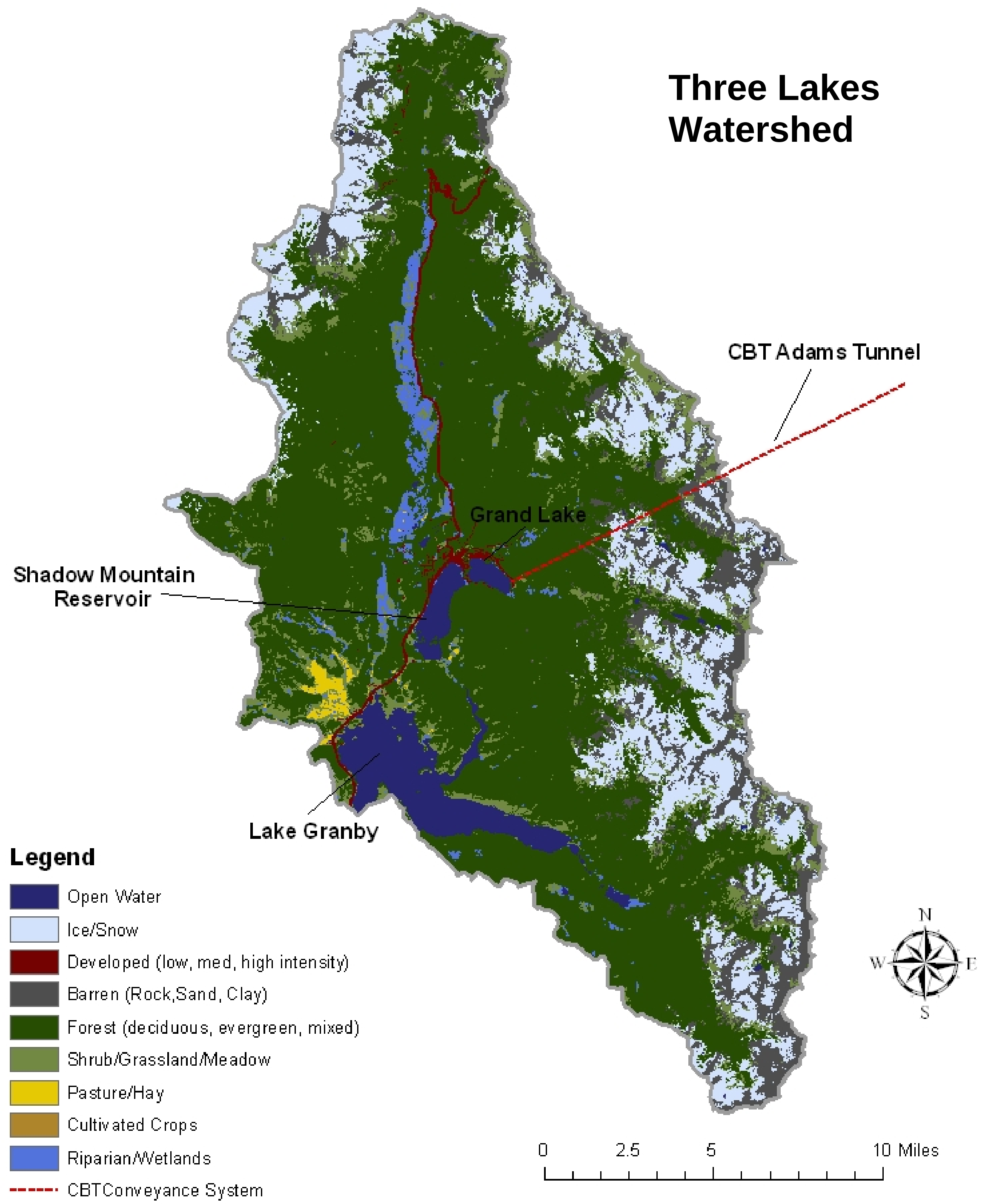


Table. 1-1. Land use/land cover types for the major watersheds associated with Horsetooth Reservoir.

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	

Figure 1-2. Land use/land cover map for the west slope CBT Project Three Lakes Watershed.



Water is pumped to Granby Reservoir from Willow Creek Reservoir and Windy Gap Reservoir. The Three Lakes Watershed covers 312 square miles and is characterized by predominantly undeveloped, natural vegetative cover (Table 1-1). Over half (60%) of the landscape area is forested, with other vegetation (meadows and wetlands), bare rock and perennial snow fields contributing a combined approximate thirty-five percent of the land cover. The Town of Grand Lake and other developed areas comprise a very small percentage of the total landscape area (0.9% or about 3 square miles), but have the potential to exert considerable influence on the quality of CBT Project water supplies due to their close proximity to surface waters. The west portal of the Alva Adams Tunnel is located at Grand Lake.

Willow Creek Watershed. CBT Project water also comes from Willow Creek Reservoir, located directly west of Lake Granby (Figures 1-1 and 1-3). Water from Willow Creek Reservoir is pumped to Lake Granby via the Willow Creek Canal. The Willow Creek Watershed is considerably smaller than the Three Lakes Watershed, with approximately 142 square miles of primarily forested landscape (81%) and significantly less exposed rock, ice and snow (0.4% and 1%, respectively). Other vegetation types include riparian areas, wetlands, meadows, and hay pasture, which together account for about seventeen percent of the land area (Figure 1-3 and Table 1-1). The developed areas in this basin are dispersed (roads) and represent just 0.5 percent of the watershed area and are expected to have a minimal impact on CBT Project water quality.

Windy Gap Watershed. Windy Gap Project water is delivered through the CBT system and can, therefore, impact water quality of Horsetooth Reservoir. The Windy Gap Watershed sits adjacent to the southern edge of Lake Granby and the Three Lakes Watershed boundary (Figure 1-1). Windy Gap Reservoir is comprised of a mixture of water from the Colorado River and the Fraser River that is delivered to Lake Granby via the Windy Gap Pump Plant and the Windy Gap Pipeline. The Windy Gap Watershed encompasses approximately 325 square miles that includes forest (65%), shrub and grassland (19%), and hay pasture (2%) lands. Rock and perennial ice and snow fields constitute roughly eight percent of the land cover (Figure 1-4). Developed area in the Windy Gap Basin is considerably greater than in the Three Lakes and Willow Creek Watersheds (6.4 square miles, or about 2% of land area) and includes the towns of Fraser, Winter Park, Tabernash, and Granby. Windy Gap Reservoir water is potentially impacted by four municipal wastewater treatment plants that discharge in the watershed.

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

Figure 1-3. Land use/land cover map for the west slope Willow Creek Watershed.

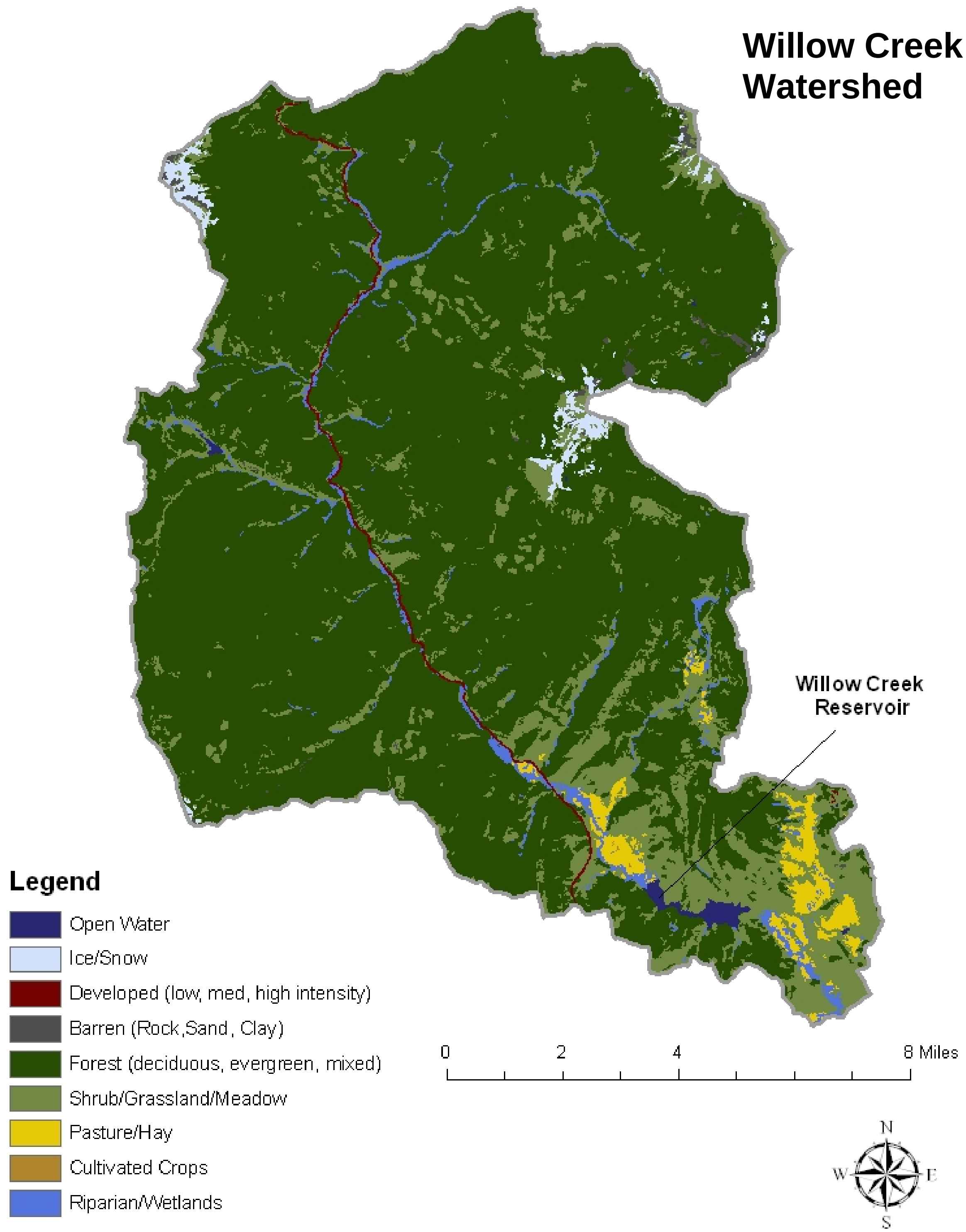
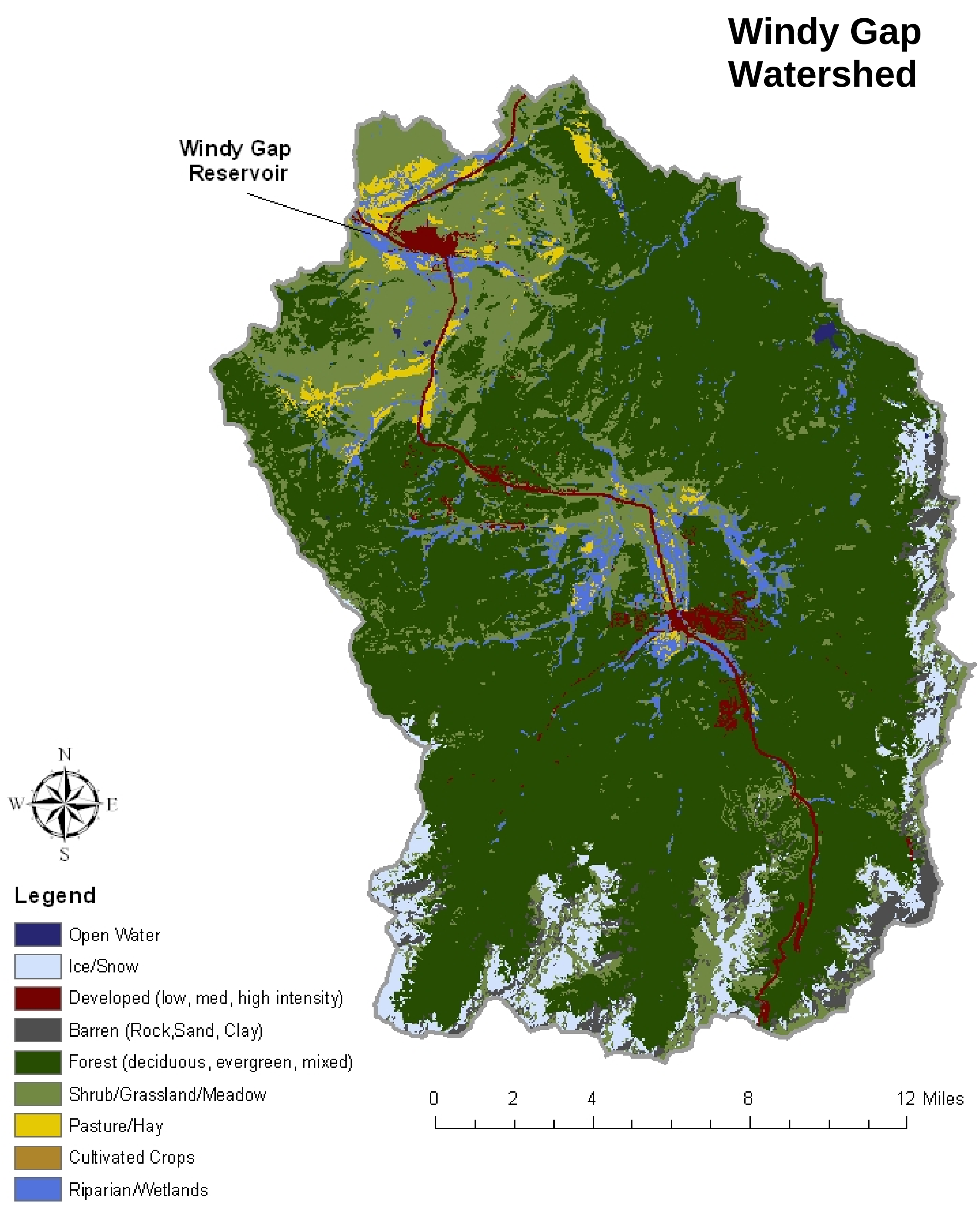


Figure 1-4. Land use/land cover map for the Windy Gap Watershed.



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 1-5) 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 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 (Figures 1-1 and 1-6). The Horsetooth Reservoir Watershed is also relatively low in elevation, which results in a different vegetation community consisting predominantly of Ponderosa Pine (*Pinus ponderosa*) forests (27%) and shrub lands/grasslands (53%). Developed areas are limited to areas west of the reservoir (0.6 sq. miles).

The local watershed surrounding Horsetooth Reservoir is small and generally not expected to significantly affect the reservoir water quality. However, 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 within the boundaries of the Horsetooth Reservoir Watershed and 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 water quality in Horsetooth Reservoir.

Although the primary purpose of Horsetooth Reservoir is to store and supply municipal and irrigation water, it also provides water and land-based recreational opportunities. The recreational uses of Horsetooth Reservoir have been managed since 1954 by Larimer County. 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 County Park lands completely surround the reservoir (Figure 1-7).

Figure 1-5. Land use/land cover map for the Big Thompson River Watershed upstream of the Dille Tunnel.

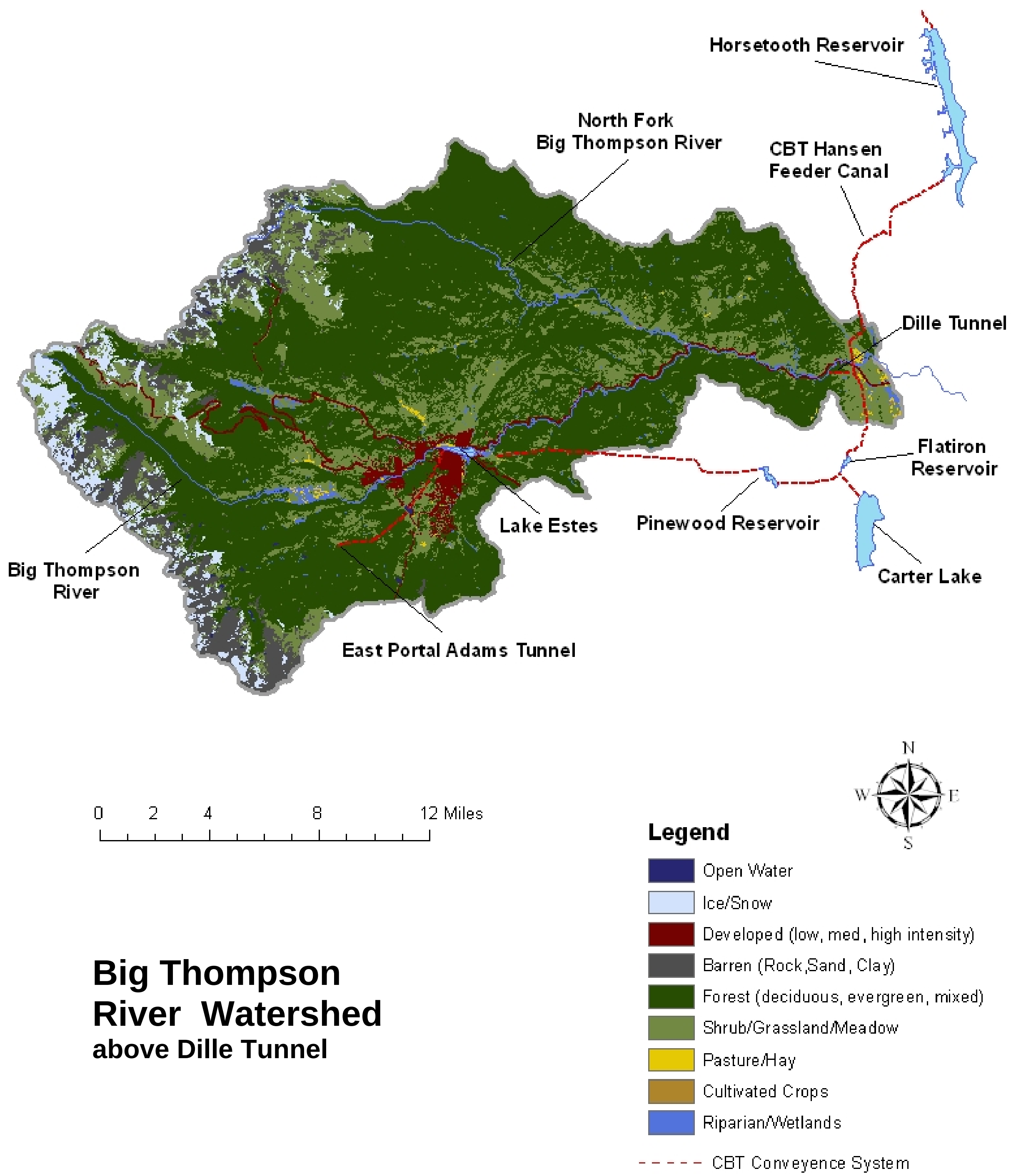
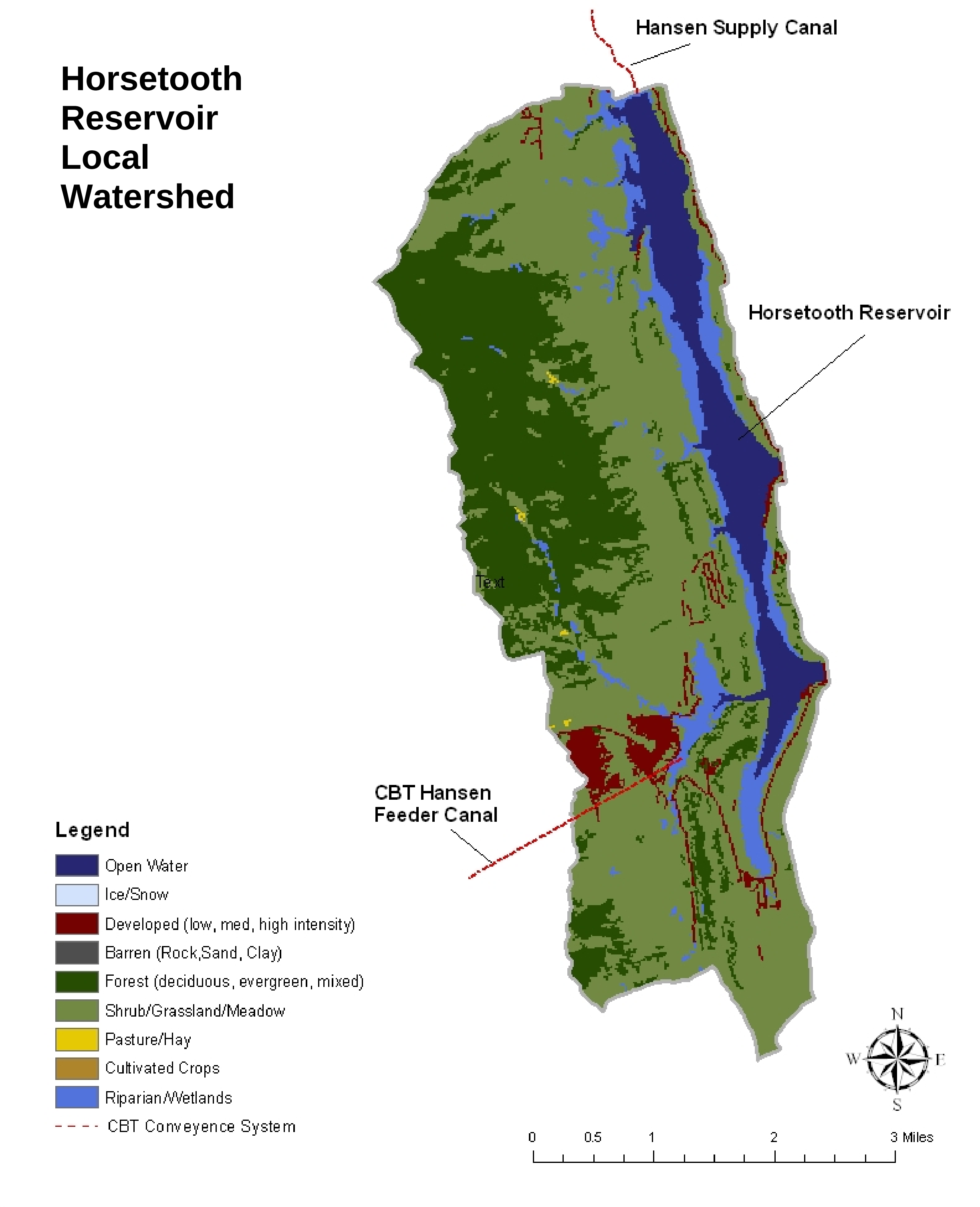


Figure 1-6. Land use/land cover map for the Horsetooth Reservoir Local Watershed



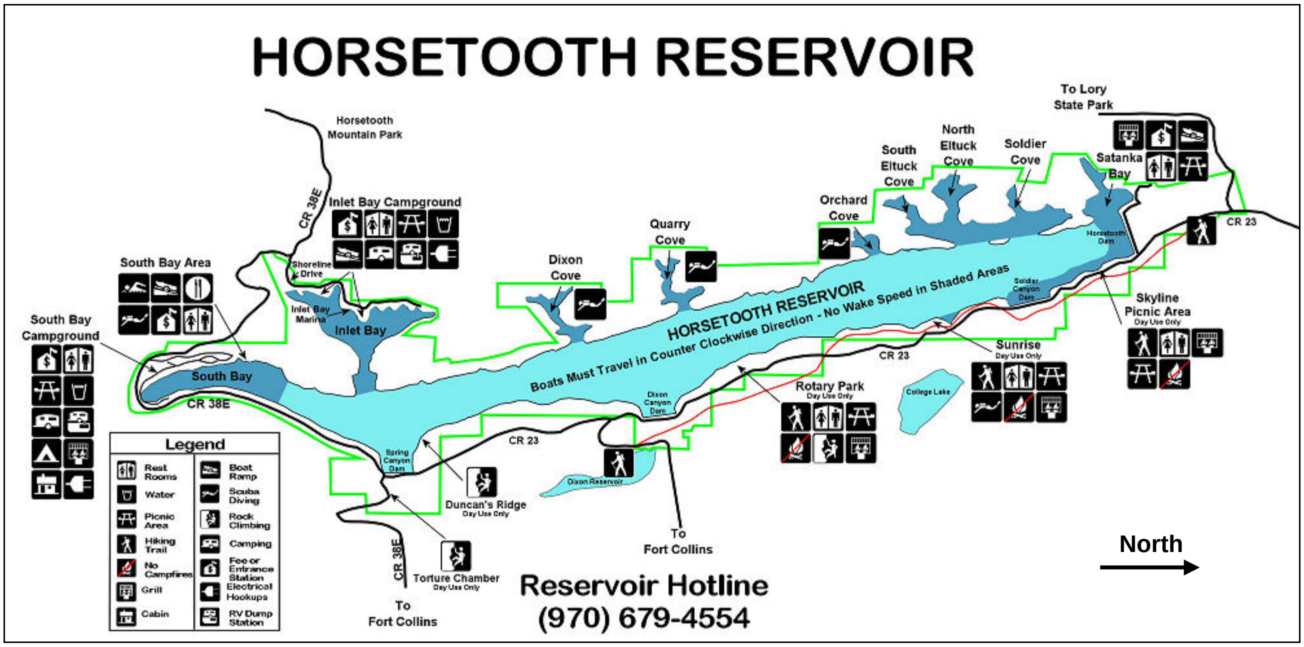


Figure 1-7. Horsetooth Reservoir County Park Recreation Map
(from http://www.larimer.org/naturalresources/horsetooth_map.htm)

The Larimer County Parks Master Plan and the Reservoirs Resource Management Plan were updated in 2007 and included recommendations for improvements at Horsetooth Reservoir County Park recreational sites/facilities. The South Bay Campgrounds Improvements Project resulted in the construction of additional campsites in 2009. The South Bay Swim Beach Improvements Project is under construction. Design is currently being conducted for improvements to the Sunrise Day Use Area, including the construction of additional parking spaces, improvements to the access road, and the addition of a vault toilet and picnic shelter.

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 1-8 and 1-9) 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

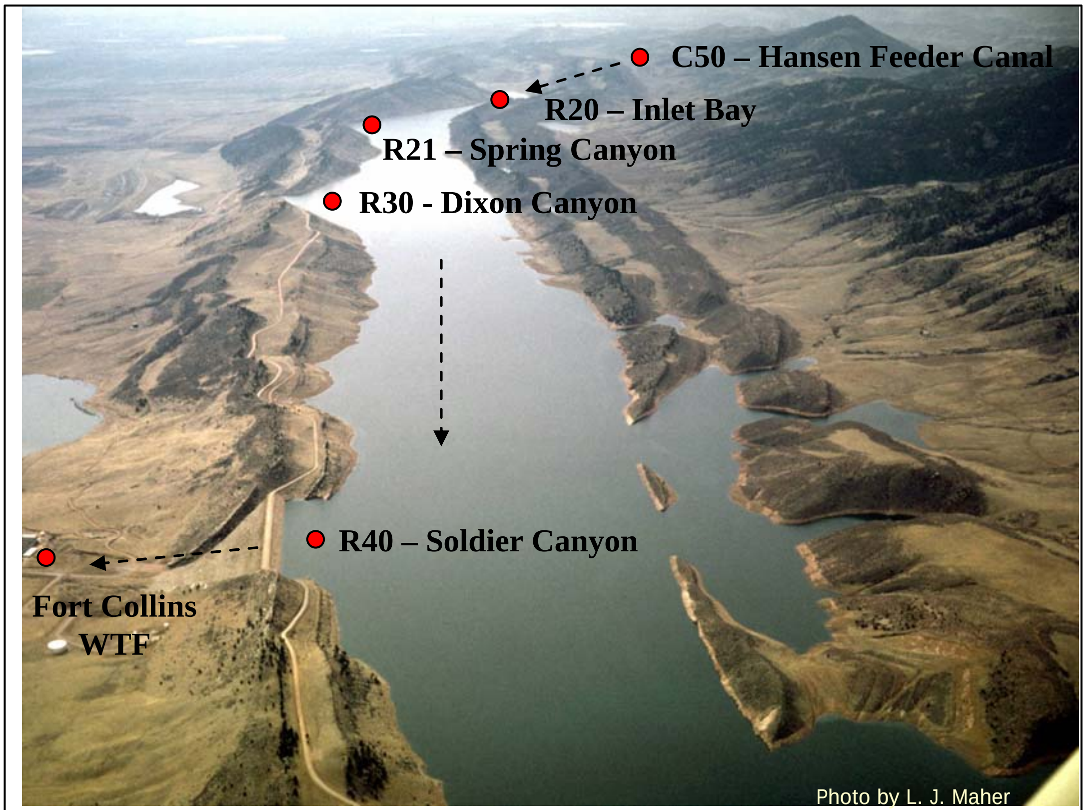


Figure 1-8. Looking south at Horsetooth Reservoir sampling locations (----> Direction of water flow).

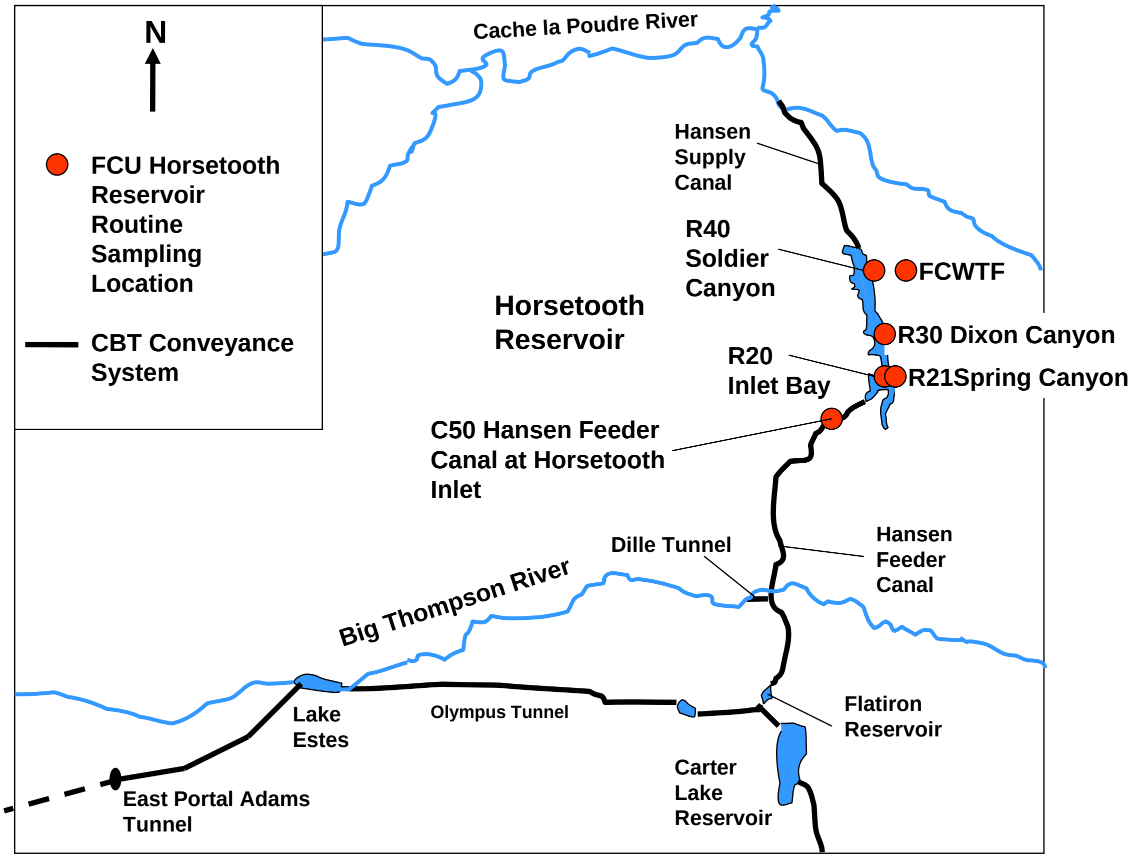


Figure 1-9. Map of FCU Horsetooth Reservoir water quality monitoring sites.

1.4 Sampling Frequency and Parameters

In 2009, there were seven routine Horsetooth Reservoir sampling events: April 20, May 18, June 29, August 3, September 8, October 5, and November 2. There were also two special sampling events (August 17 and September 21) associated with obtaining additional information to evaluate potential geosmin sources and production sites; sampling was conducted for only a subset of the routine parameters during these special events.

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 (including nutrients, trace metals, and BTEX) include many values below their respective Reporting Limits, as can been seen in the various time series plots presented in this report.

Changes made to the sampling frequency and parameters in 2009 included the following:

- Reduced the sampling frequency for arsenic, lead, and silver in Horsetooth Reservoir to once per year (during the September sampling event) because of the large number of non-detects in the historic data (note that the sampling frequency for these parameters did not change for the Hansen Feeder Canal (C50)).

- Added calcium and magnesium at R21 (Spring Canyon, all depths) in order to obtain more data to assess the potential for zebra/quagga mussels to thrive in Horsetooth.

- Added geosmin sampling, starting with the August 3 event, at depths of 1 meter below surface, within the metalimnion, and at 1 meter above bottom at Inlet Bay Narrows (R20), Spring Canyon (R21), Dixon Canyon (R30), and Soldier Canyon (R40).

- Beginning in 2009, phytoplankton enumeration (cells/mL) and identification to the species level (when possible) are conducted by Richard Dufford (private consultant) using a Leitz phase contrast inverted microscope by the method of Utermohl (1958). Aliquot volume ranges from 2 to 10 mL depending on turbidity. Phytoplankton greater than 30 micrometers in diameter are first enumerated at x125 magnification. Smaller algae are then counted at x500 and x1250. The entire bottom of the chamber is viewed during the x125 count. At least 100 units of the most numerous algae are counted using the strip count method at the higher magnifications (APHA, 1989). A minimum of 300 units are counted during the entire process (AWWA, 2002). Diatoms are identified after clearing in 30% hydrogen peroxide and mounting in Zrax Mounting Medium (Weber, 1973).

Table 1- 3. 2009 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

1.5 Regulatory and Other Issues

This section provides an overview of new, revised, and/or proposed water quality regulations that directly impact Horsetooth Reservoir, and an overview of ongoing watershed issues of concern.

1.5.1 Revisions to Colorado's Monitoring and Evaluation (M&E) List and Section 303(d) List

In 2009, the Water Quality Control Division (WQCD) of the Colorado Department of Public Health and Environment (CDPH&E) proposed to combine Colorado's Monitoring and Evaluation List (Regulation #94) into Regulation #93 (Colorado's List of Water Quality Limited Segments requiring Total Maximum Daily Loads, also referred to as the Section 303(d) List). At the same time, revisions were proposed to the M&E List and the Section 303(d) List. The public rulemaking hearing before the Colorado Water Quality Control Commission for these revisions was Feb. 8, 2010; the Commission adopted the final action documents pertaining to these revisions on March 9, 2010 and they became effective on April 30, 2010. The outcome was the approval of the proposed 2010 Section 303(d) List and the M&E List as rules (revised Regulation #93) and the repeal of Regulation #94. The listing methodology used by the WQCD for the 2010 listing cycle was documented in May 2009.

The 2010 revisions to the M&E List and the Section 303(d) List included moving Horsetooth Reservoir (COSPCP14) from the Section 303(d) List for dissolved oxygen (D.O.) 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. The WQCD's attainment analysis for Horsetooth Reservoir concluded the following with respect to D.O.:

> *"Horsetooth Reservoir was originally placed on the 303d list due to exceedances in the DO standard (temperature); the profiles examined showed insufficient DO at depths where the temperature was below the standard, a concept defined as adequate refuge. This attainment decision was made in the 2008 rulemaking hearing when the temperature standard for Horsetooth Reservoir was 18.2° C. The Commission has since adopted a new temperature standard of 22.8°C for Horsetooth Reservoir. When we re-assessed Horsetooth Reservoir with this new standard, the attainment status was different."*

> *"Horsetooth Reservoir was in attainment of both the temperature and DO standard in the epilimnion for all profiles examined so the Division recommends Horsetooth Reservoir be removed from the 303d list for DO (temp). When we strictly interpret the current standard and assess D.O. in the metalimnion, 27 of the 79 profiles show DO depletion in this layer so the Division recommends Horsetooth Reservoir for the M&E list for DO. This attainment decision could be different in two years when this reservoir is reassessed with the revised dissolved oxygen standard in Reg. 31."*

The 2010 revisions also included placing Horsetooth Reservoir on the M&E List for copper and arsenic (aquatic life standards). Dissolved copper and dissolved arsenic data collected by the USGS and NCWCD from 2003 to 2008 were used to make this determination. The WQCD's attainment analysis concluded the following with respect to the M&E Listing for copper and arsenic:

> *"For the epilimnion and the hypolimnion at site HT-DIX, the 85th percentile for copper and arsenic exceeded the chronic standard. The sample size for both layers is not sufficient to warrant listing Horsetooth Reservoir on the 303(d) for these parameters. For this reason, the Division recommends Horsetooth Reservoir be placed on the M&E list so that additional data can be collected for future assessments."*

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

1.5.2 WQCD Proposal for Footnote 9 of Regulation No. 31: Assessing Dissolved Oxygen in Lakes and Reservoirs

The WQCD is proposing changes to Footnote 9 of Regulation No. 31. The WQCD proposal for Footnote 9 (dated September 21, 2009) focuses on maintaining D.O. within the preferred habitat for fish and uses specific depths (and not terms like epilimnion, metalimnion and hypolimnion, whose boundaries can be indistinct, subjective and/or labor-intensive to determine) in the assessment methodology for the Aquatic Life Use Classification. The proposed changes to Footnote 9 also include D.O. assessment methodologies for the Recreation, Agriculture, and Water Supply use classifications. The proposed assessment methodology for the Water Supply use classification is the minimum D.O. measured at the intake (the standard is 3.0 mg/L).

Once the proposed changes to Footnote 9 are adopted and Horsetooth Reservoir is reassessed with the revised D.O. methodology, the reservoir's status with regard to the M&E List and 303(d) List for D.O. may change again.

1.5.3 WQCD Nutrient Criteria for Protection of High-Quality Water Supply Reservoirs

The WQCD is in the process of developing a nutrient standard to help maintain or reduce the disinfection byproduct (DBP) formation potential of lakes and reservoirs that supply raw water directly to water treatment plants. Controlling nutrients and algal growth may also result in other benefits for drinking water utilities in Colorado, including less coagulant usage and/or reduced reliance on activated carbon for taste and odor control efforts.

The WQCD will select the proposed standard based on an understanding of the relationship of DBPs with nutrients, phytoplankton, chlorophyll, and organic carbon. They anticipate that the proposal will be a summer average chlorophyll-a standard to support a new High-Quality Water Supply Reservoirs sub-classification to the existing Water Supply use classification. The WQCD anticipates that the sub-classification for High-Quality Water Supply Reservoirs would not automatically apply to all high-quality or direct-use water supply reservoirs, but would be applied to individual reservoirs through the basin regulation rulemaking hearing process. Their proposal will be part of a larger proposal for nutrient standards for which a rulemaking hearing is scheduled in June 2011.

In 2010, the WQCD is conducting a study with Dr. Scott Summers of the University of Colorado, Boulder (CU) to better understand the relationship of DBPs with nutrients, phytoplankton, chlorophyll, and organic carbon in Colorado reservoirs. Data collected as part of this study will be used to support criteria development. The project includes synoptic sampling of 20 to 30 lakes/reservoirs and intensive sampling of approximately 10 lakes/reservoirs. The intensive sampling is being conducted by several utilities in Colorado, with the laboratory analysis conducted by CU. The City of Fort Collins is participating in this study by conducting the intensive sampling of Horsetooth Reservoir. Samples will be collected by FCU at Soldier Canyon Dam 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.

1.5.4 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 the trophic structure of 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.

The first identified populations of dreissinid mussels west of the Continental Divide were found in 2007 in Lake Mead and very quickly spread to downstream reservoirs on the Lower Colorado River water delivery systems throughout Arizona and California. The ability of the mussels to attach to hard surfaces and to survive out of water for up to 2 weeks facilitates the rapid spread of zebra and quagga mussels to unconnected water bodies as they travel on boats and trailers that have been exposed to contaminated waters. In late 2007, the first adult mussels in Colorado were found in Pueblo Reservoir, although identification could not be confirmed by DNA due to fungal damage of the specimens. In July 2008, quagga mussel larvae (veligers) were conclusively identified in Lake Granby, an upper western slope reservoir of the CBT conveyance system that feeds into Horsetooth Reservoir. Willow Creek Reservoir, Shadow Mountain Reservoir, Grand Lake are other CBT reservoirs that have since also tested positive for zebra and quagga mussel veligers. To date, no veligers have been found in any eastern slope reservoir of the CBT project. In addition, with the exception of the two unconfirmed adults in Pueblo Reservoir, there have been no adult mussels yet found in any Colorado waters.

Because Horsetooth Reservoir is a terminal reservoir in the CBT system, introduction of zebra or quagga mussels would likely occur either as a result of recreational boating and fishing activities or through transfer from upstream infested canals and reservoirs that feed into Horsetooth. As such, preventing infestations in Horsetooth Reservoir depends on two main prevention efforts – the Larimer County Boat Inspection Program and the Colorado Division of Wildlife (CDOW) Zebra/Quagga Mussel Monitoring Program.

Beginning on April 1, 2009, Larimer County implemented mandatory inspections for all boats on Carter and Boyd Lakes and Horsetooth Reservoir. The mandatory inspection of all boats goes beyond the 2009 state regulations that limit inspections to out-of-state boats or those that have been on infected lakes. 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.

1.5.5 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 though 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.

According to information provided by the US Forest Service (USFS) website (http://www.fs.fed.us/r2/news/press-kits/2010/index.shtml), 3.6 million acres in Colorado and southern Wyoming have been affected since 1996. Results of the 2009 USFS Forest Health Aerial Survey show that the area affected by mountain pine beetles in Larimer County (which includes the Big Thompson Watershed and other east slope components of the Colorado-Big Thompson Project) grew from 280,000 to 500,000 acres from 2008 through 2009.

Within the CBT Project watershed areas both west and east of the Continental Divide, bark beetles, including the mountain pine beetle, have significantly altered the vegetative structure of the landscape, by killing extensive acreage of Lodgepole Pine, Ponderosa Pine, and Englemann Spruce (*Picea englemannii*) trees. Currently, much of the affected western slope forested area consists of grey dead trees that have already shed their needles, whereas the outbreak has only more recently spread to the eastern slope. In the eastern slope areas, many of the affected trees still retain their needles (Figure 1-10), but also include some areas with grey standing dead trees. In many cases, but especially on the western slope, forest salvage logging and hazard tree removal activities have begun, thus increasing the proportion of non-forested landscape from that presented in Table 1-1. Changes in land cover are expected to continue for up to several decades following forest die back.

One of the major risks associated with the increasing number of dead and dying trees is the elevated risk of high severity wildfires. 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). However, potentially widespread changes in the vegetative cover that occur either as a result of extensive forest die-back or from severe wildfire have the potential to affect water quality in the impacted watersheds, including potential changes in stream flow and temperatures, sediment loads, as well as in-stream nutrient and TOC levels.

In May 2010, the Western Water Assessment published a synthesis report on the research findings presented at an April 2010 symposium entitled "MPB Science Symposium: Impacts on the Hydrologic Cycle and Water Quality" that was hosted in Boulder, Colorado (Lukas and Gordon, 2010). Findings from this report indicate that the effects of the bark beetle infestation on CBT water quantity and quality remains uncertain, and depend on many factors, including the extent and severity of outbreak, forest composition, stand age, as well as elevation, slope and aspect of affected areas. Specifically, the report indicates that there have not been any consistent effects of bark beetle outbreak on water yield due to the changes in land cover (Elder/Hubbard, Stednick and Brooks). However, changes in water quality were reported and include the following:

- Increases in TOC and DOC concentration in streams (Stednick and McCutchan)
- Increases soil (N) and stream nutrient levels (N and P) (Rhoades, Clow and McCutchan)
- Increases in stream temperatures where riparian areas were affected (Stednick)

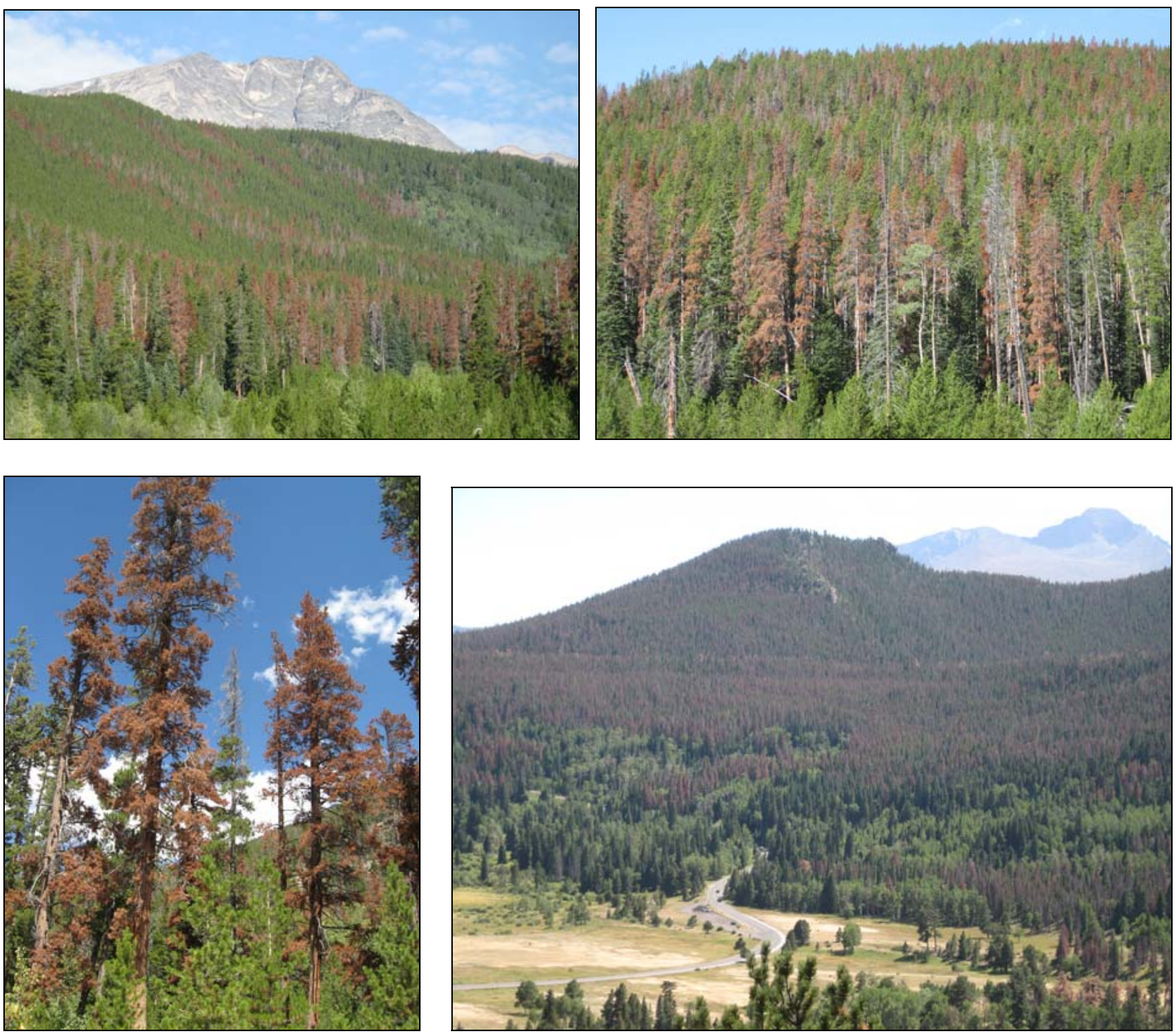


Figure 1-10. East slope bark beetle impacted area: Rocky Mountain National Park, near Fall River (part of the Big Thompson River Watershed); photos taken on September 5, 2010 (by Judy Billica, FCU).

2.0 HORSETOOTH RESERVOIR HYDROLOGY

2.1 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). There are some deliveries out of the canal between HFCBBSCO and the reservoir. These deliveries are measured at Station HFCLOVCO (Hansen Feeder Canal Loveland Turnout) and must be subtracted from the measured HFCBBSCO flow in order to compute the net inflow to Horsetooth Reservoir. Accordingly, the net Hansen Feeder Canal inflow to Horsetooth Reservoir is calculated as:

Hansen Feeder Canal Inflow to Horsetooth = 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 2-1 for 2005 through 2009. 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 2009, the canal was shut down from September 11 to September 25. The total 2009 annual inflow to Horsetooth Reservoir from the Hansen Feeder Canal was 107,100 acre-feet (ac-ft) as summarized on Table 2-1.

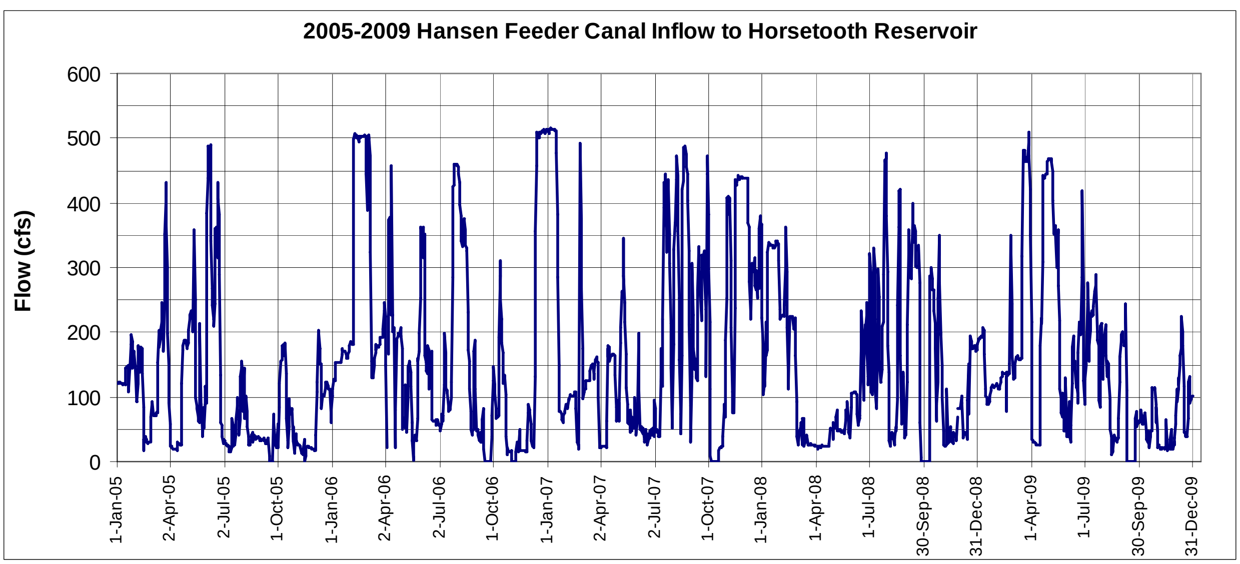


Figure 2-1. 2005 to 2009 Hansen Feeder Canal Inflow to Horsetooth Reservoir (HFCBBSCO - HFCLOVCO).

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 Charles Hansen Supply Canal at Horsetooth Dam, and the Soldier Canyon Dam Outlet. The Charles Hansen Supply Canal operates during the irrigation season and conveys water to the City of Greeley Bellvue Water Treatment Plant 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 City of Greeley Bellvue Water Treatment Plant 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 2-1). 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 2-1. Horsetooth Reservoir seepage data is not available and is assumed to be an insignificant 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 2-2 and summarized on Table 2-1 for 2005 through 2009. Note from Table 2-1 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.

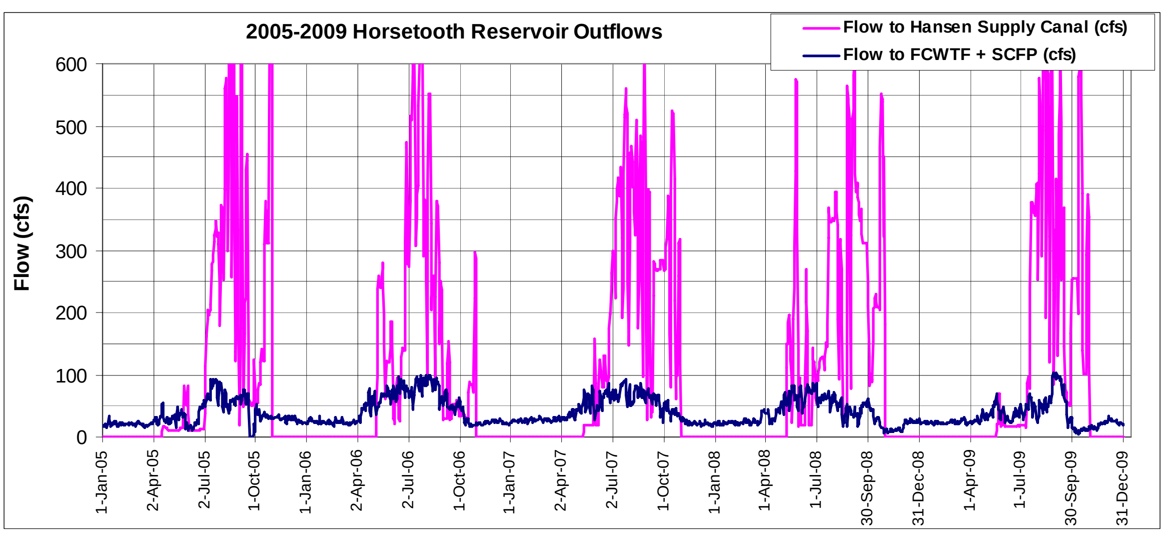


Figure 2-2. 2005 to 2009 Horsetooth Reservoir Outflows at Soldier Canyon Dam Outlet and the Hansen Supply Canal (Note: 1 cfs = 0.646 mgd).

Table 2-1. Summary of 2005 - 2009 Annual Hydrologic Data for Horsetooth Reservoir.

	Units	Data Source	2005	2006	2007	2008	2009
INFLOWS:							
Direct Precipitation	Inches /yr	Sum of USBR Daily Operations Report data (data provided by NCWCD)	16.2	10.9	13.6	13.3	21.8
	ac-ft/yr	Calculated, assumed reservoir surface area of 1900 acres	2,600	1,700	2,200	2,100	3,500
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
Total estimated inflow	Total ac-ft/yr	Calculated: Sum of annual inflow values	78,900	135,300	145,400	102,300	110,600
OUTFLOWS:							
Evaporation	ac-ft/yr	Sum of USBR Daily Operations Report data (data provided by NCWCD)	4,100	3,800	4,100	4,000	3,100
Soldier Canyon Outlet to Dixon Feeder Canal Replacement Deliveries	ac-ft/yr	Sum of monthly data from NCWCD	730	680	780	600	620
Soldier Canyon Outlet to Dixon Feeder Canal CBT Project Deliveries	ac-ft/yr	Sum of USBR Daily Operations Report data (data provided by NCWCD)	250	530	260	220	180
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
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
Flow to Hansen Supply Canal	ac-ft/yr	Sum of USBR Daily Operations Report data (data provided by NCWCD)	74,300	72,300	85,200	79,900	74,000
Total estimated outflow	Total ac-ft/yr	Calculated: Sum of annual outflow values	104,480	110,110	122,270	113,170	102,540
VOLUME & HYDRAULIC RESIDENCE TIME:							
Volume, Annual average	ac-ft	Average of daily values from USBR Daily Operations Report (data provided by NCWCD)	111,700	92,500	100,100	103,000	100,480
Estimated Hydraulic Residence Time	years	Calculated: [average annual reservoir volume] / [total estimated annual outflow]	1.1	0.84	0.82	0.91	0.98

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

2.2 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 2-3 and 2-4). Water levels and volumes are highest in the late winter and early spring before water is released to meet irrigation demands on the eastern Plains.

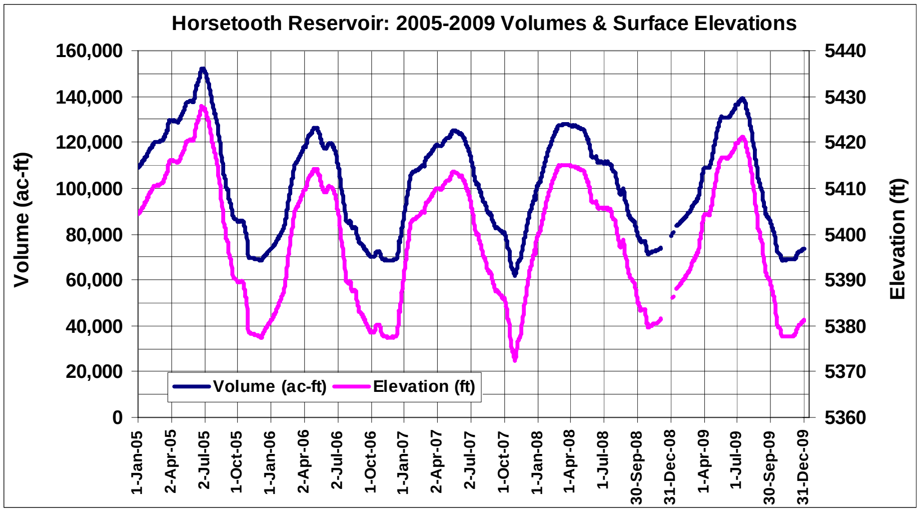


Figure 2-3. 2005 to 2009 Daily Horsetooth Reservoir volumes and water surface elevations.

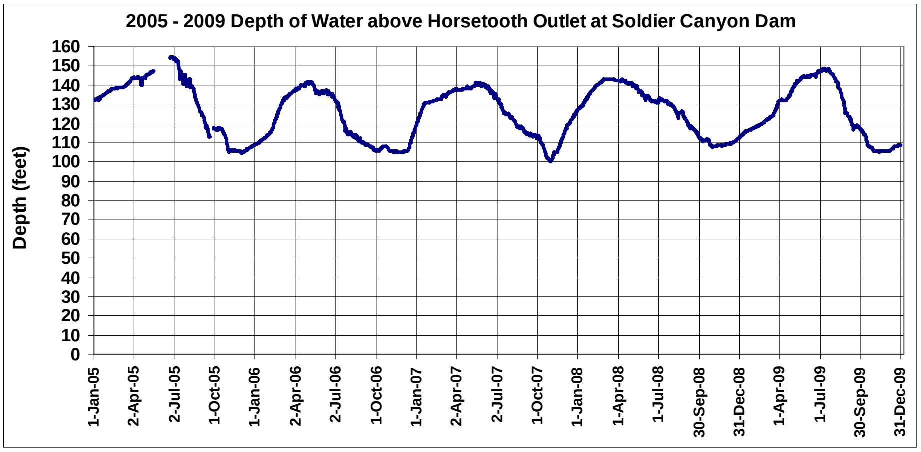


Figure 2-4. 2005 to 2009 Depth of Water above Horsetooth Outlet at Soldier Canyon Dam.

The estimated annual hydraulic residence time was calculated as the average reservoir volume over the year divided by the total annual outflow (Table 2-1). The estimated hydraulic residence time for 2009 is 0.98 years, and ranged from 0.82 to 1.1 years for the five year period of 2005 through 2009.

3.0 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 nutrients and TOC to calculate mass loads to the reservoir.

3.1 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 2009 sonde temperature, dissolved oxygen, and specific conductance data are found on Figures 3-1, 3-2, and 3-3, respectively. The temperature and dissolved oxygen plots show diurnal fluctuations as well as seasonal changes in the data. The 2009 temperature data (Figure 3-1) show an increasing trend in values until late summer, followed by a decreasing trend to the end of the year. In 2009, the maximum water temperature measured in the Hansen Feeder Canal was 19.9°C on August 10. The drop in water temperature observed during the second half of August is related to the fact that flow in the Adams Tunnel was significantly reduced during the period of August 13-26, resulting in a higher proportion of colder Big Thompson River water blending with Adams Tunnel water in Lake Estes.

The 2009 dissolved oxygen data (Figure 3-2) 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 as observed on Figure 3-4. On a daily basis, the minimum dissolved oxygen values occur in the early morning. The annual minimum dissolved oxygen concentration of approximately 6.5 mg/L occurred during the period of August 17-18. This does not correspond to the date of highest water temperature, indicating that other factors where impacting D.O. levels and were likely related to the significant changes in Adams Tunnel, Hansen Feeder Canal, and Dille Tunnel flows that were occurring during this time.

The 2009 specific conductance sonde data (Figure 3-3) 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. In 2009, Big Thompson River water made up over 50% of the water flowing into Lake Estes from May 17 to July 9. Minimum specific conductance values occurred in the Hansen Feeder Canal water during the period of about June 27 to July 20. The specific conductance then slowly increased over the next several months. The sharp, short-term increase observed during the second half of August is related to the significant reduction in flow from the Adams Tunnel during the period of August 13-26. The specific conductance data do not show significant diurnal variations.

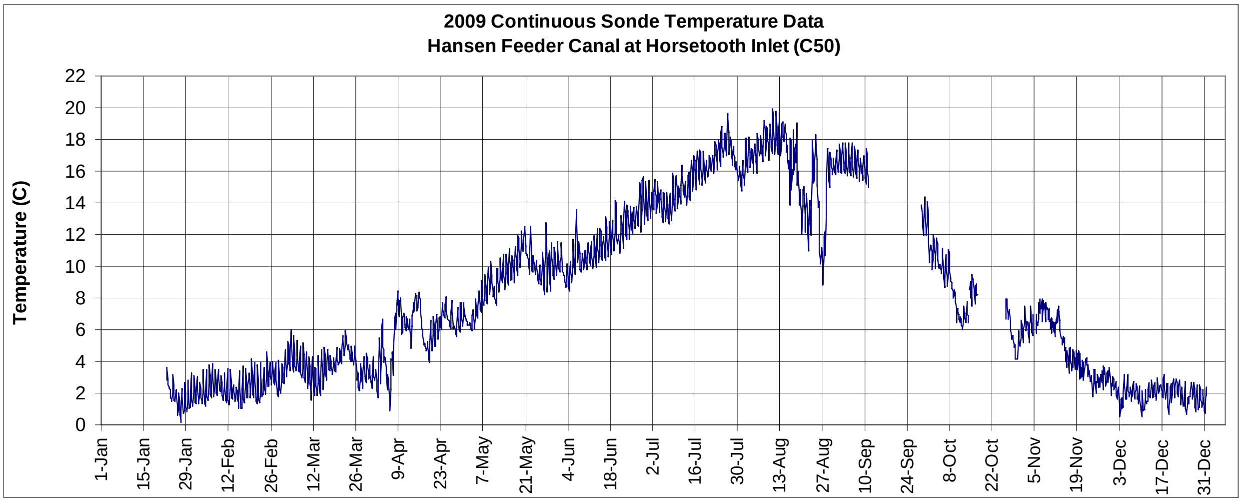


Figure 3-1. 2009 Hansen Feeder Canal continuous sonde temperature data.

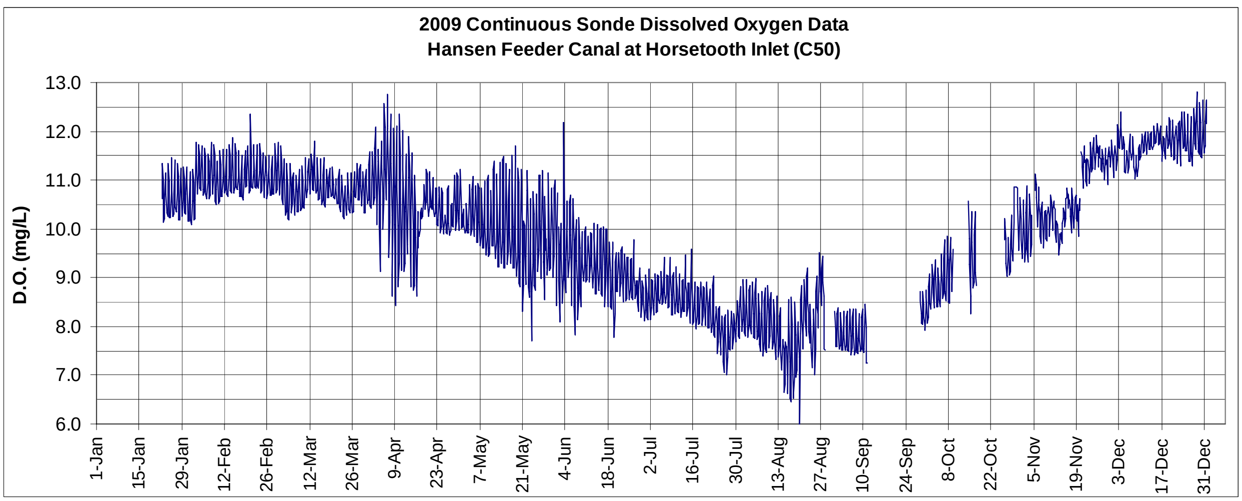


Figure 3-2. 2009 Hansen Feeder Canal continuous sonde dissolved oxygen data.

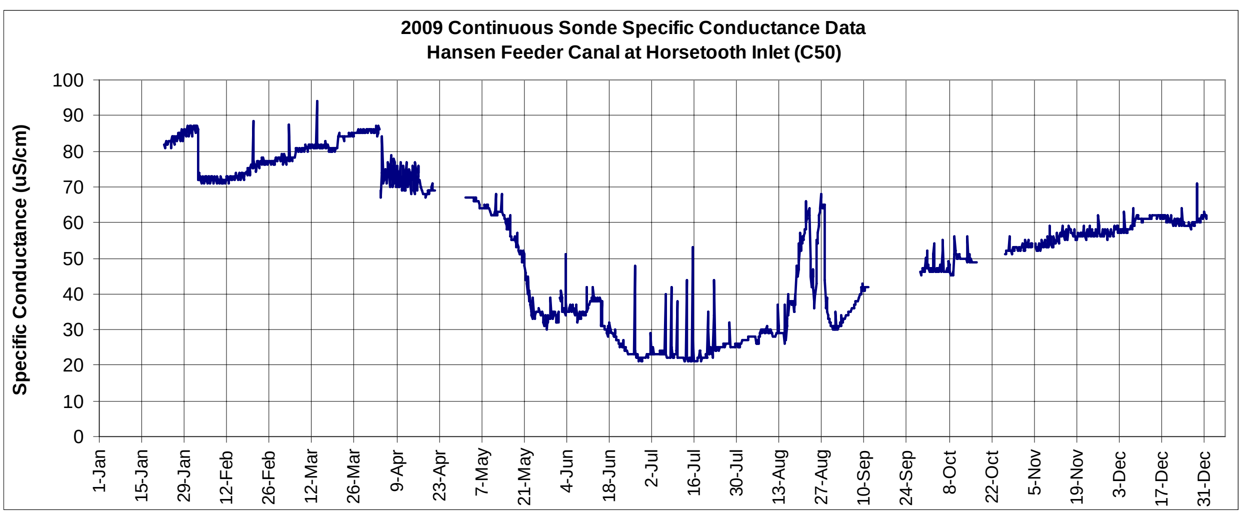


Figure 3-3. 2009 Hansen Feeder Canal continuous sonde specific conductance data.

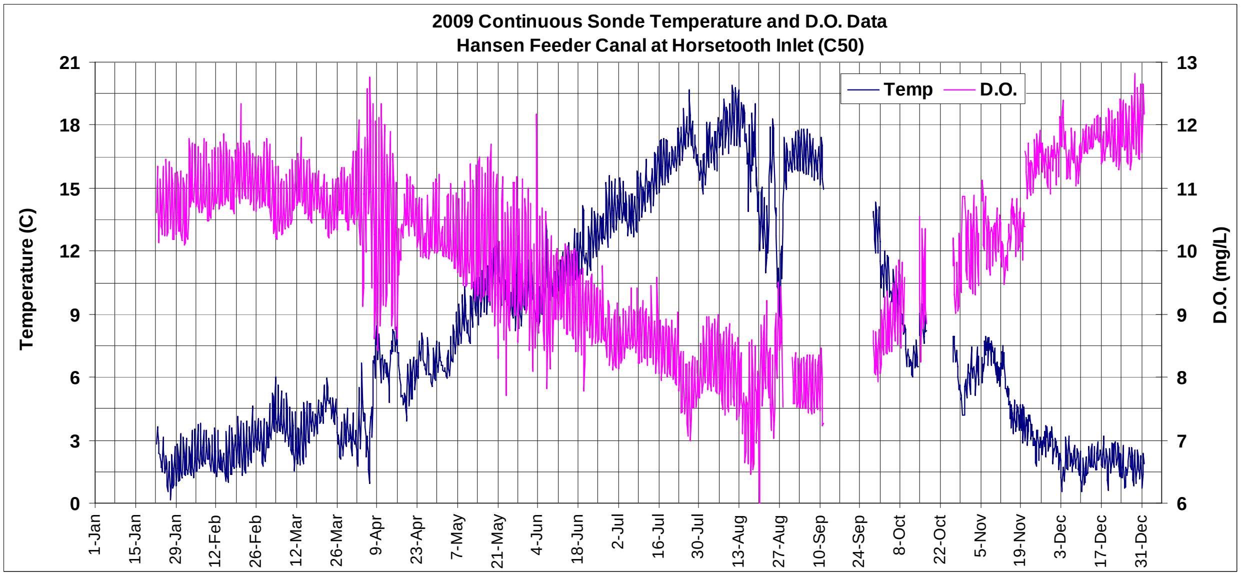


Figure 3-4. Comparison of 2009 Hansen Feeder Canal continuous sonde temperature and dissolved oxygen data.

3.2 Grab Sample Data

3.2.1 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 3-5). Alkalinity and pH exhibit the same pattern with values lowest in June and July (Figure 3-6). 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. Turbidity is generally lowest from January through March, although values throughout the year are rarely above 4 ntu (Figure 3-7).

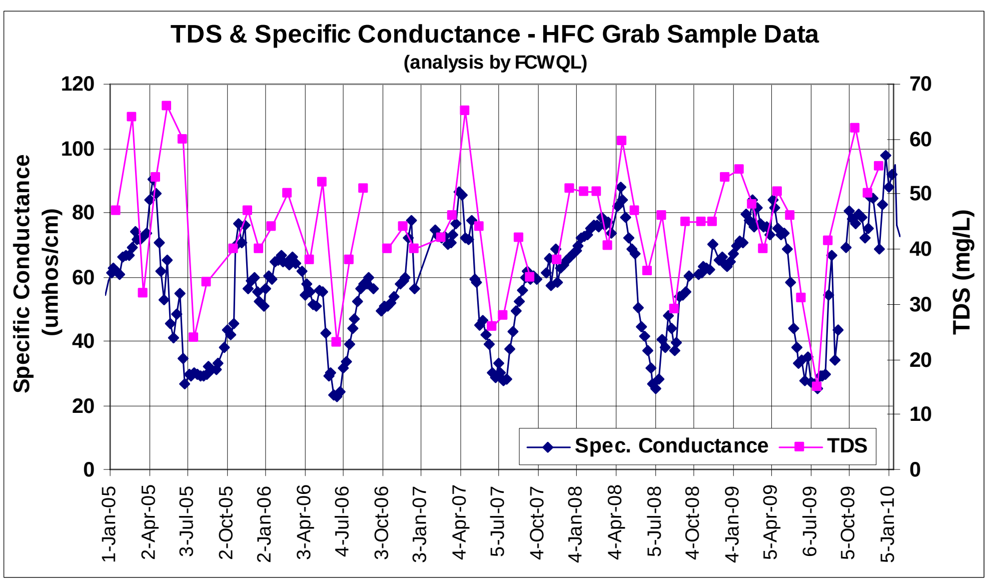


Figure 3-5. Hansen Feeder Canal grab sample TDS and specific conductance data.

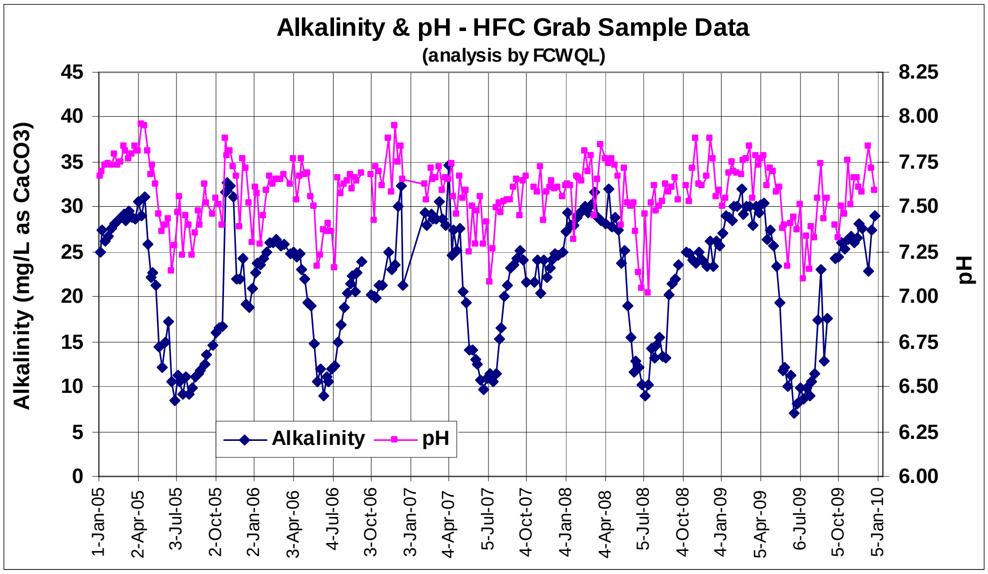


Figure 3-6. Hansen Feeder Canal grab sample alkalinity and pH data.

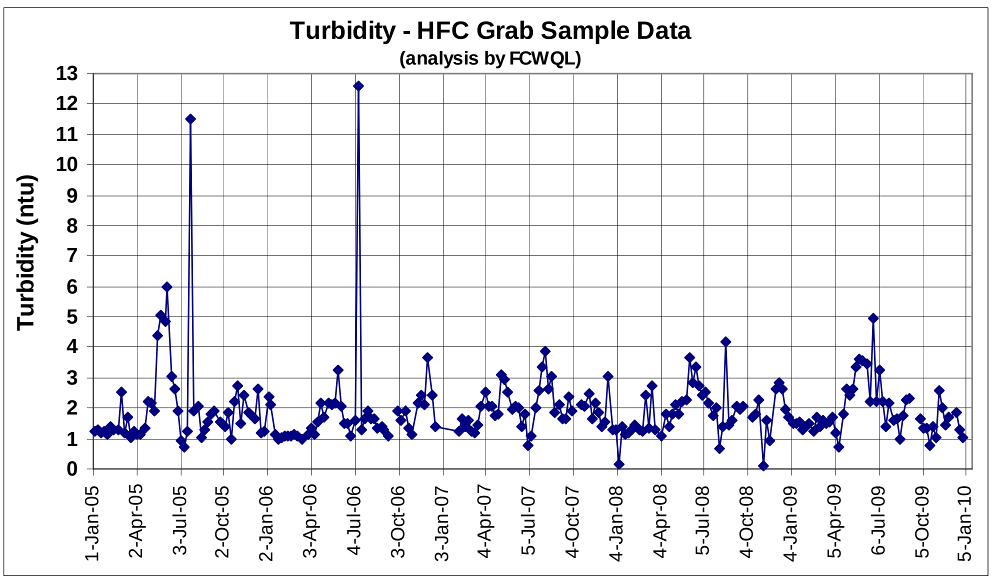


Figure 3-7. Hansen Feeder Canal grab sample turbidity data.

3.2.2 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 3-8. During most of the year, the TOC concentration in Hansen Feeder Canal inflow is within the range of 3 to 4 mg/L. The TOC increases during the spring snowmelt runoff period (mid-May to mid-June) because the Big Thompson River (with its runoff-related high TOC concentrations) comprises a significant fraction of the total flow in the Hansen Feeder Canal.

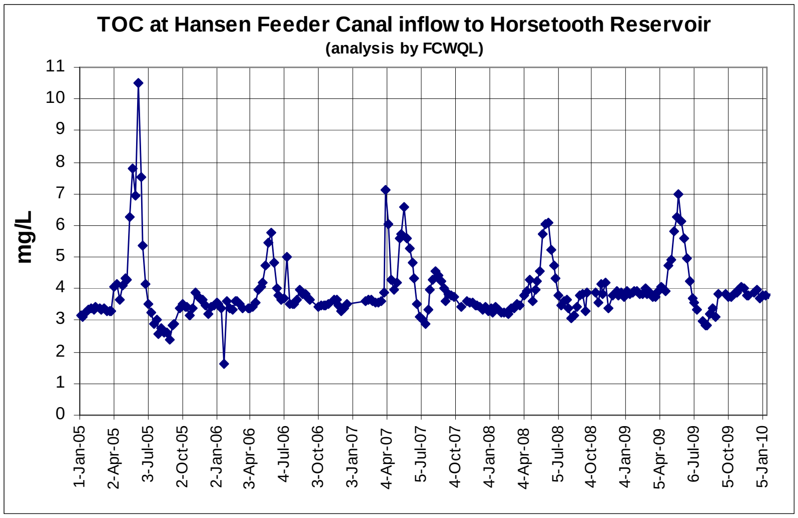


Figure 3-8. Hansen Feeder Canal TOC concentrations.

Monthly and annual TOC box-and-whisker plots are given in Figures 3-9 and 3-10, respectively, for the period of 2005 through 2009. Note that for the box-and-whisker plots in this report, each box corresponds to the middle 50% of the data in that group. The bottom of the box represents the 25th percentile; the horizontal line within the box indicates the median or 50th percentile; and the top of the box represents the 75th percentile. The whiskers extend to representative extreme values of the group. For these plots, the upper whisker extends to the maximum data point within 1.5 box heights from the top of the box; the lower whisker extends to the minimum data point within 1.5 box heights from the bottom of the box. Outliers are indicated by "*" and are observations that are beyond the upper or lower whisker. A crude test for significance of change between two or more groups can be performed by examining whether the boxes for the groups overlap.

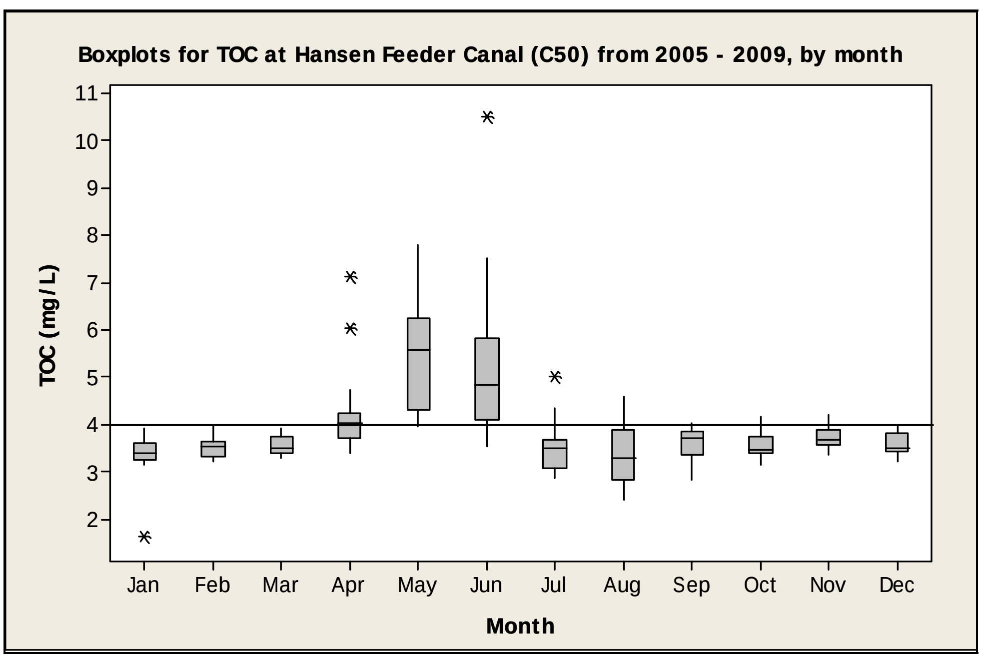


Figure 3-9. Monthly boxplots for TOC at the Hansen Feeder Canal (C50).

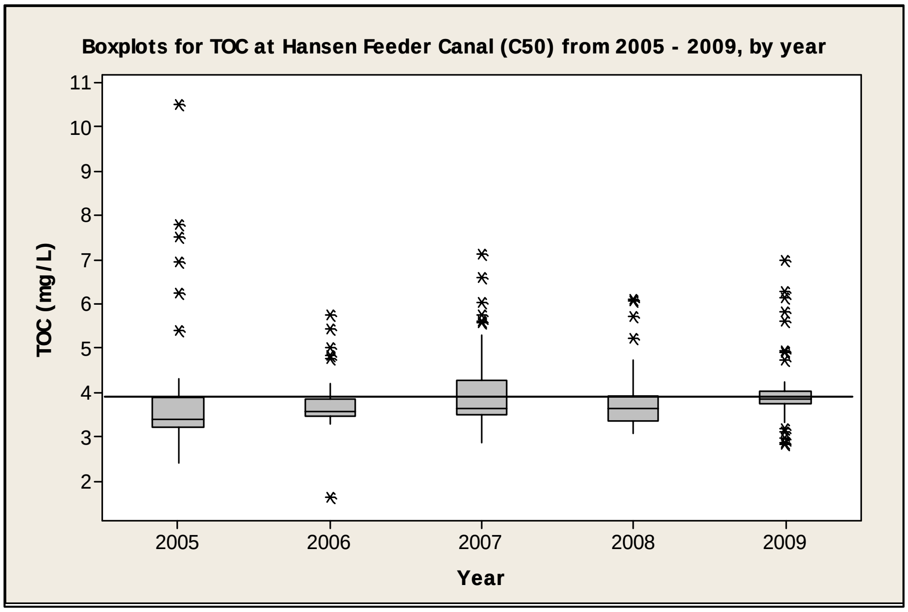


Figure 3-10. 2005-2009 Annual boxplots for TOC at the Hansen Feeder Canal (C50).

The monthly box plots show the higher TOC concentrations that occur in the spring (May and June) due to the influence of the spring snowmelt runoff. The annual box plots do not indicate any obvious time trends over the 2005-2009 five year period.

3.2.3 Major Ions

The major ions include calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+}), potassium (K^{+}), sulfate (SO_4^{-2}), chloride (Cl^{-}), and bicarbonate (HCO_3^{-}). A plot of these ions, except for bicarbonate, is shown on Figure 3-11. The individual ions show the general seasonal pattern of lower concentrations during the spring runoff period. Note that the alkalinity values graphed on Figure 3-6 can be converted to an equivalent concentration of HCO_3^- in mg/L by dividing the alkalinity (expressed in units of mg/L as $CaCO_3$) by 0.8202. With alkalinity generally ranging from approximately 10 to 30 mg/L as $CaCO_3$, the equivalent concentration of HCO_3^- generally ranges from 12 to 36 mg/L. Calcium and bicarbonate are the predominant cation and anion, respectively, found in Hansen Feeder Canal water flowing into Horsetooth Reservoir.

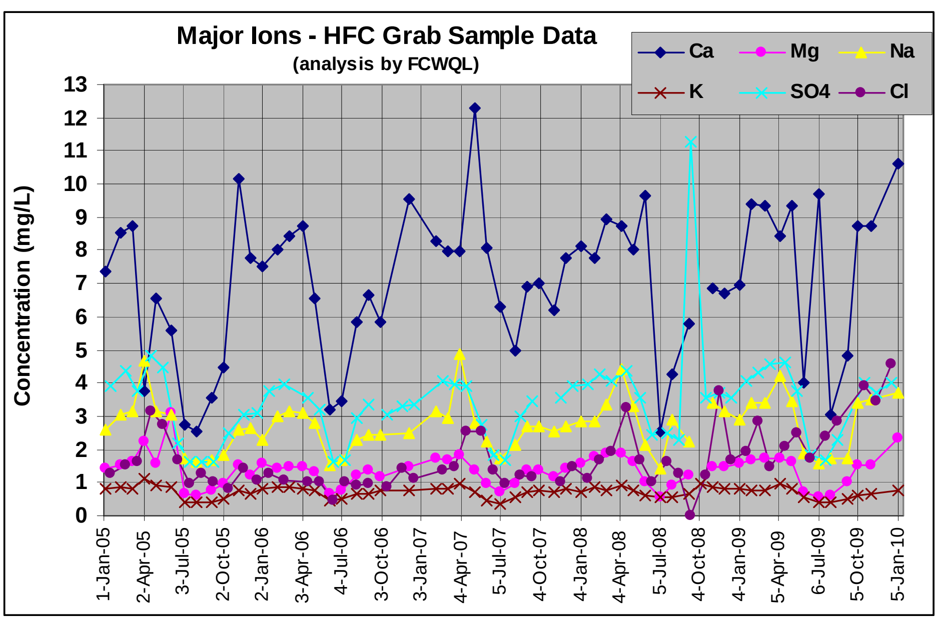


Figure 3-11. Concentrations of major ions in the Hansen Feeder Canal.

3.2.4 Nutrients

Nitrogen and phosphorus are major nutrients that support algal growth in water. Total phosphorus (TP) and ortho-phosphate are the two forms of phosphorous that are measured as part of the Horsetooth Reservoir Water Quality Monitoring Program. Ortho-phosphate is the form of phosphorus that is readily available to algae. TP includes dissolved, particulate, adsorbed, organic, and inorganic forms of phosphorus. Time series plots and monthly and annual box-plots for ortho-phosphate and TP are shown on Figures 3-12 through 3-15. Ortho-phosphate concentrations are generally below the 0.005 mg/L reporting limit, although occasional spikes in concentration occur, ranging up to approximately 0.03 mg/L. Total P concentrations averaged approximately 0.02 mg/L over the 2005-2009 five year time period.

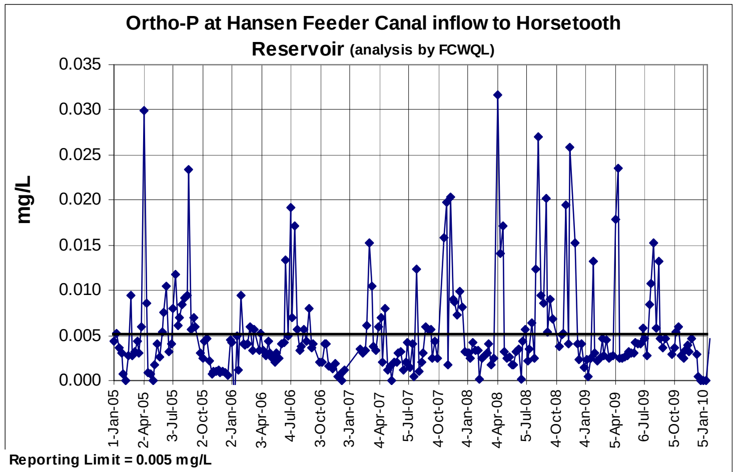


Figure 3-12. 2005-2009 Hansen Feeder Canal ortho-phosphate concentrations.

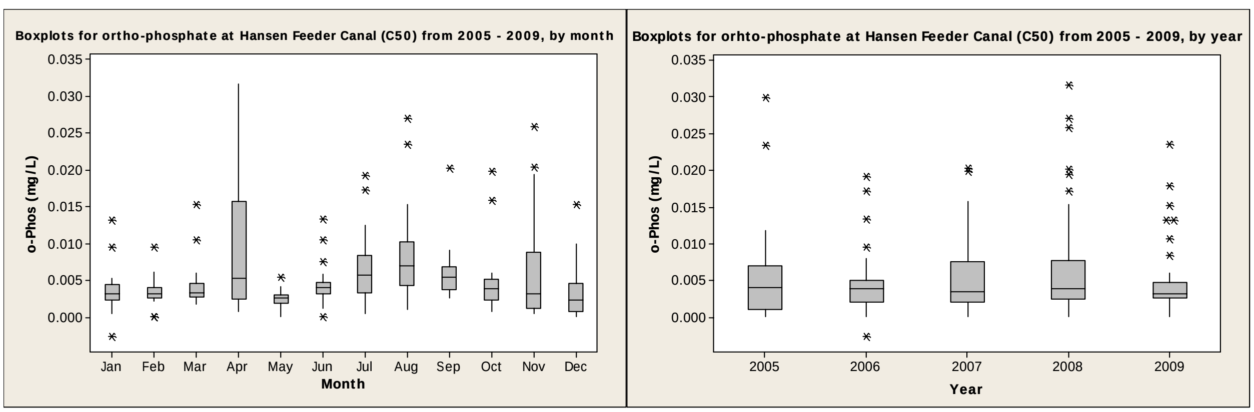


Figure 3-13. 2005-2009 Monthly and annual boxplots for ortho-phosphate at the Hansen Feeder Canal (C50).

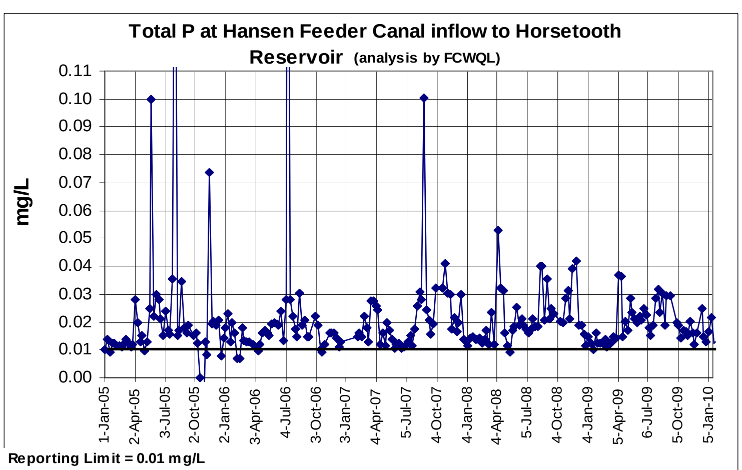


Figure 3-14. 2005-2009 Hansen Feeder Canal Total P concentrations.

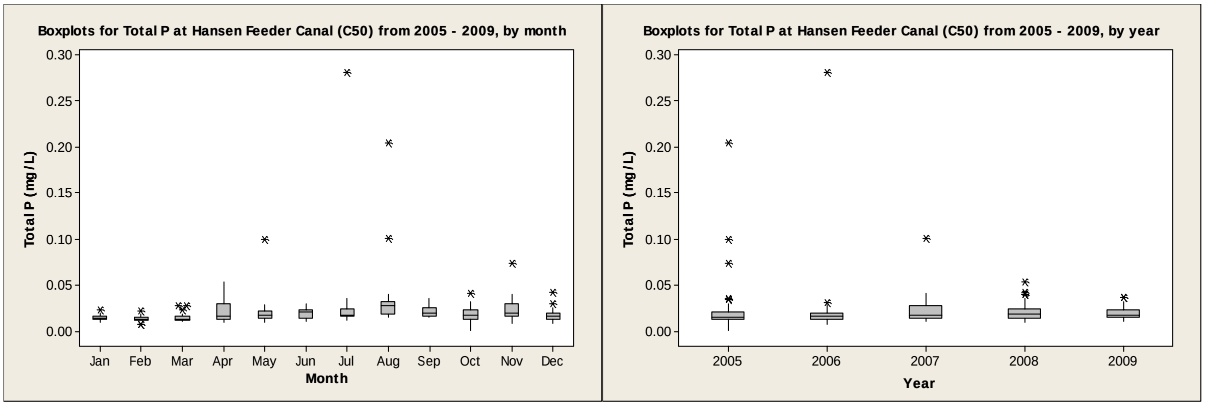


Figure 3-15. 2005-2009 Monthly and annual boxplots for Total P at the Hansen Feeder Canal (C50).

The forms of nitrogen measured for this monitoring program include ammonia, nitrate, nitrite, and Total Kjeldahl Nitrogen (TKN). TKN is ammonia plus organic nitrogen and represents the total amount of oxidizable nitrogen. Time series plots and monthly and annual boxplots for nitrate, ammonia, and TKN are shown on Figures 3-16 through 3-21.

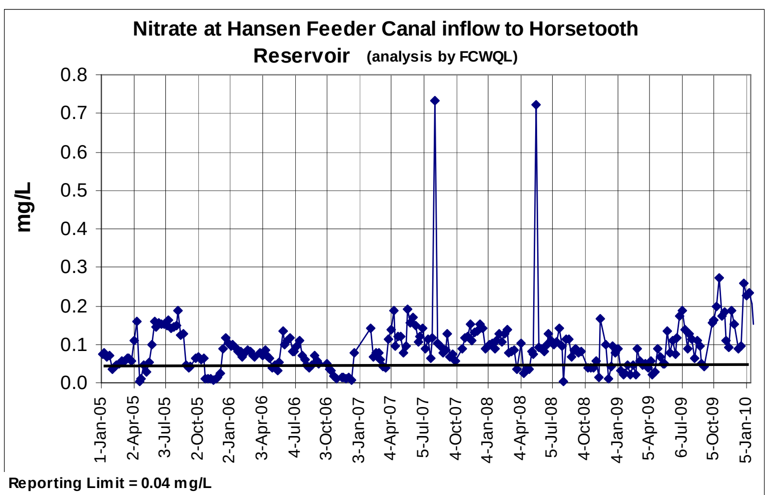


Figure 3-16. 2005-2009 Hansen Feeder Canal nitrate concentrations.

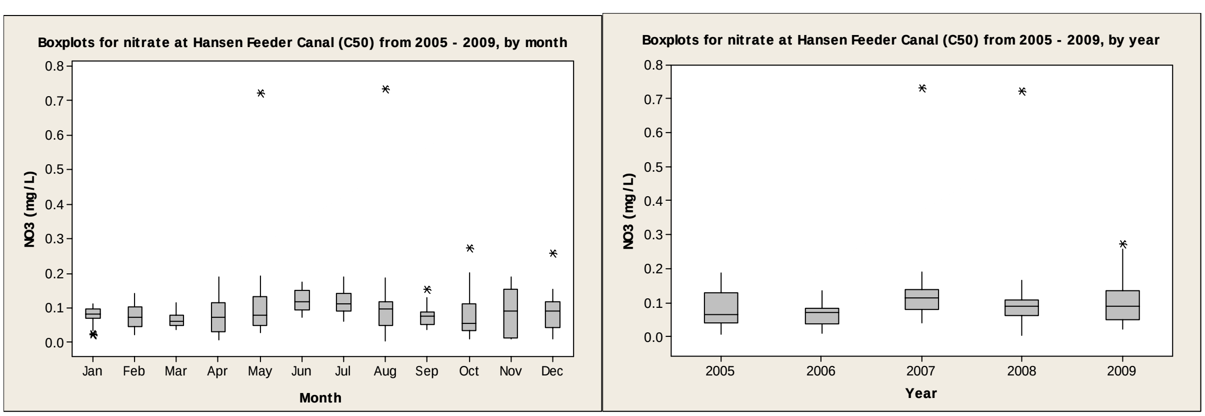


Figure 3-17. 2005-2009 Monthly and annual boxplots for nitrate at the Hansen Feeder Canal (C50).

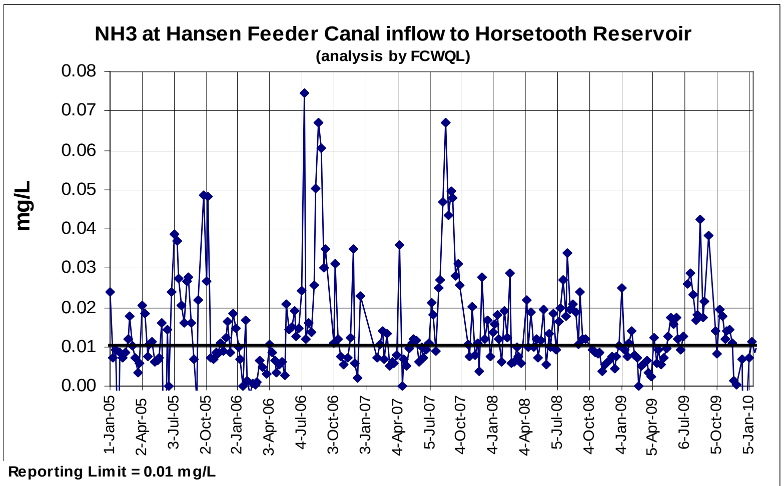


Figure 3-18. 2005-2009 Hansen Feeder Canal ammonia concentrations.

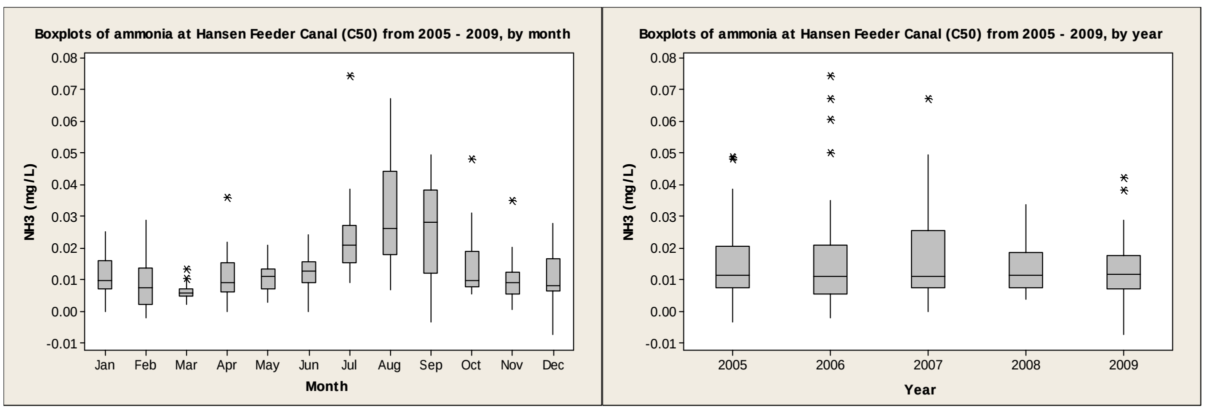


Figure 3-19. 2005-2009 Monthly and annual boxplots for ammonia at the Hansen Feeder Canal (C50).

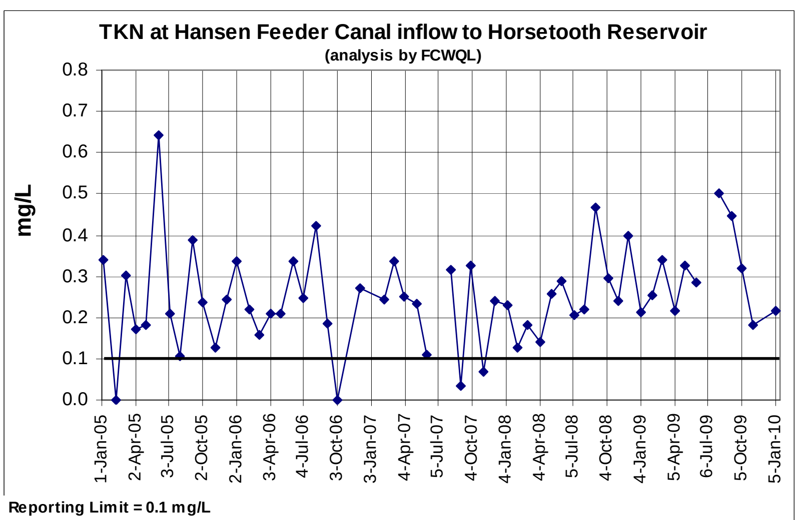


Figure 3-20. 2005-2009 Hansen Feeder Canal TKN concentrations.

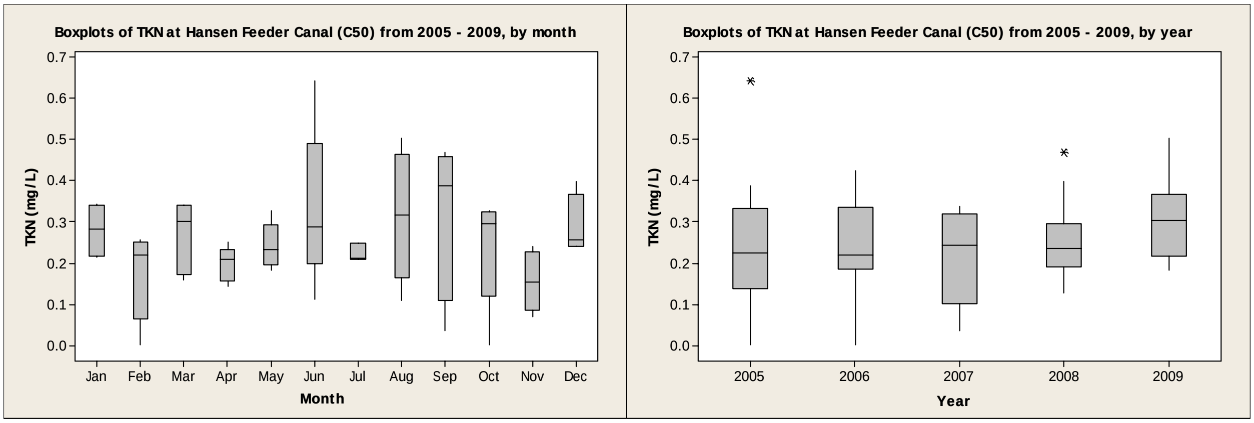


Figure 3-21. 2005-2009 Monthly and annual boxplots for TKN at the Hansen Feeder Canal (C50).

3.2.5 Chlorophyll-a

Hansen Feeder Canal chlorophyll-a data are plotted for 2005-2009 on Figure 3-22. Monthly and annual box-and-whisker plots are given in Figure 3-23 for the period of 2005 through 2009.

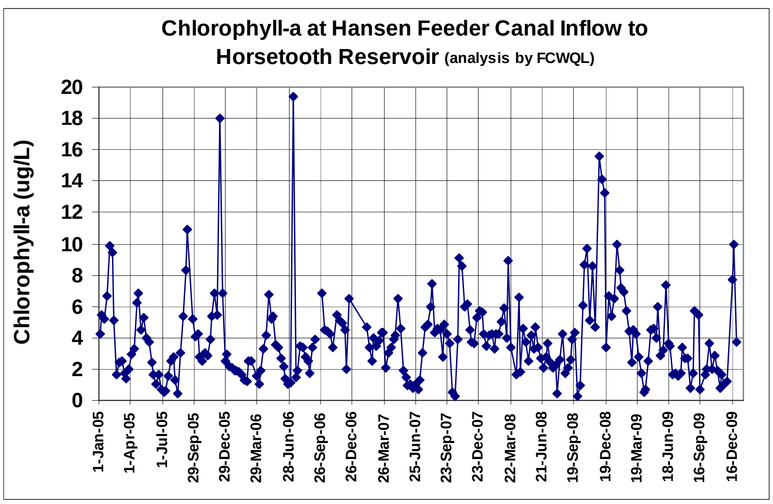


Figure 3-22. 2005-2009 Hansen Feeder Canal chlorophyll-a concentrations.

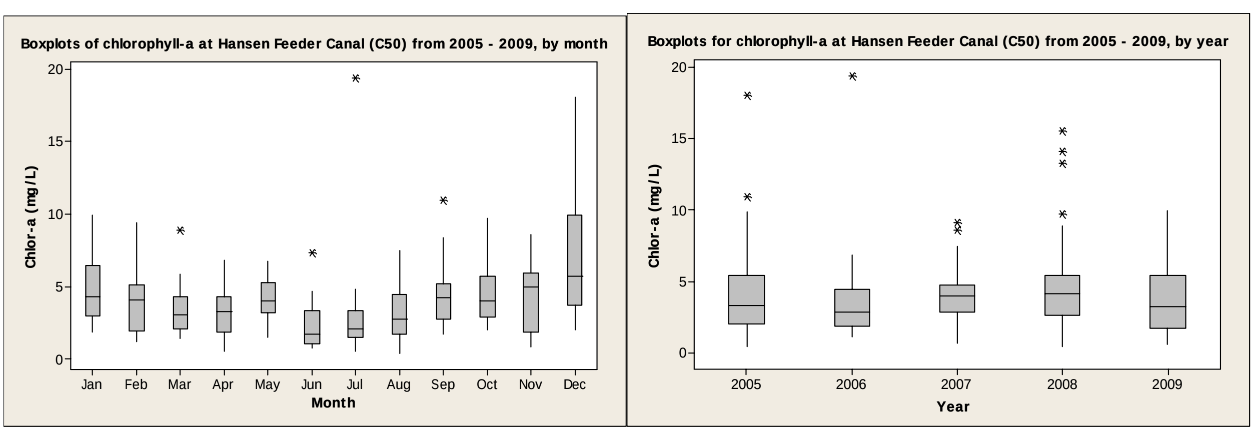


Figure 3-23. 2005-2009 Monthly and annual boxplots for chlorophyll-a at the Hansen Feeder Canal (C50).

3.2.6 Metals

The Hansen Feeder Canal inflow to Horsetooth Reservoir has been sampled for metals on a frequency ranging from 3/year to 12/year. The exceptions are copper which is sampled weekly, and manganese which was sampled weekly through 2007 prior to changing to monthly sampling. Summary statistics are presented on Table 3-1 for the metals data collected during the five-year period of 2005 through 2009. All analysis was conducted by the FCWQL.

Table 3-1. 2005 - 2009 Metals Data Summary Statistics for Hansen Feeder Canal Inflow to Horsetooth Reservoir (all metals total unless specified otherwise).

Metal	Reporting Limit (ug/L)	Maximum Contaminant Level [1] (ug/L)	N	Minimum (ug/L)	Maximum (ug/L)	Median (ug/L)	85th Percentile (ug/L)
Aluminum (Al)	5	[50-200]	57	22.9	1,000	87.4	217
Antimony (Sb)	2	6	14	<2	<2	<2	<2
Arsenic (As)	2	10	15	<2	<2	<2	<2
Barium (Ba)	3	2,000	14	5.7	17.7	8.6	14.9
Beryllium (Be)	0.2	4	14	<0.2	<0.2	<0.2	<0.2
Cadmium (Cd)	0.1	5	14	<0.1	0.105	<0.1	<0.1
Chromium (Cr)	0.5	100	14	<0.5	0.54	<0.5	<0.5
Copper (Cu), dissolved	3	[1,300]	205	<3	21.1	<3	5.4
Copper (Cu), total	3		204	<3	37.9	3.3	7.2
Iron (Fe)	10	[300]	58	6.2	761	137	219
Lead (Pb)	1	15	57	<1	1.39	<1	<1
Manganese (Mn), dissolved	1	[50]	168	<1	135	1.9	4.6
Manganese (Mn), total	1		167	2.82	332	12.1	17.5
Mercury (Hg)	0.2	2	10	<0.2	<0.2	<0.2	<0.2
Molybdenum (Mo)	2		14	<2	<2	<2	<2
Nickel (Ni)	2		14	<2	<2	<2	<2
Selenium (Se)	1	50	14	<1	<1	<1	<1
Silver (Ag)	0.5	[100]	15	<0.5	<0.5	<0.5	<0.5
Thallium (Tl)	1	2	14	<1	<1	<1	<1
Zinc (Zn)	25	[5,000]	14	<25	<25	<25	<25

[1]Bracketed MCL's are secondary drinking water standards; un-bracketed MCLs are primary drinking water standards.

Metals that have been routinely detected above their respective reporting limits in Hansen Feeder Canal water include aluminum, barium, copper, iron, and manganese. Lead, cadmium, and chromium have each been detected once at concentrations above their respective reporting limits over the period of 2005 through 2009 (note that these detected concentrations were very close to the reporting limits, and significantly less than their respective maximum contaminant levels).

Prior to 2008, Northern Water used copper sulfate to control algal growth in the Hansen Feeder Canal. Because of concerns related to the addition of copper to the aquatic ecosystem, Northern Water stopped using copper sulfate in 2008 and began using the algaecide Phycomycin® SCP (active ingredient sodium carbonate peroxyhydrate) for their algae control program. A plot of dissolved copper concentrations for the period of 2005 through 2009 (Figure 3-24) shows that concentrations dropped below the reporting limit of 3 ug/L after Northern Water stopped using copper sulfate.

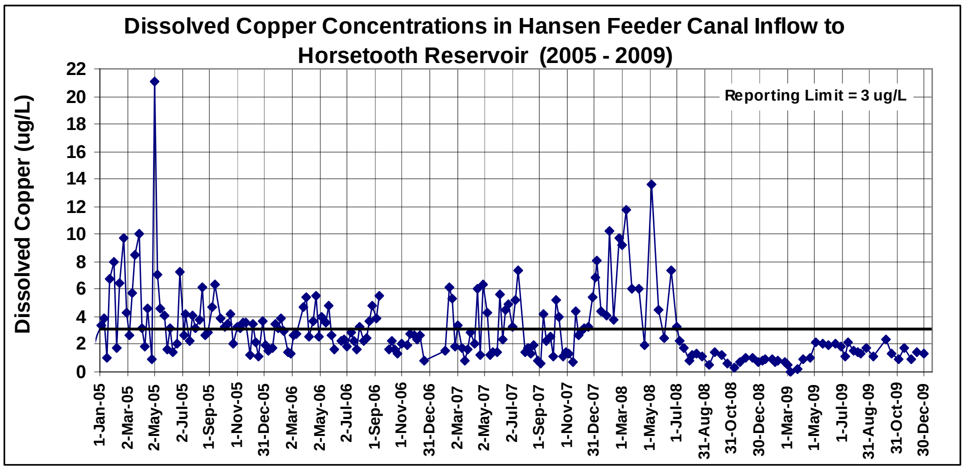


Figure 3-24. Concentrations of dissolved copper in the Hansen Feeder Canal.

3.3 Flow Weighted Concentrations and Mass Loads to Horsetooth Reservoir

Annual flow weighted concentrations and mass loads of TOC and nutrients entering Horsetooth Reservoir from the Hansen Feeder Canal were calculated using the daily flow data for the Hansen Feeder Canal (see Section 2.1) and constituent concentrations measured by the FCWQL. The calculations are supported by weekly (or near weekly) concentrations of TOC, ortho-phosphate, total phosphorus (TP), ammonia (NH_3), and nitrate (NO_3).

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 mass loads and annual flow weighted concentrations are summarized on Table 3-2.

Table 3-2. Hansen Feeder Canal at Horsetooth Inlet (C50): 2005 - 2009 Annual Nutrient and TOC Summary Statistics and Mass Loads to Horsetooth Reservoir.

	2005	2006	2007	2008	2009
Total Annual Canal Inflow (ac-ft/yr)	76,300	133,600	143,200	100,200	107,100
Total Organic Carbon:					
Number of Samples	51	47	46	51	49
Mean Conc. (mg/L)	3.8	3.7	4.1	3.8	4.0
Standard Error (mg/L)	0.21	0.091	0.14	0.10	0.12
Median Conc. (mg/L)	3.4	3.6	3.6	3.7	3.9
Flow Weighted Mean Conc. (mg/L)	4.5	3.7	3.8	3.7	4.1
Annual Load (kg/yr)	428,200	602,700	676,000	460,900	542,400
Annual Load (ton/yr)	472	664	745	508	598
Ortho-Phosphate:					
Number of Samples	51	47	47	51	50
Mean Conc. (mg/L)	0.0051	0.0043	0.0056	0.0073	0.0050
Standard Error (mg/L)	0.00075	0.00057	0.00070	0.0011	0.00064
Median Conc. (mg/L)	0.0040	0.0039	0.0038	0.0040	0.0033
Flow Weighted Mean Conc. (mg/L)	0.004	0.004	0.005	0.005	0.004
Annual Load (kg/yr)	410	640	850	650	540
Annual Load (ton/yr)	0.4	0.7	0.9	0.7	0.6
Total Phosphorus (TP):					
Number of Samples	50	47	47	51	50
Mean Conc. (mg/L)	0.023	0.022	0.022	0.022	0.019
Standard Error (mg/L)	0.0043	0.0057	0.0020	0.0014	0.00095
Median Conc. (mg/L)	0.015	0.016	0.018	0.019	0.018
Flow Weighted Mean Conc. (mg/L)	0.023	0.019	0.023	0.020	0.019
Annual Load (kg/yr)	2,150	3,050	4,020	2,470	2,480
Annual Load (ton/yr)	2.4	3.4	4.4	2.7	2.7
Ammonia (NH3):					
Number of Samples	49	47	47	51	48
Mean Conc. (mg/L)	0.015	0.016	0.018	0.014	0.014
Standard Error (mg/L)	0.0016	0.0025	0.0021	0.0015	0.0017
Median Conc. (mg/L)	0.011	0.011	0.011	0.012	0.012
Flow Weighted Mean Conc. (mg/L)	0.013	0.014	0.020	0.014	0.011
Annual Load (kg/yr)	1,180	2,380	3,470	1,740	1,510
Annual Load (ton/yr)	1.3	2.6	3.8	1.9	1.7
Nitrate (NO3):					
Number of Samples	51	47	47	51	50
Mean Conc. (mg/L)	0.078	0.064	0.15	0.12	0.11
Standard Error (mg/L)	0.0073	0.0046	0.025	0.022	0.019
Median Conc. (mg/L)	0.064	0.070	0.11	0.097	0.088
Flow Weighted Mean Conc. (mg/L)	0.086	0.071	0.13	0.10	0.082
Annual Load (kg/yr)	8,050	11,700	22,500	11,900	10,800
Annual Load (ton/yr)	8.9	12.9	24.8	13.2	11.9

The calculated annual mass loads generally track the annual discharge; i.e., the higher the annual flow, the higher the mass load. This is particularly evident for TOC as shown on Figure 3-25. The monthly TOC loads (Figure 3-28 (a)) also predominately track changes in monthly flows (Figure 3-28 (b)) and not changes in monthly TOC concentrations (Figure 3-28 (c)), as can be seen by comparing the patterns of the three plots (the monthly load plot more closely follows the patterns of the monthly flow plot). Because of this, even though the months of May and June are generally characterized by the highest TOC concentrations, the highest TOC loads to the reservoir do not necessary occur during this time.

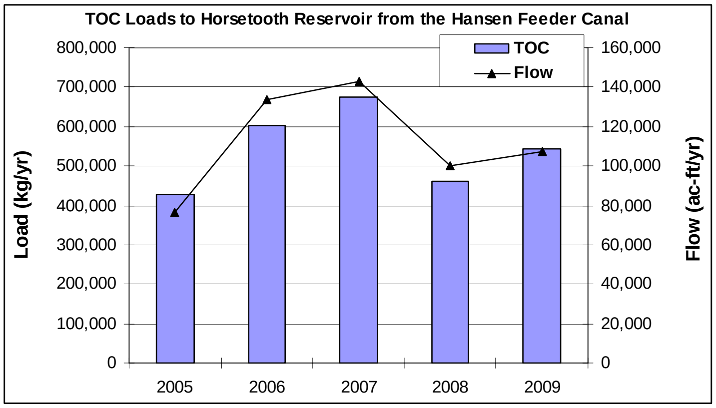


Figure 3-25 Hansen Feeder Canal annual TOC loads to Horsetooth Reservoir.

The mass loads for the nutrients were all highest in 2007, the year with the highest total inflow (Figures 3-26 and 3-27). However, increases or decreases in mean constituent concentrations between years (as can be caused, for example, by a small number of high values) resulted in annual mass loads that did not always track with the flow. Note that the ortho-phosphate load (the form of phosphorus that is immediately available to algae) averaged only about 21 percent of the total phosphorus load over the five year period of 2005-2009.

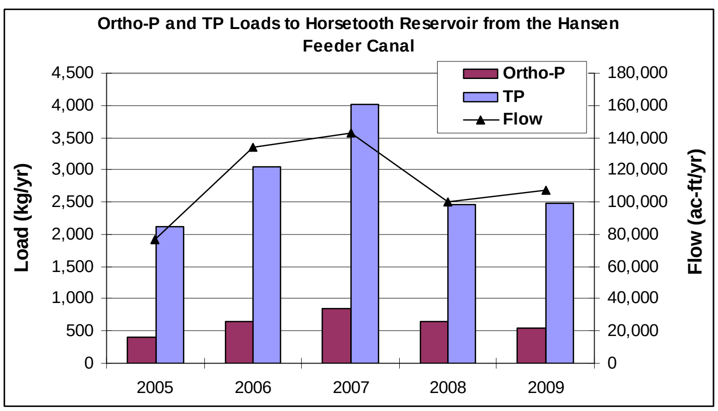


Figure3-26. Hansen Feeder Canal annual ortho-P and Total P loads and flow to Horsetooth Reservoir.

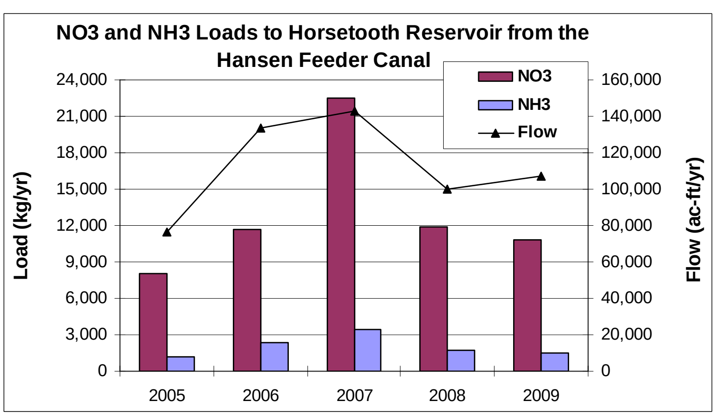
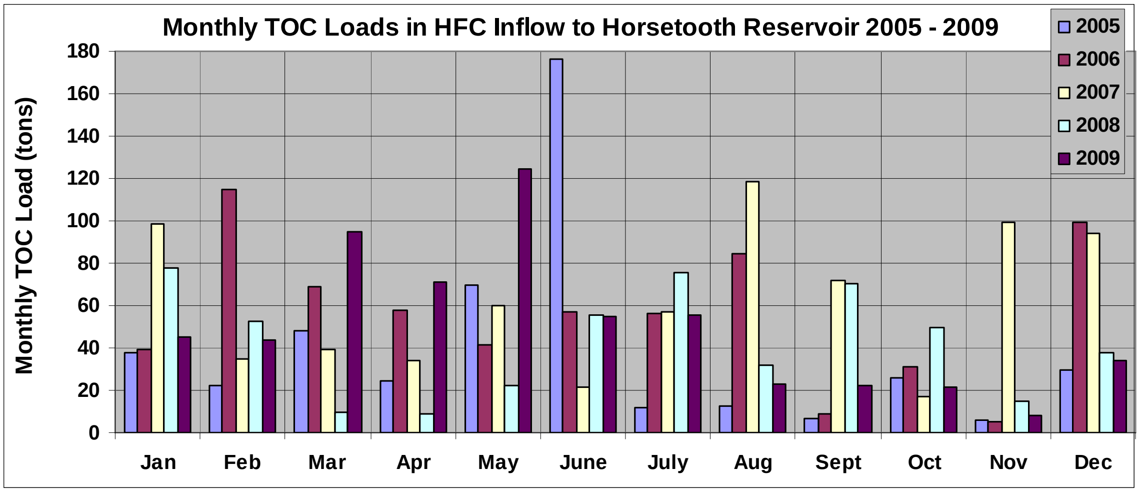
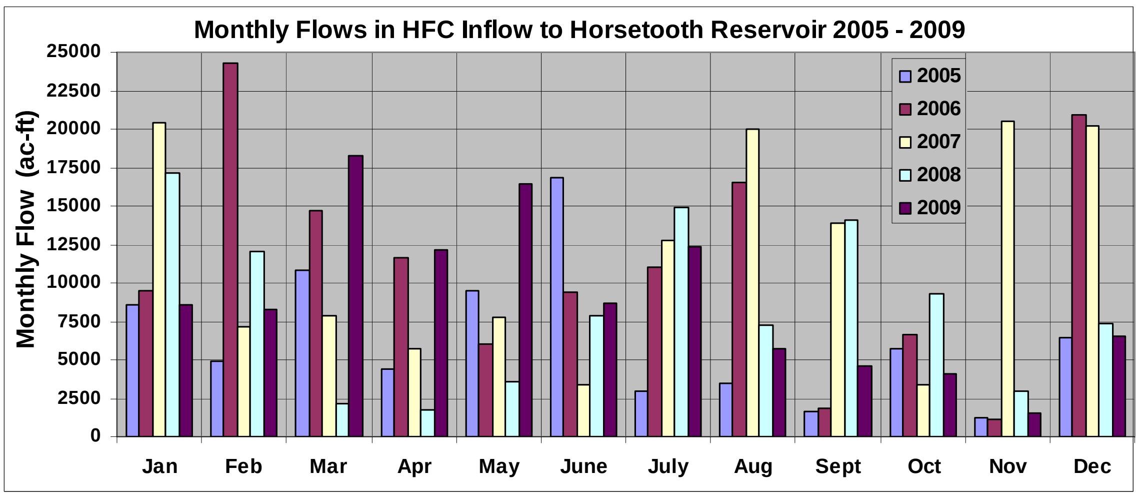


Figure 3-27. Hansen Feeder Canal annual nitrate and ammonia loads and flow to Horsetooth Reservoir.

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



(b) Monthly Hansen Feeder Canal flows.



(c) Monthly average TOC concentrations.

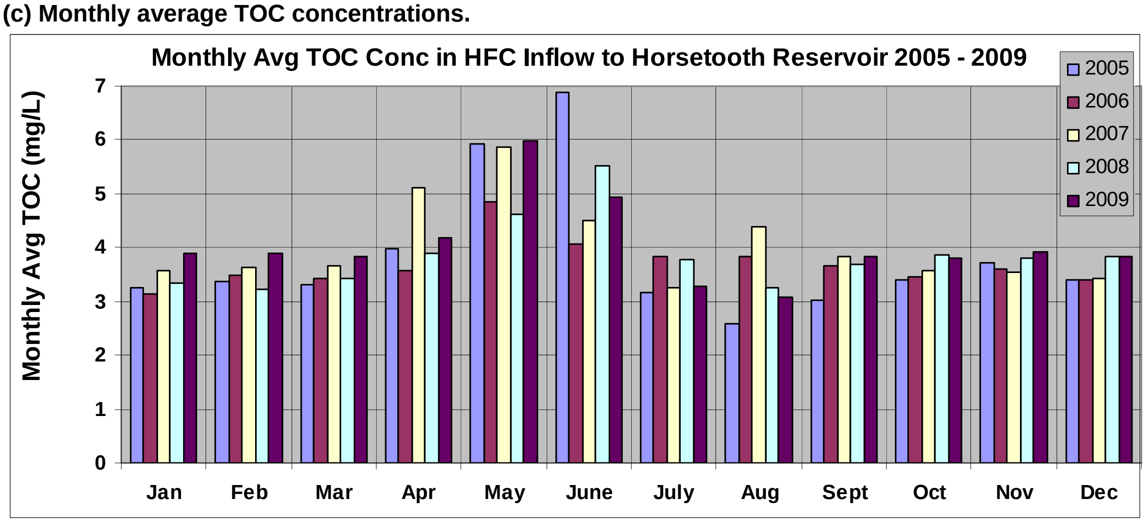


Figure 3-28. Hansen Feeder Canal Inflow to Horsetooth Reservoir: Comparison of (a) calculated monthly TOC loads, (b) monthly Hansen Feeder Canal flows, and (c) monthly average TOC concentrations.

There are other methods that can be used to estimate mass loads in flowing waters. For example, the USGS's LOAD ESTimator (LOADEST) uses streamflow, constituent concentrations, and other variables to develop a regression model for the estimation of constituent loads in streams and rivers. The resulting regression model is then used to estimate loads over a specified time interval (see http://water.usgs.gov/software/loadest/). This approach, however, is not appropriate for the Hansen Feeder Canal because the method was developed for natural systems and relies on the existence of a correlation between water quality concentrations and flow. Flow in the Hansen Feeder Canal is regulated by CBT Project operations and, because of this, a correlation between flow and water quality is not observed. This can be seen in Figures 3-29 and 3-30 for TOC versus flow and nitrate versus flow, respectively, at the inflow to Horsetooth Reservoir for data collected from 2005 through 2009.

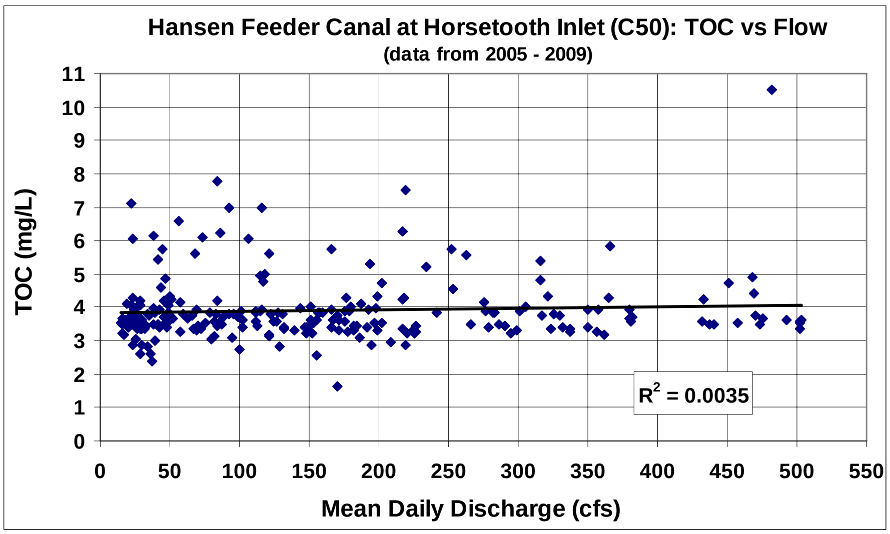


Figure 3-29. Hansen Feeder Canal TOC versus flow (at Horsetooth Inlet).

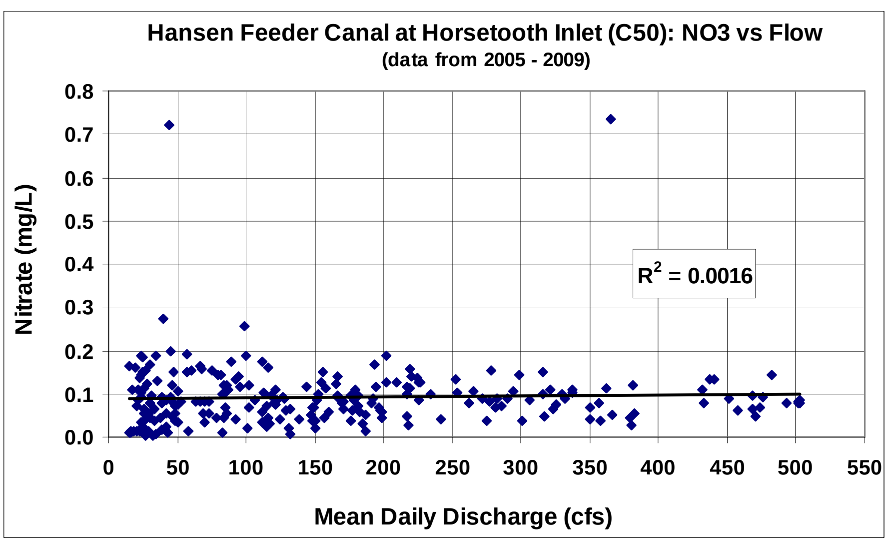


Figure 3-30. Hansen Feeder Canal nitrate versus flow (at Horsetooth Inlet).

4.0 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.

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

The 2009 temperature, dissolved oxygen (D.O.), and specific conductance profiles for Horsetooth Reservoir are shown on Figures 4-1, 4-2, and 4-3, respectively. 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 May 18 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 24 (Figure 4-4). 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 2 sampling event.

Similar to previous years, the dissolved oxygen profiles (Figure 4-2) 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 4-4 for Soldier Canyon.

The 2005-2009 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 4-5. 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.

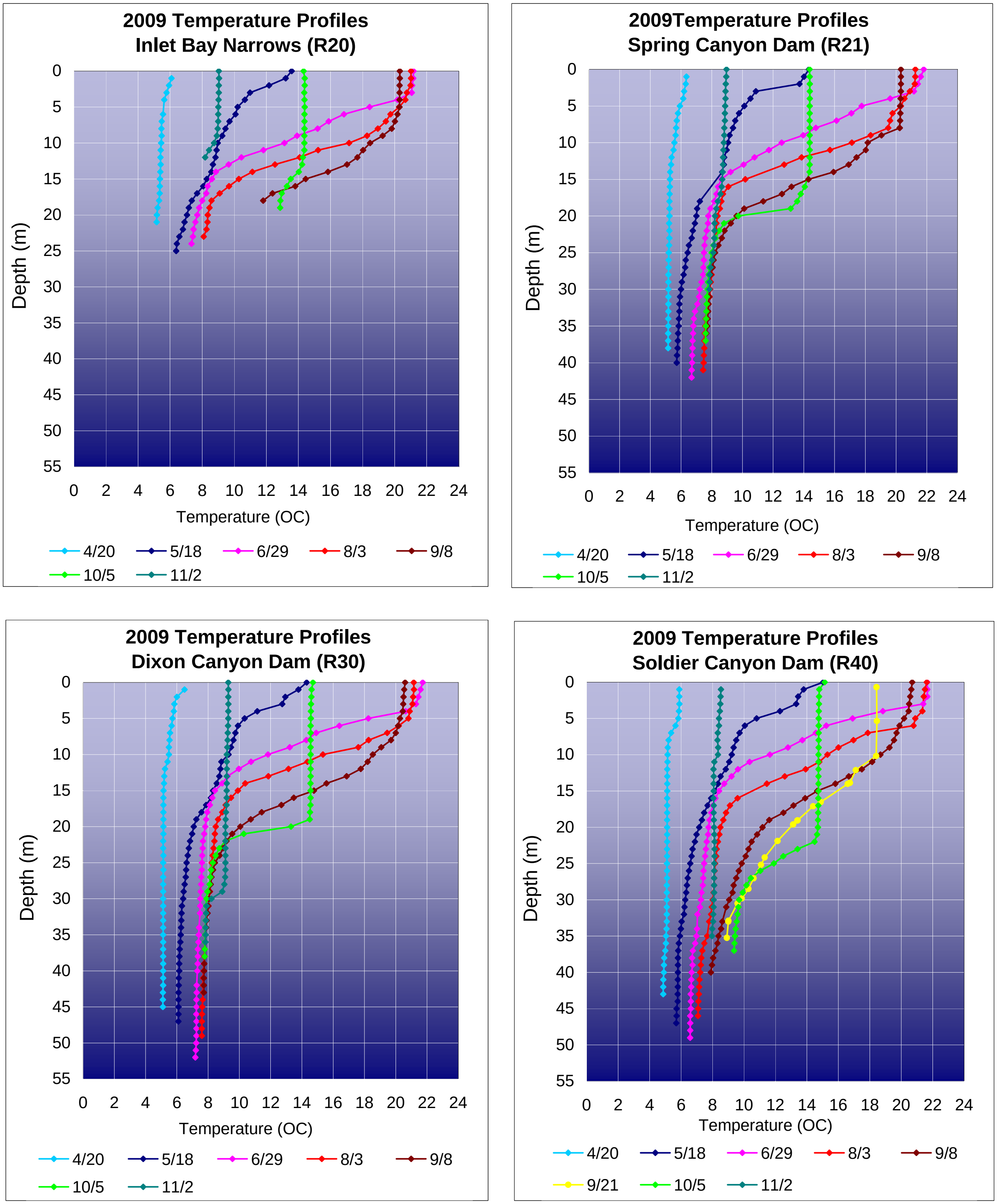


Figure 4-1. 2009 Temperature profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40).

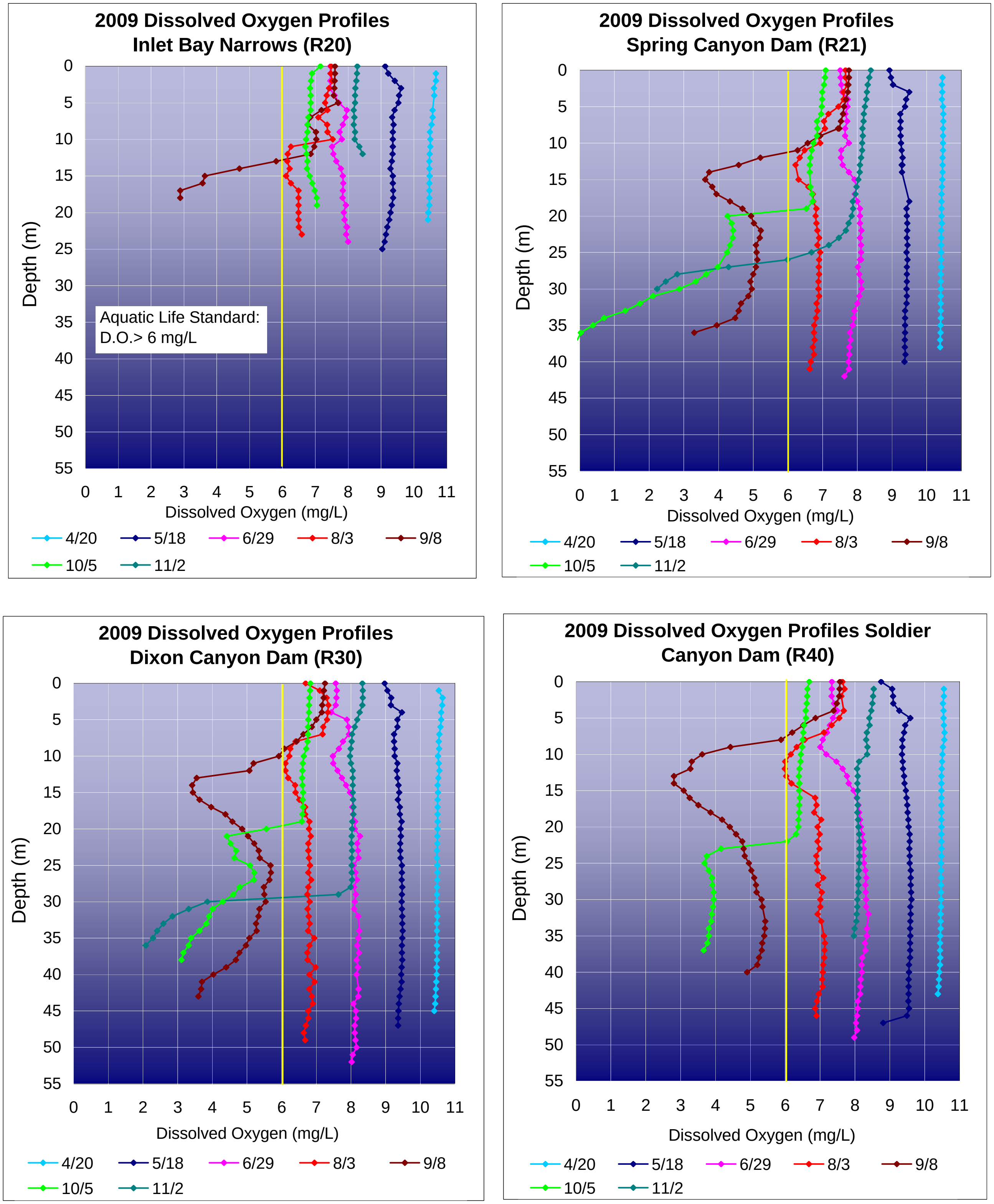


Figure 4-2. 2009 Dissolved oxygen profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40); Aquatic Life Standard: D.O. > 6 mg/L.

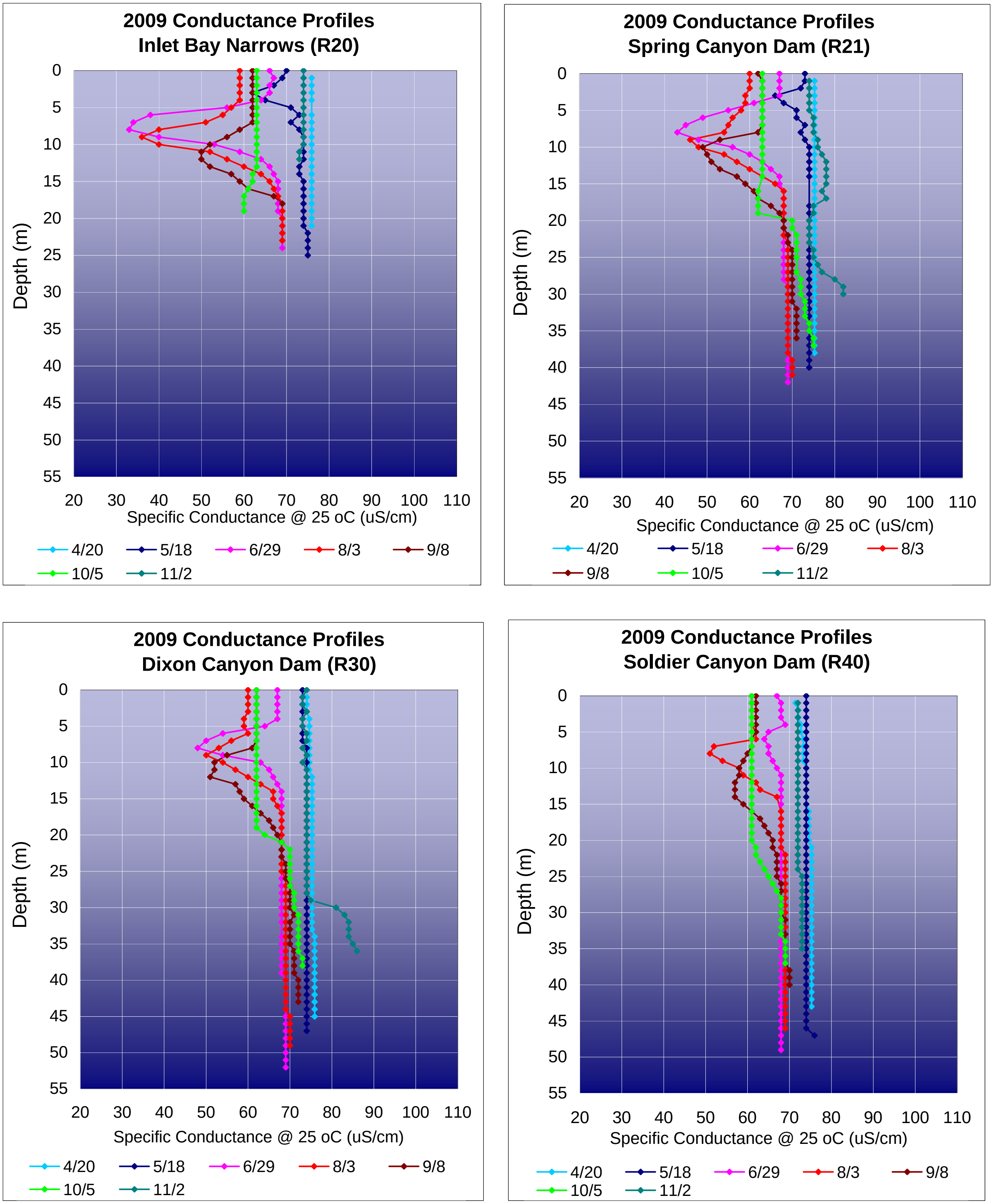


Figure 4-3. 2009 Specific conductance profiles for Inlet Bay Narrows (R20), Spring Canyon Dam (R21), Dixon Canyon Dam (R30), and Soldier Canyon Dam (R40).

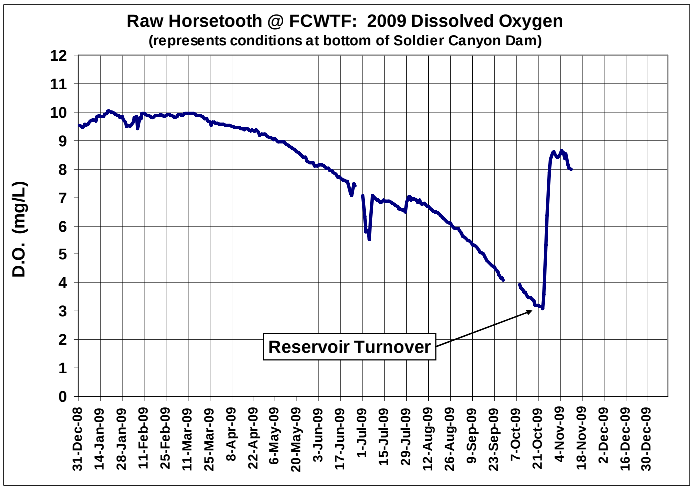


Figure 4-4. 2009 Continuous D.O. data for Horsetooth Reservoir water at FCWTF raw water sample station.

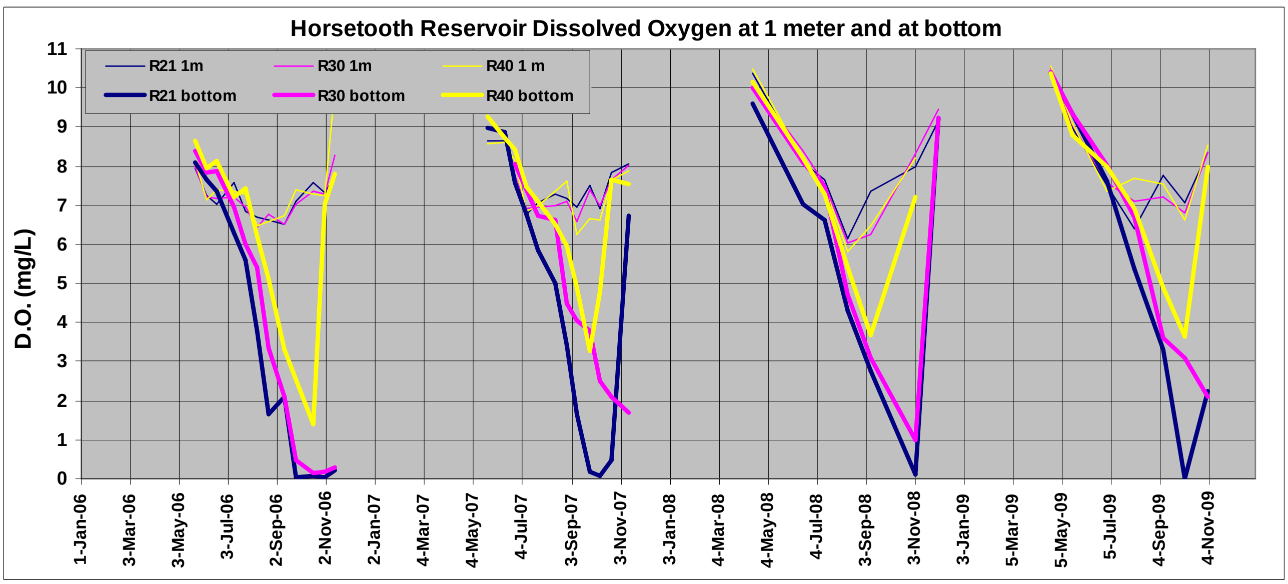


Figure 4-5. Dissolved oxygen at 1 meter and at the reservoir bottom at Spring Canyon (R21), Dixon Canyon (R30), and Soldier Canyon (R40).

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 will plunge 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. Figure 4-6(a) is a conceptual diagram of interflow while Figures 4-6(b) and (c) indicate the reservoir depths where Hansen Feeder Canal water temperatures (from the continuous canal sonde data set) match the water temperatures measured in profiles obtained in 2009 at the Inlet Bay Narrows and at Spring Canyon, respectively. These figures indicate the approximate depths where the Hansen Feeder Canal interflow likely existed during the 2009 sampling season. Figures 4-6(b) and (c) indicate that the plunge depth increased over the summer and into the fall.

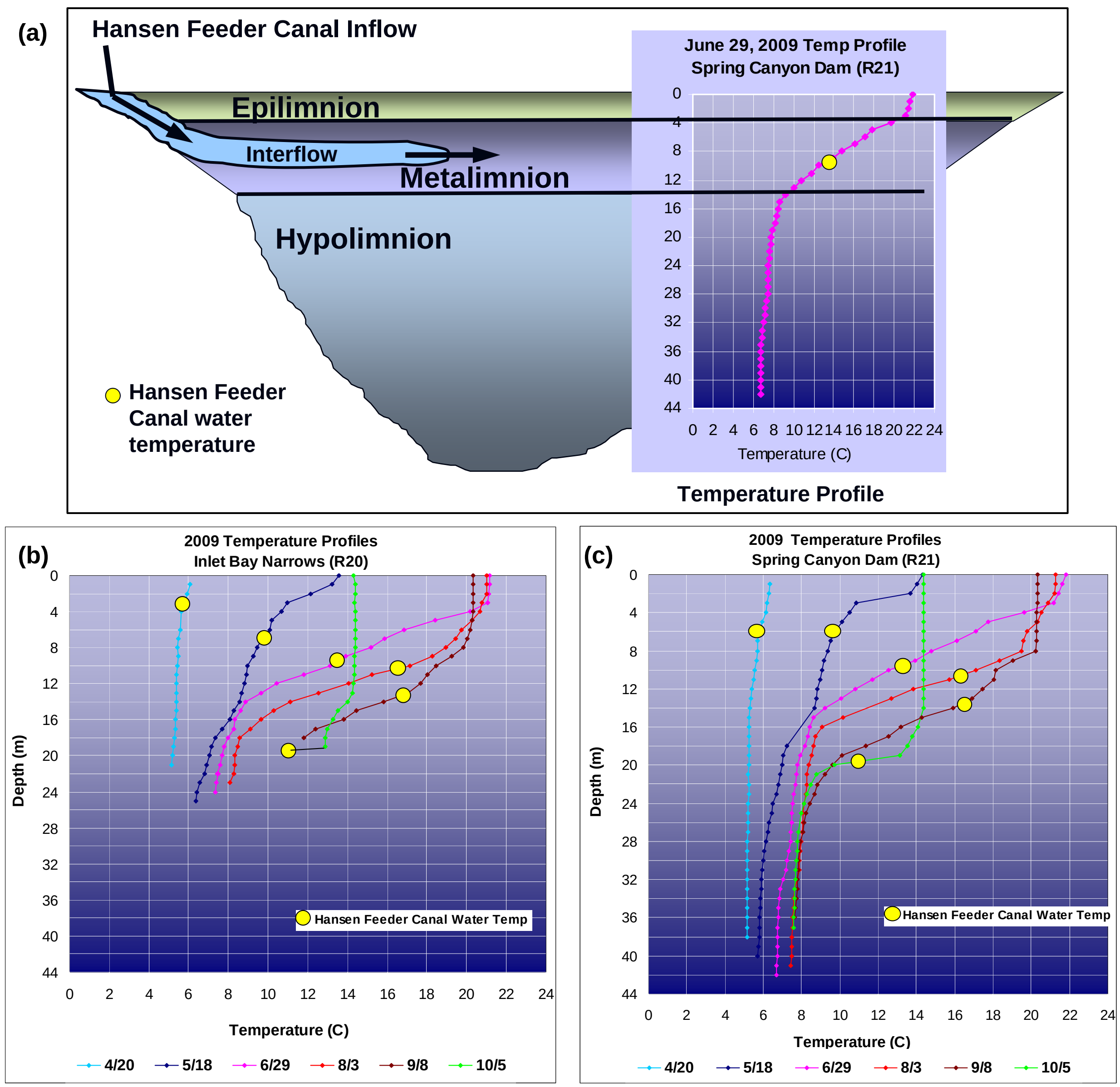


Figure 4-6. Occurrence of interflow: (a) conceptual diagram of interflow, (b) comparison of Hansen Feeder Canal water temperature with 2009 temperature profiles at Inlet Bay Narrows, and (c) comparison of Hansen Feeder Canal water temperature with 2009 temperature profiles at Spring Canyon.

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 that that of the ambient Horsetooth Reservoir water during the late spring and summer (Billica and Oropeza, 2009) and can therefore be used as a tracer of the interflow process.

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 4-3 shows the presence of a specific conductance minima in the metalimnion of all of the profiles collected on June 29, 2009, August 3, 2009, and September 8, 2009, indicating the occurrence of interflow all the way to Soldier Canyon. The Hansen Feeder Canal flow to Horsetooth Reservoir was off during the two week period of September 11 – 24, 2009. The lack of inflow during that time, combined with cooling Horsetooth Reservoir water temperatures, may have resulted in the collapse of the distinct interflow (see the October 5 profiles of Figure 4-3). However, rising specific conductance in Hansen Feeder Canal water during the fall (see Figure 3-3) impacts the use of specific conductance as a tracer of the interflow process (i.e., interflow may still exist, as suggested by the temperature profiles of Figure 4-6, but it cannot be observed with the specific conductance data). Hydrodynamic numerical modeling will be required in order to more fully understand the flow patterns in Horsetooth Reservoir and their impact on water quality, including the fate of Hansen Feeder Canal water in Horsetooth Reservoir.

4.2 Grab Sample Data

4.2.1 General Parameters: Secchi depth, alkalinity, TDS, turbidity

Secchi Depth. The clarity or transparency of Horsetooth Reservoir as measured by secchi depth varies with the season due to the presence of turbidity particles (organic or inorganic) and algae. The 2005 - 2009 secchi depth data collected by the City of Fort Collins from Horsetooth Reservoir are plotted on Figure 4-7. The plots indicate that Secchi depth generally drops from early spring to mid-summer. Secchi depth then generally rises again into the early fall and may have a second drop associated with fall turnover.

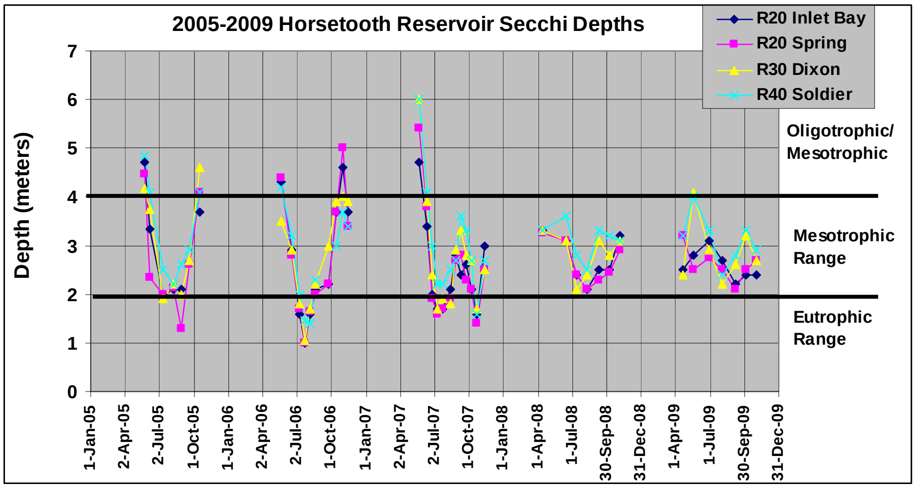


Figure 4-7. 2005-2009 Horsetooth Reservoir Secchi depths.

Secchi disk readings of 2 m to 4 m (or Trophic-State Index values between 50 and 40) fall into the mesotrophic range, while secchi disk readings of 0.5 m to 2 m (or Trophic-State Index values between 70 and 50) fall in the eutrophic range. The Trophic-State Index (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.

Alkalinity. Alkalinity data for all reservoir sample sites are plotted together on Figure 4-8. The values for all sites generally fall within a fairly narrow range (25 to 35 mg/L as $CaCO_3$). Alkalinity values within the metalimnion at Spring Canyon (the R21 Comp A site) drop below 25 mg/L in the spring and summer due to the low alkalinity in the Hansen Feeder Canal inflows during that time. The bottom of Spring Canyon (the R21 bottom + 1

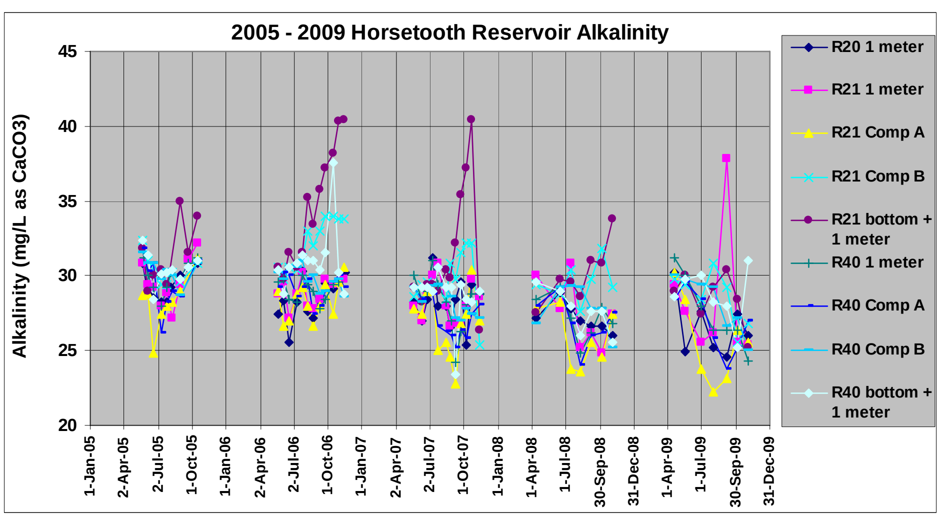


Figure 4-8. 2005-2009 Horsetooth Reservoir alkalinity.

meter site) shows an increase in alkalinity during the fall. The reduction of nitrate ions (denitrification) under anoxic conditions produces alkalinity and may be a possible source of internal alkalinity generation at the bottom of the reservoir. The alkalinity at the bottom of Spring Canyon increased the most during 2006 and 2007 when anoxic conditions were more persistent (as was indicated by the D.O. levels on Figure 4-5).

Total Dissolved Solids (TDS). TDS data, only collected at Soldier Canyon Dam (R40), are plotted on Figure 4-9. Visual inspection of the plot does not reveal any apparent pattern to the data. The 2009 TDS values fell within a tighter range (approximately 40 to 60 mg/L) than the previous years.

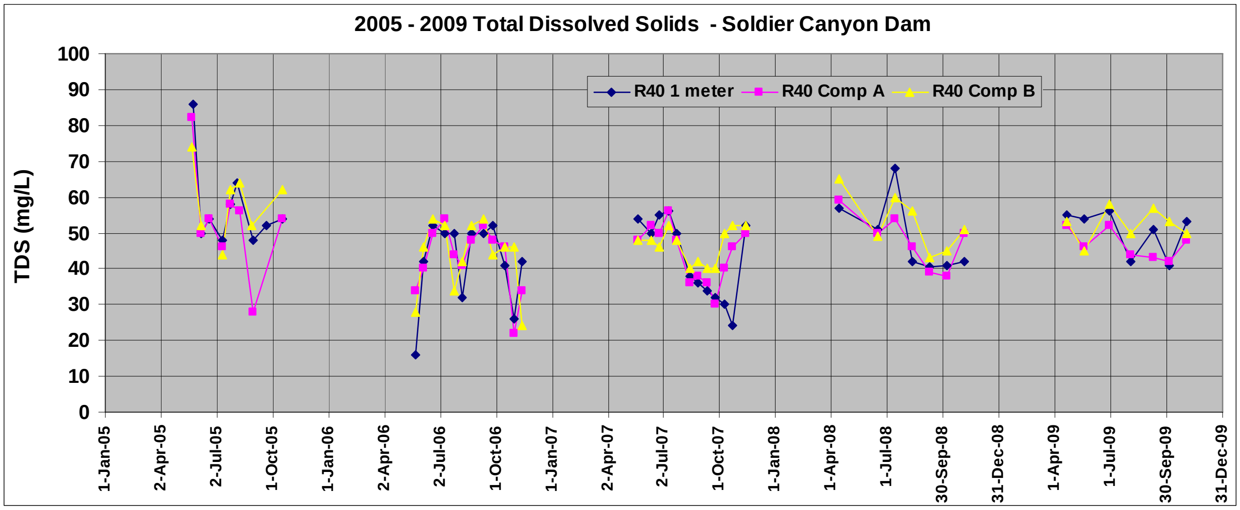


Figure 4-9. 2005-2009 Horsetooth Reservoir total dissolved solids.

Turbidity. Horsetooth Reservoir turbidity data is plotted on Figure 4-10. Although it varies from year to year, a general pattern can be observed of low turbidity in the spring, increasing turbidity over the spring and summer, decreasing turbidity into the late summer/early fall, and increasing turbidity again in the mid-fall.

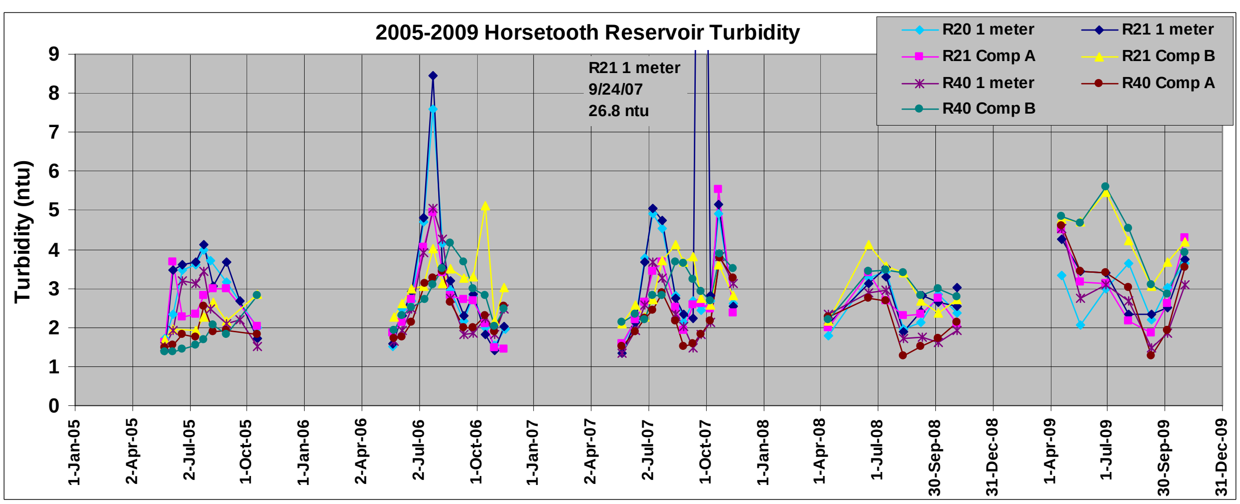


Figure 4-10. 2005-2009 Horsetooth Reservoir turbidity.

4.2.2 Total Organic Carbon (TOC)

FCWTF Raw Horsetooth Reservoir Data. A plot of weekly TOC data collected from 1997 through 2009 at the FCWTF raw Horsetooth sample station and analyzed by the FCWQL is shown on Figure 4-11(a). This figure indicates an upward trend in TOC concentrations over the period of record. This trend was previously documented in the Haby and Loftis (2007) report prepared for the Big Thompson Watershed Forum. Figure 4-11(b) is a plot of the TOC data from May 2002 through 2009, the data set collected after the FCWQL changed from a Shimadzu TOC Analyzer to a Sievers TOC Analyzer in May 2002. The TOC data over the past 7.5 years indicates a small increasing trend (note that the y-axis of Figure 4-11(b) has a range of 2.0 to 4.0 that exaggerates the trend). Annual averages of the weekly FCWTF raw Horsetooth Reservoir TOC data shown on Figure 4-12 indicate small fluctuations over the past seven years (note the y-axis range of 2.0 to 3.4), with a small increasing trend.

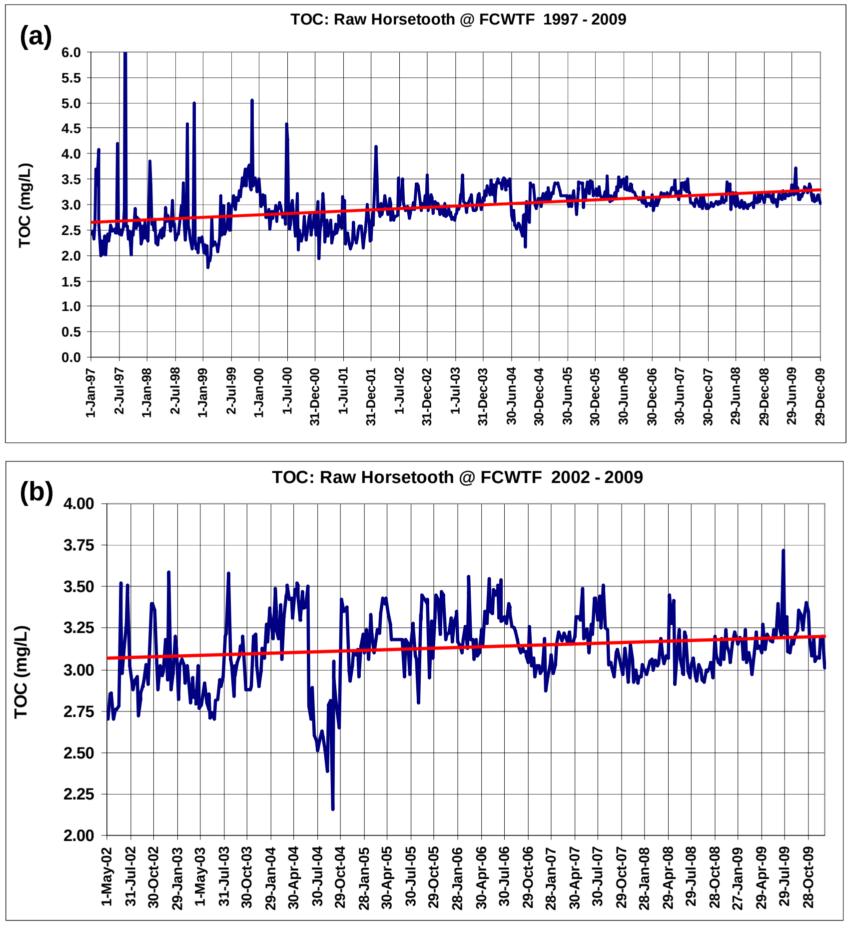


Figure 4-11. TOC at the FCWTF raw Horsetooth Reservoir sample station from (a) 1997 through 2009, and (b) May 2002 through 2009 (note differences in y-axis scales).

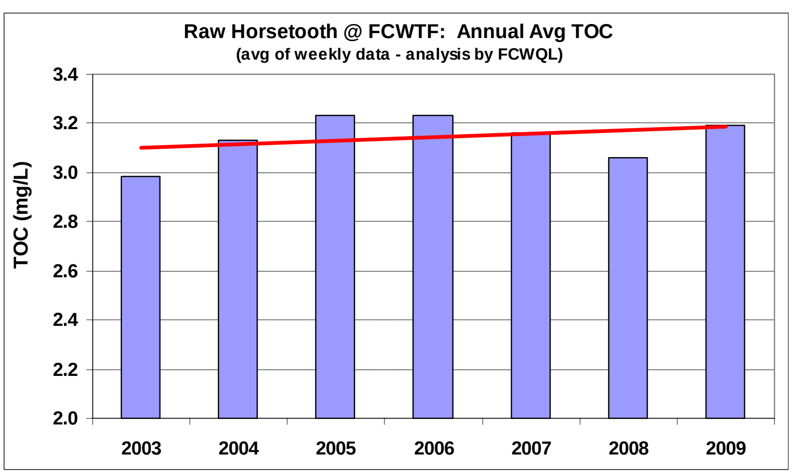


Figure 4-12. 2003 - 2009 Annual average TOC concentrations at the FCWTF raw Horsetooth Reservoir sample station.

TOC Data for Reservoir Sites. TOC data collected within the reservoir allows for an evaluation of TOC differences with reservoir depth and with reservoir length. Figures 4-13 (a) and (b) are plots of TOC at various depths at Spring Canyon Dam and Soldier Canyon Dam, respectively (note range of y-axis). Composite A is a composite of samples taken at depths of 5, 10, and 15 meters, and in mid- to late-summer generally represents the metalimnion. Composite B is a composite of samples taken at 5 meter increments from a depth of 20 meters to approximately 5 meters above the reservoir bottom and generally represents the hypolimnion. Visual inspection of the figures indicates that the TOC between depths of 1 and 15 meters (1-meter and Comp A samples) 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 peaks in bottom TOC occasionally occur at both Spring and Soldier Canyons.

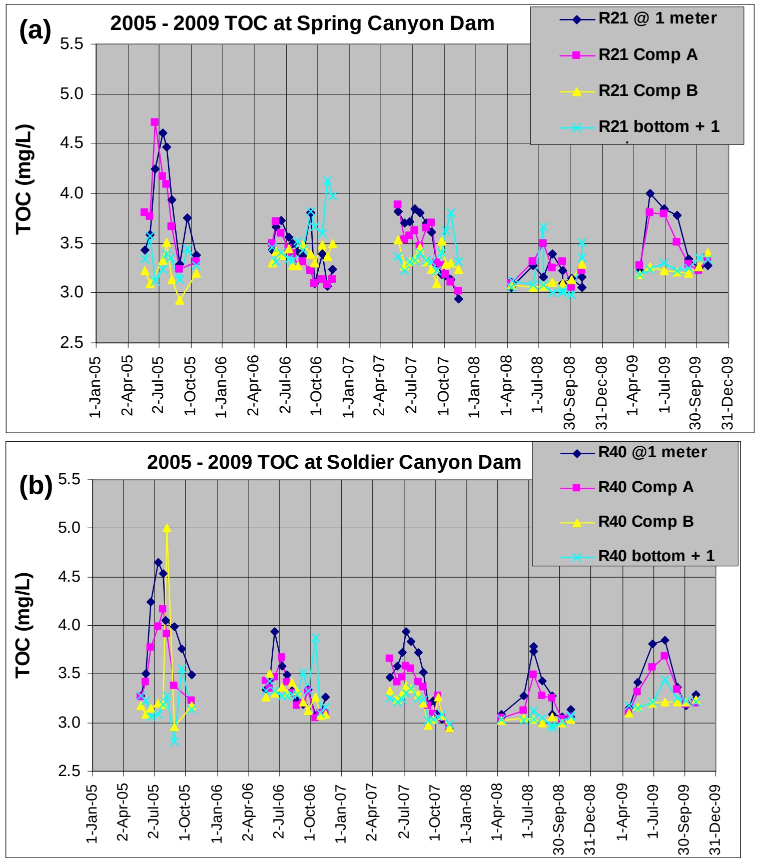


Figure 4-13. 2005-2009 TOC at (a) Spring Canyon, and (b) Soldier Canyon (note y-axis scales).

Figure 4-14 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 2009 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 3.2.2).

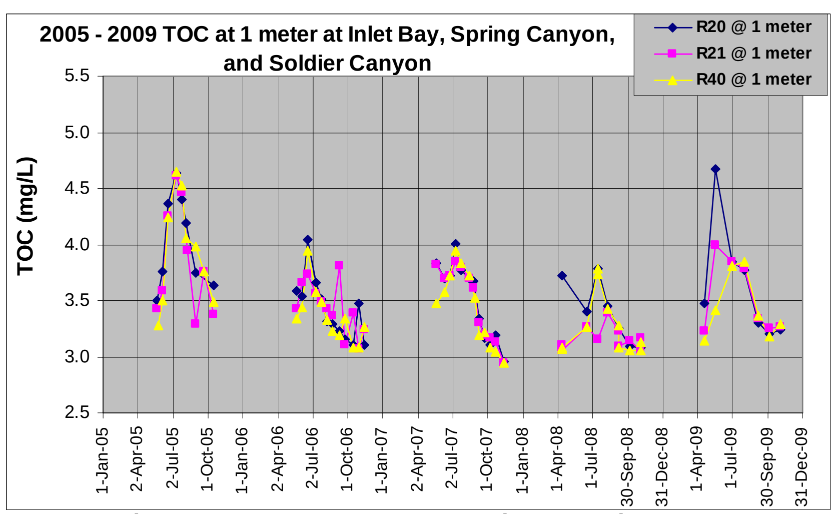


Figure 4-14. 2005-2009 Horsetooth Reservoir 1 meter TOC.

Figure 4-15 compares 2005-2009 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.

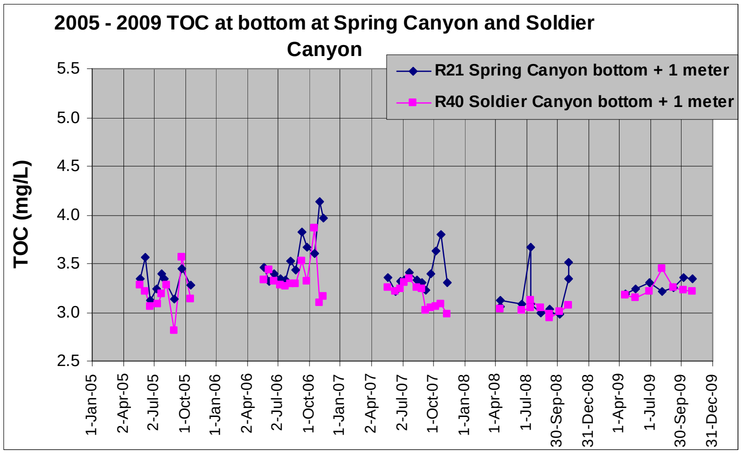


Figure 4-15. 2005-2009 TOC at Horsetooth Reservoir bottom (bottom + 1 meter).

Comparison of TOC concentrations for Horsetooth Inflow water and Horsetooth Outflow water. Annual flow-weighted TOC concentrations for the Hansen Feeder Canal at the Horsetooth inlet (see Section 3.3, Table 3-2) are compared to the annual average TOC concentrations at the FCWTF (calculated from weekly data) on Figure 4-16 for 2005 through 2009. 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.

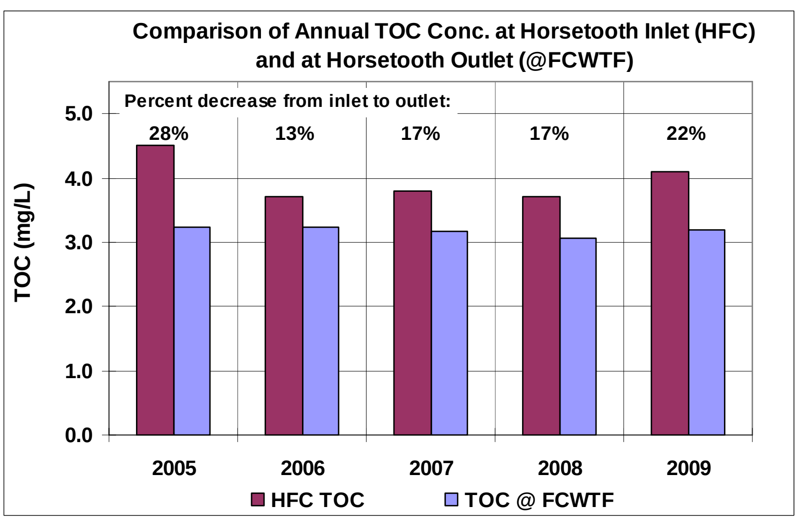


Figure 4-16. Comparison of annual flow-weighted TOC measured at the Hansen Feeder Canal inflow to Horsetooth Reservoir and the annual average TOC measured at the FCWTF.

4.2.3 Major Ions

The major ions determined in water samples collected from Soldier Canyon Dam (R40) are calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+}), potassium (K^{+}), and sulfate (SO_4^{-2}). Analysis for calcium, magnesium, and sulfate is conducted on Spring Canyon Dam (R21) water samples.

Similar to the Hansen Feeder Canal, the predominant cation and anion found in Horsetooth Reservoir waters is calcium and bicarbonate (HCO_3^-), respectively. Calcium concentrations, plotted on Figure 4-17, averaged approximately 8.8 mg/L with a range of 3.8 to 17.5 mg/L during the period of 2005 to 2009. Bicarbonate concentrations are obtained by dividing the alkalinity (expressed in units of mg/L as $CaCO_3$) by 0.8202. With alkalinity generally ranging from approximately 25 to 35 mg/L as $CaCO_3$ (Figure 4-8), the equivalent concentration of HCO_3^- generally ranges from 30 to 43 mg/L. Average concentrations (over the period of 2005-2009) of other ions in Horsetooth Reservoir include 3.8 mg/L for sulfate, 1.6 mg/L for magnesium, 0.82 mg/L for potassium, and 2.6 mg/L for sodium. These concentrations reflect the average concentrations in Hansen Feeder Canal influent waters (see Figure 3-11).

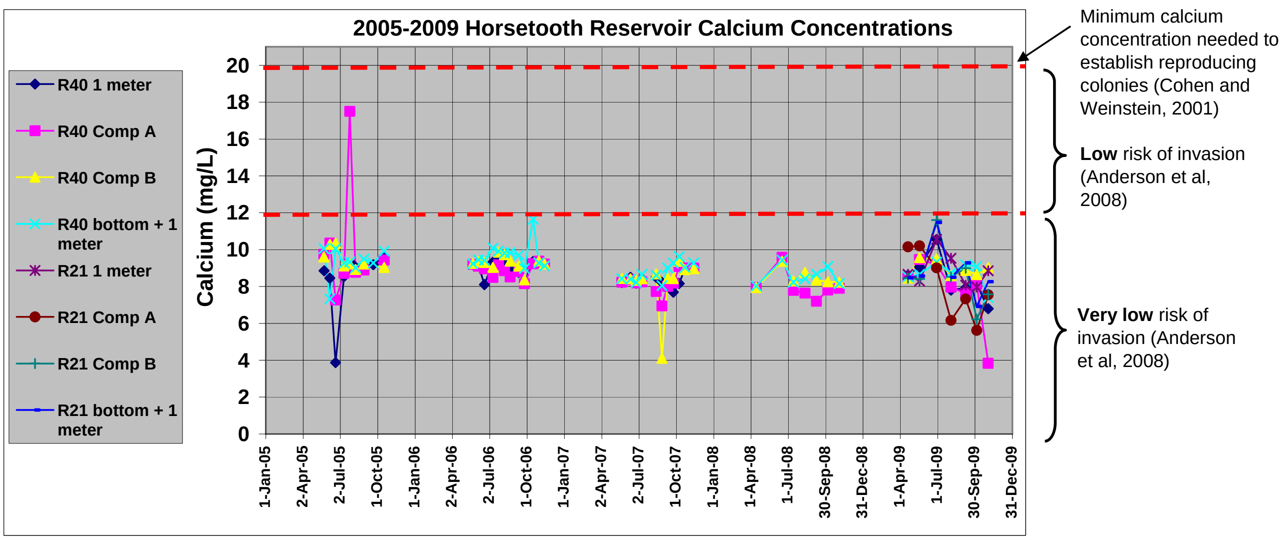


Figure 4-17. 2005-2009 Horsetooth Reservoir calcium concentrations compared to reported thresholds for invasive mussel habitat suitability.

Horsetooth Reservoir habitat suitability for Invasive Mussels based on calcium concentrations. Calcium is considered to be a key limiting factor for many mussels for maintaining basic metabolic function as well as shell formation, and has been shown to be a useful predictor for assessing invasion risk (Whittier et al, 2008; Cohen and Weinstein, 2001). Distribution studies have shown that zebra and quagga mussels appear to have higher calcium requirements than many other freshwater mussels and that optimal conditions for establishing reproducing colonies occur where concentrations are above 20 mg/L. Mussels have been found to occur in low abundance below this threshold, but in such cases, the water bodies most likely serve population sinks rather than hosts to reproducing colonies (Whittier et al., 2008). It should also be noted that much of the research on habitat suitability thresholds has focused on the zebra mussel, with much less known about the quagga mussel.

As shown in Figure 4-17, calcium concentrations in Horsetooth Reservoir are below 12 mg/L, a threshold commonly used to identify water bodies at very low risk for dreissinid invasion (Anderson et al, 2008). It is important to note though, that calcium levels can be affected by seasonal changes in temperature, precipitation, inflows and thermal gradients, and when a water body is not uniformly mixed, micro-zones may exist where conditions are favorable to support colonization (Cohen, 2008).

4.2.4 Nutrients

Nitrogen and phosphorus 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 water quality problems associated with algae include the 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; the production of toxins by cyanobacteria; filter clogging issues; increased 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. Hansen Feeder Canal inflows over the 2005-2009 time period have been characterized by annual flow weighted mean concentrations that have averaged below the 0.005 mg/L reporting limit for ortho-phosphate, and averaged 0.021 mg/L for total phosphorus.

TP includes dissolved, particulate, adsorbed, organic, and inorganic forms of phosphorus. It is considered the best figure 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 4-18. 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.

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 4-19) 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.

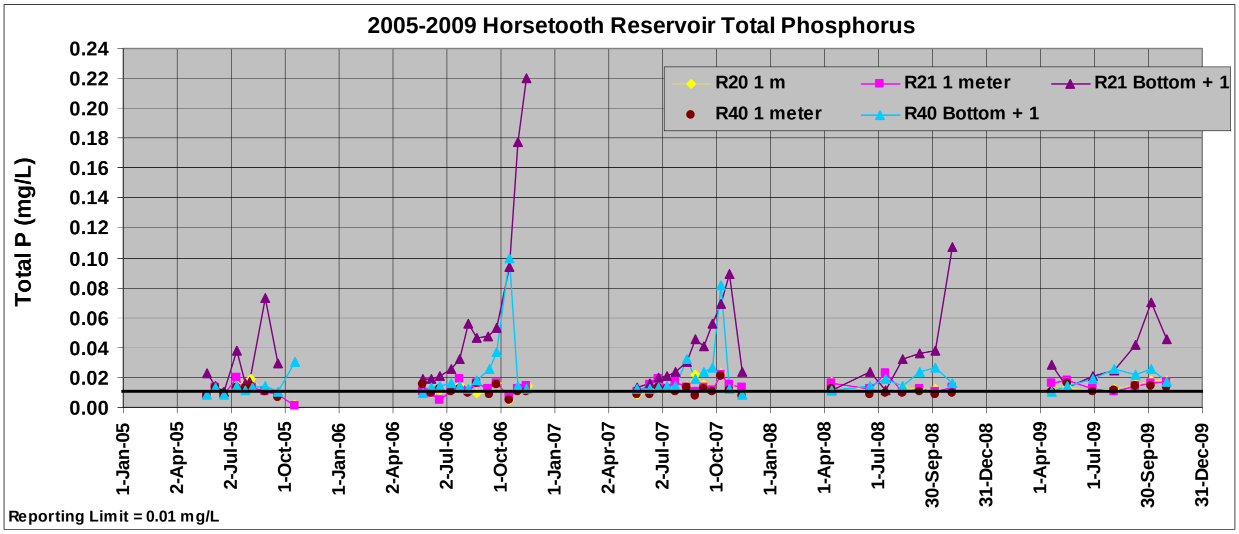


Figure 4-18. 2005-2009 Total P at Inlet Bay (R20), Spring Canyon (R21), and Soldier Canyon (R40).

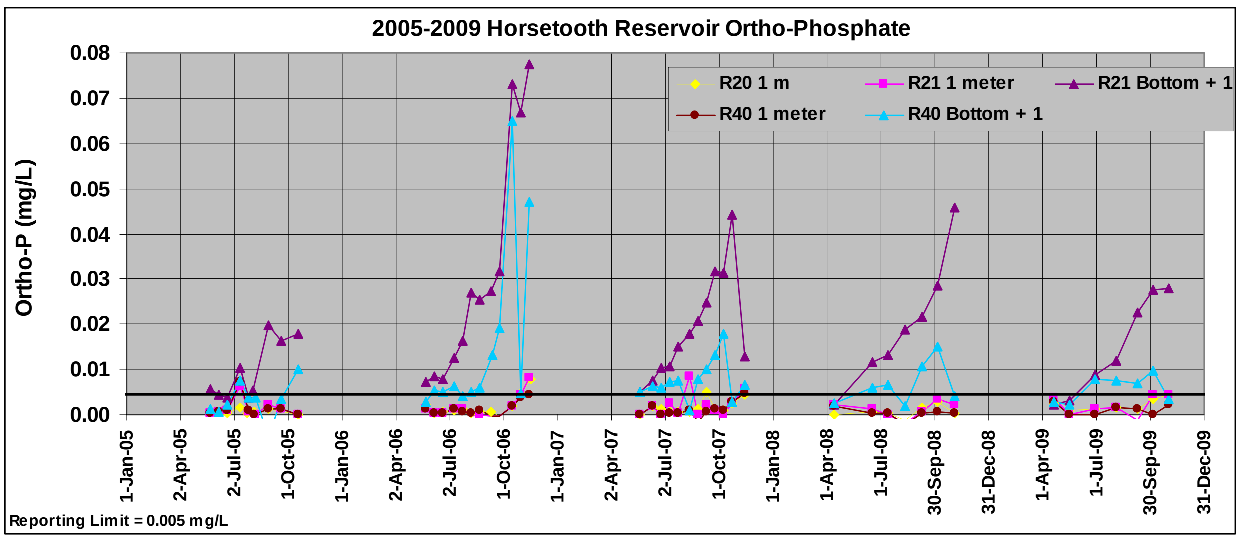


Figure 4-19. 2005-2009 Ortho-phosphate at Inlet Bay (R20), Spring Canyon (R21), and Soldier Canyon (R40)

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. Hansen Feeder Canal inflows over the

2005-2009 time period have been characterized by annual flow weighted mean concentrations that have averaged 0.093 mg/L for nitrate and 0.014 mg/L for ammonia. 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 4-20 (a) and (b), 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 4-20 (a) and (b)). 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. This is particularly evident at Spring Canyon since this process is not impacted by hypolimnetic withdrawal (as is the case at Soldier Canyon).

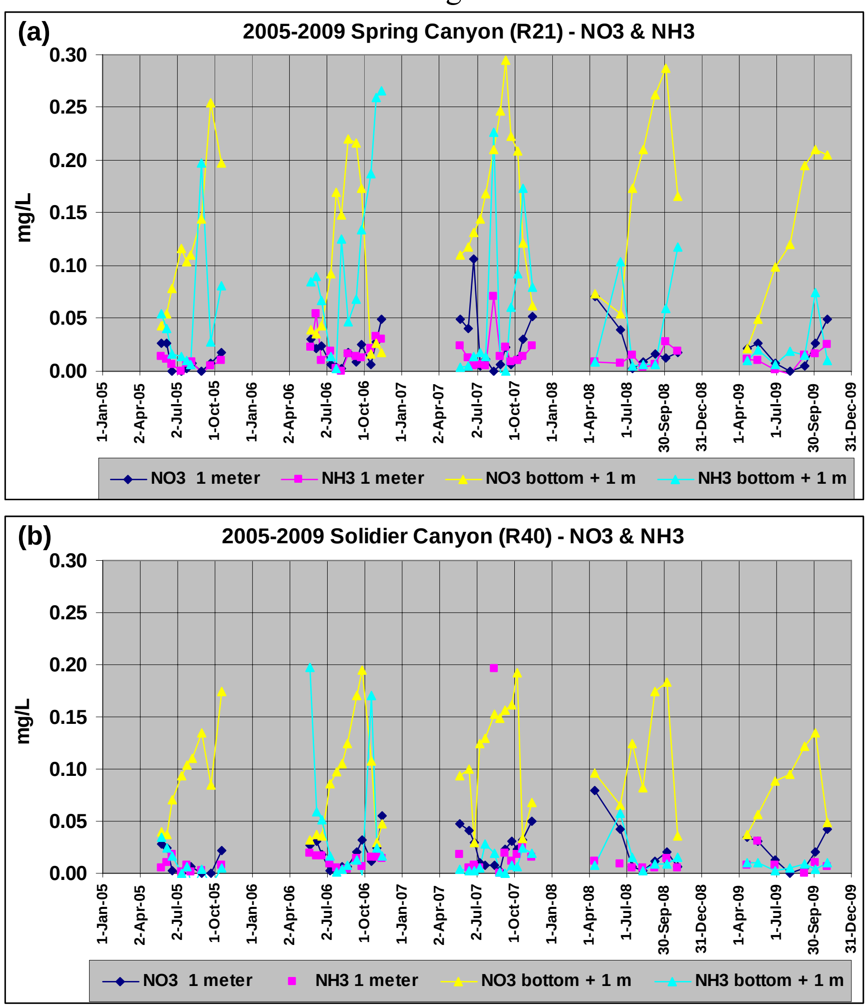


Figure 4-20. 2005-2009 nitrate and ammonia at (a) Spring Canyon, and (b) Soldier Canyon.

Total nitrogen (the sum of the concentrations of nitrate, nitrite and TKN) is plotted on Figure 4-21 for Spring Canyon and Soldier Canyon at depths of 1 meter and 1 meter above bottom. Over the 2005-2009 time period, total nitrogen at the reservoir bottom (bottom + 1 meter) has ranged up to approximately 0.7 mg/L and averaged 0.39 mg/L at Spring Canyon (R21) and 0.30 mg/L at Soldier Canyon (R40). At the reservoir surface (1 meter), total nitrogen over the 2005-2009 time period has averaged 0.25 mg/L at both Spring and Soldier Canyons.

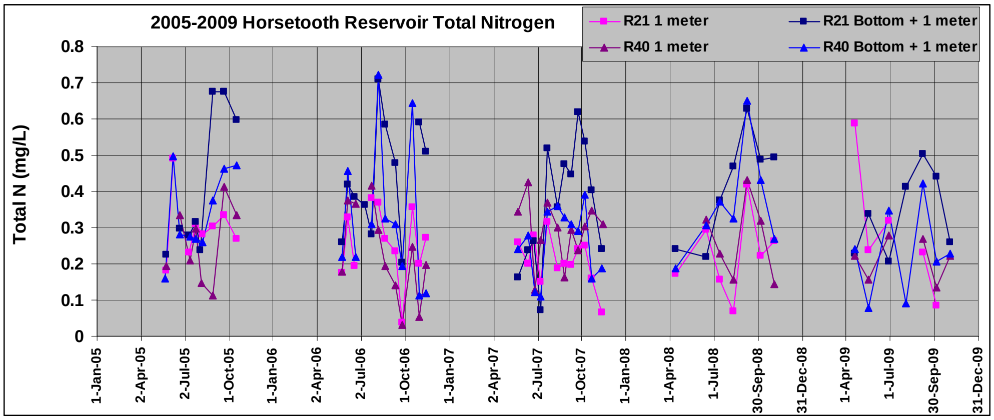


Figure 4-21. 2005-2009 Total nitrogen at Spring Canyon (R21) and Soldier Canyon (R40).

4.2.5 Chlorophyll-a and phytoplankton

Chlorophyll-a. Chlorophyll-a concentrations measured at one meter below surface during the 2005-2009 time period are plotted on Figure 4-22. 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 following equation (Carlson, 1977): TSI = 30.6 + 9.81 ln[Chlor-a in ug/L]. The mean chlorophyll-a concentrations for Horsetooth Reservoir fall into the mesotrophic range.

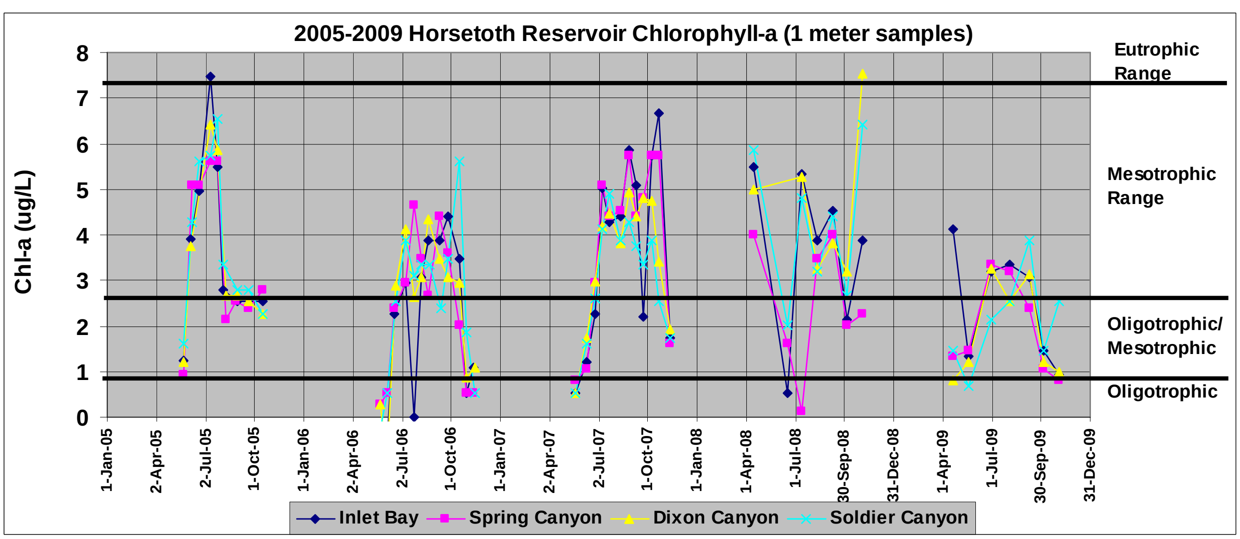
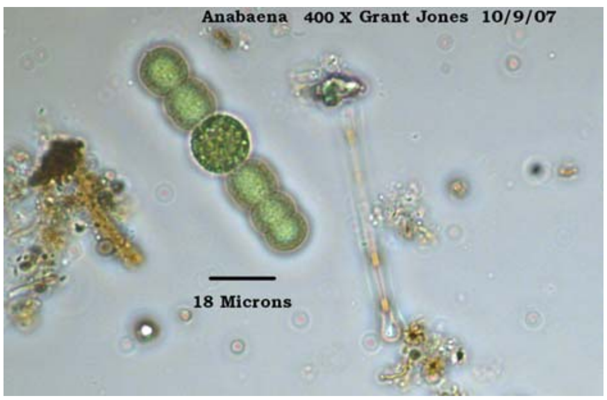


Figure 4-22. 2005-2009 Horsetooth Reservoir chlorophyll-a concentrations (1 meter samples).

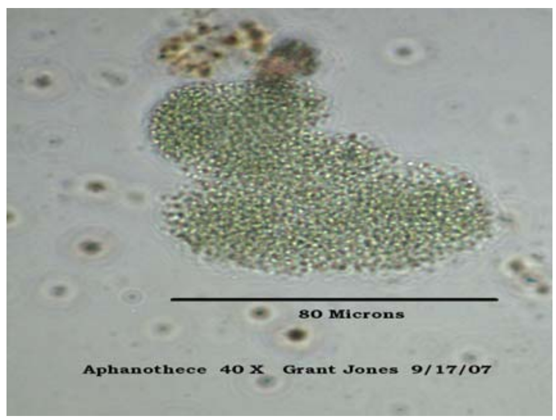
Phytoplankton. Beginning in 2009, phytoplankton identification and enumeration has been conducted by Richard Dufford, with identification to the *species* level (when possible). Photomicrographs of some common phytoplankton genera observed in Horsetooth Reservoir water samples in 2009 are shown on Figure 4-23. By density (number of cells/mL), Cyanophytes (blue-green algae) and Chlorophytes (green algae) were the dominant contributors to the total phytoplankton composition in 2009, as shown on Figure 4-24. The Cyanophytes were dominant through September, while the Chlorophytes were dominant in October and November. The 2009 phytoplankton data are contained in Appendix A.

The predominant blue-green algae species identified in the 2009 Horsetooth Reservoir 1-meter water samples included *Aphanothece smithii, Cyanodictyon plantonium, and Merismopedia tenuissima*. None of these species produce geosmin. Geosmin-producing species comprised a small fraction of the total phytoplankton count in 2009, generally 5 percent or less of the total density. Identified geosmin-producing species included *Anabaena lemmermannii* which was observed in the September 8 samples. *Synechococcus capitatus* was observed in the September, October and November samples and, although the *Synechococcus* genus has been identified as including geosmin producers, it is not known if *Synechococcus capitatus* produces geosmin.

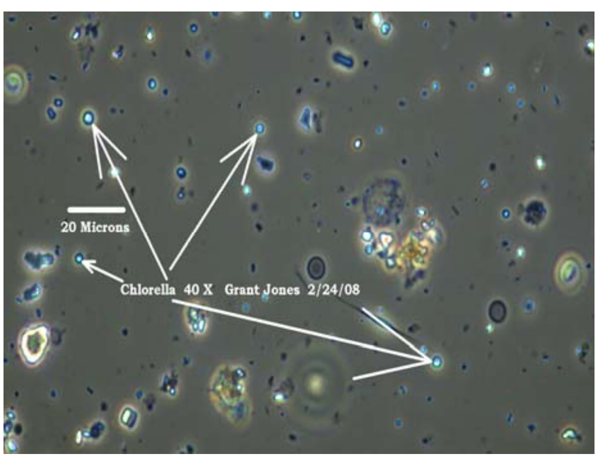
The predominant green algae found in the 2009 Horsetooth Reservoir water samples was *Chlorella minutissima*. *Chlorella* has been identified as a filter clogger and taste and odor (not geosmin) producer.



Blue-green algae: *Anabaena*



Blue-green algae: *Aphanothece*



Green algae: *Chlorella*

Figure 4-23. Photomicrographs of some common phytoplankton genera found in Horsetooth Reservoir (photos taken by Grant Jones, FCU).

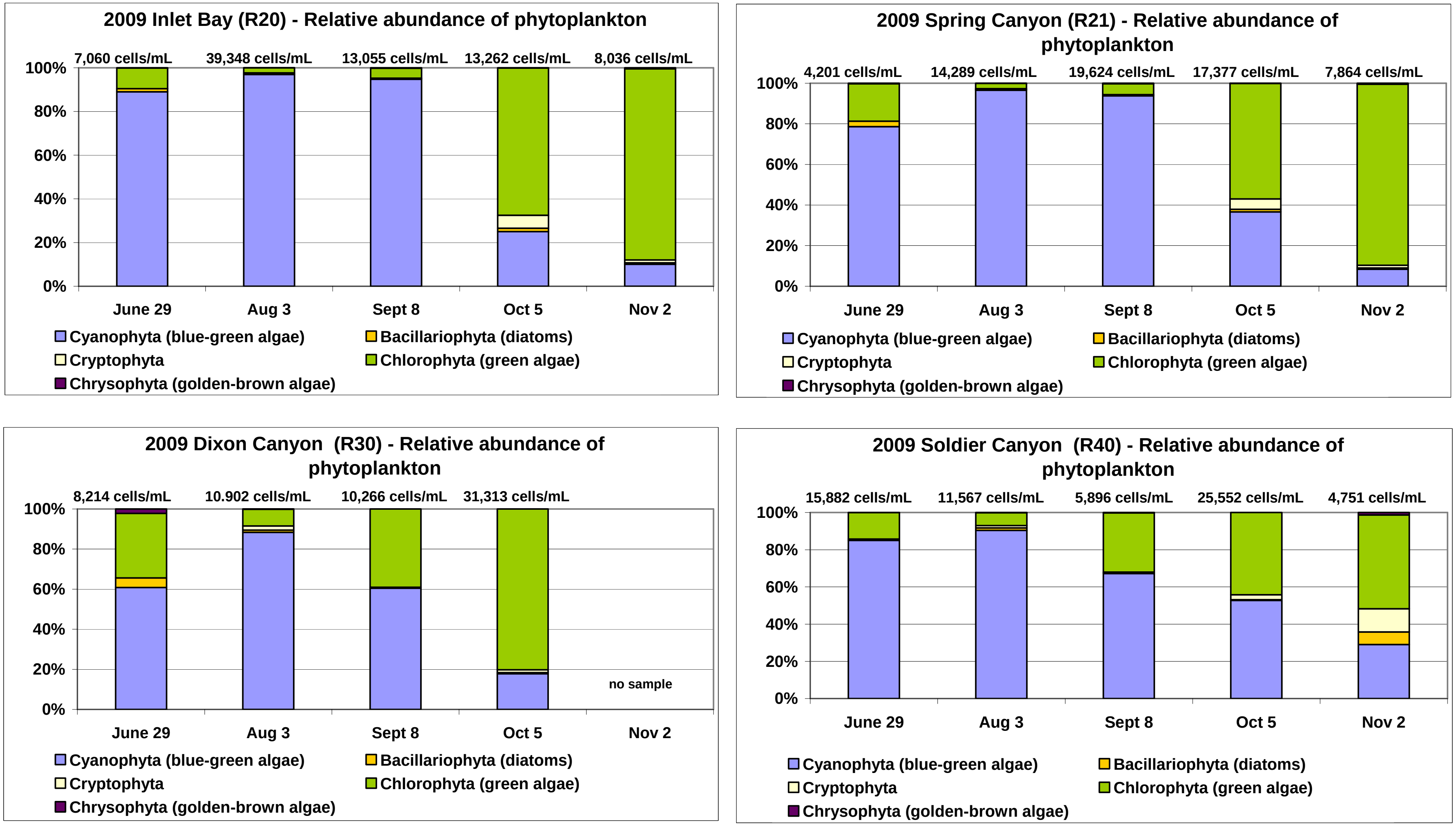


Figure 4-24. Relative abundance (based on # cells/mL) of phytoplankton found in 2009 1-meter samples from Horsetooth Reservoir.

4.2.6 Metals

Metals analysis for Soldier Canyon (R40) water samples includes aluminum, arsenic, iron, lead, manganese, and silver. Iron and manganese analysis is also conducted on samples from Spring Canyon (R21). Aluminum, iron, and manganese analysis is conducted for both dissolved and total concentrations; arsenic, lead, and silver are analyzed for total concentrations only. Summary statistics are presented in Table 4-1 for the metals data collected during the five year period of 2005 through 2009.

Table 4-1. 2005-2009 Metals Data Summary Statistics for Horsetooth Reservoir (bottom samples highlighted in yellow).

Metal	Reporting Limit (ug/L)	Sampling Location	N	Min (ug/L)	Max (ug/L)	Median (ug/L)	85th Percentile (ug/L)
Aluminum - Dissolved	5	Soldier Canyon - 1 meter	29	7.4	175	50.7	85.8
		Soldier Canyon - bottom + 1 m	34	5.2	243	54.4	104
Aluminum - Total	5	Soldier Canyon - 1 meter	40	58.7	673	206	348
		Soldier Canyon - bottom + 1 m	46	48.3	942	290	585
Arsenic	2	Soldier Canyon - 1 meter	34	<2	<2	<2	<2
		Soldier Canyon - bottom + 1 m	40	<2	<2	<2	<2
Iron - Dissolved	10	Inlet Bay - 1 meter	33	<10	199	26.4	55.6
		Spring Canyon - 1 meter	33	<10	73.0	27.0	43.1
		Spring Canyon - bottom + 1 m	33	<10	98.7	30.1	55.4
		Soldier Canyon - 1 meter	34	<10	74.2	23.4	53.2
		Soldier Canyon - bottom + 1 m	34	<10	237	29.8	51.0
Iron - Total	10	Inlet Bay - 1 meter	45	37.3	445	122	225
		Spring Canyon - 1 meter	46	39.5	413	111	212
		Spring Canyon - bottom + 1 m	46	31.6	1,646	178	272
		Soldier Canyon - 1 meter	46	38.1	318	110	182
		Soldier Canyon - bottom + 1 m	46	20.0	740	150	283
Lead	1	Soldier Canyon - 1 meter	34	<1	1.1	<1	<1
		Soldier Canyon - bottom + 1 m	40	<1	<1	<1	<1
Manganese - Dissolved **FCWTF Target = 5 ug/L**	1	Inlet Bay - 1 meter	44	<1	20.8	1.9	6.3
		Spring Canyon - 1 meter	46	<1	23.8	1.7	5.3
		Spring Canyon - Comp A	45	<1	25.1	1.1	4.3
		Spring Canyon - Comp B	44	<1	456	4.5	147
		Spring Canyon - bottom + 1 m	45	<1	1,012	13.7	565
		Soldier Canyon - 1 meter	46	<1	6.9	<1	3.1
		Soldier Canyon - Comp A	45	<1	5.0	<1	1.7
		Soldier Canyon - Comp B	45	<1	108	1.9	7.9
		Soldier Canyon - bottom + 1 m	45	<1	610	3.2	19.6
Manganese - Total	1	Inlet Bay - 1 meter	45	2.5	27.3	6.6	12.1
		Spring Canyon - 1 meter	46	1.7	32.1	5.9	11.5
		Spring Canyon - Comp A	45	3.7	91.4	6.6	15.2
		Spring Canyon - Comp B	44	1.1	623	28.6	270
		Spring Canyon - bottom + 1 m	46	3.5	2,084	68.5	871
		Soldier Canyon - 1 meter	46	<1	13.6	4.6	7.4
		Soldier Canyon - Comp A	45	<1	16.3	4.5	8.4
		Soldier Canyon - Comp B	45	3.8	140	11.9	29.5
		Soldier Canyon - bottom + 1 m	46	3.8	1,421	19.2	64.9
Silver	0.5	Soldier Canyon - 1 meter	34	<0.5	<0.5	<0.5	<0.5
		Soldier Canyon - bottom + 1 m	40	<0.5	<0.5	<0.5	<0.5

Arsenic and silver concentrations have all been below their respective reporting limits. The maximum lead concentration was just above the reporting limit of 1 ug/L, with all other lead values below the reporting limit.

Total manganese and dissolved manganese concentrations are both significantly higher for the reservoir bottom samples than for the near surface samples. Dissolved manganese concentrations are higher at the bottom (bottom + 1 meter) of Spring Canyon than at the bottom of Soldier Canyon (Figure 4-25) because of the more significant depletion of dissolved oxygen that occurs at the bottom of Spring Canyon. The median dissolved manganese concentration at the bottom of Soldier Canyon over the 2005-2009 five-year time period was 3.2 ug/L (Table 4-1), compared to 13.7 ug/L at the bottom of Spring Canyon. The 2008 and 2009 September and October dissolved manganese concentrations at the bottom of Soldier Canyon were below the FCWTF treated water target for dissolved manganese of 5 ug/L.

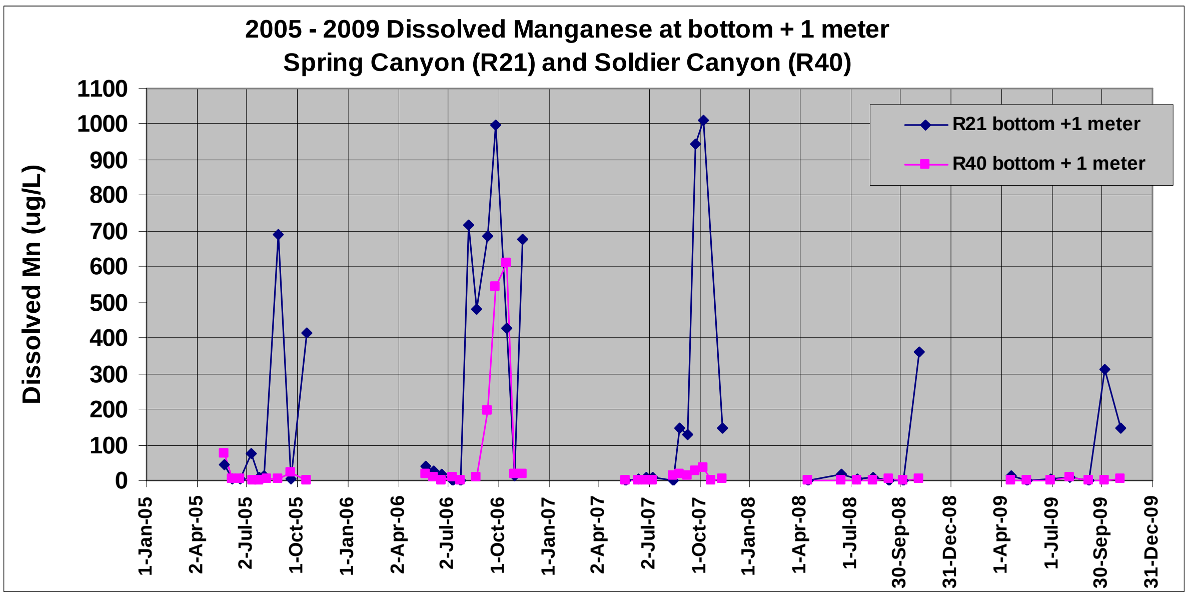


Figure 4-25. 2005-2009 Dissolved manganese at the bottom of Spring Canyon (R21) and Soldier Canyon (R40).

Median concentrations of aluminum and iron do not vary as significantly along the reservoir length and depth compared to the manganese concentrations (Table 4-1).

4.2.7 Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)

The Fort Collins Water Quality Laboratory has been measuring concentrations of benzene, toluene, ethylbenzene, and xylenes (together referred to as BTEX, with chemical structures as shown in Figure 4-26) in Horsetooth Reservoir for several years. These aromatic hydrocarbon compounds are indicators of contamination by petroleum-based fuels such as those that may enter Horsetooth Reservoir through the operation and maintenance of boat engines (Figure 4-27). Primary drinking water standards (Maximum Contaminant Levels or MCLs) have been established for these compounds to protect public health. Benzene is a known carcinogen, while toluene, ethylbenzene, and xylene are potential carcinogens.

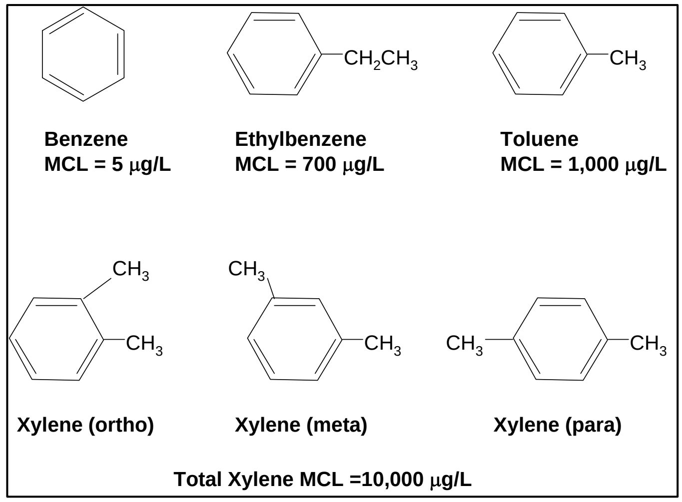


Figure 4-26. BTEX compound structures.

On July 5, 2000, a special sampling event was conducted on Horsetooth Reservoir to collect data that would be considered representative of worse case conditions relative to BTEX (the day after a holiday when significant boating takes place on Horsetooth Reservoir). Samples were collected at four depths (0, 3, 6, and 9 meters below the water surface) at Inlet Bay Marina, South Bay, and Soldier Canyon. Benzene, toluene and xylenes were detected at Inlet Bay Marina and Soldier Canyon at the 0 and 3 meter depths (see pg. 81 of Billica and Oropeza, 2009). However, all values were significantly below their respective MCLs. The July 5, 2000 data showed that none of the compounds were detected below a depth of 3 meters.

Figure 4-27. Boats at Inlet Bay Marina

Samples for BTEX analysis are routinely collected at 1 meter. BTEX data for 1 meter samples from Inlet Bay, Spring Canyon, and Soldier Canyon for 2005 through 2009 are plotted on Figures 4-28 through 4-31. The data show that these organic contaminants are occasionally detected in Horsetooth Reservoir at concentrations above the reporting limit of 0.4 ug/L, but far below their respective MCLs. The data show that these compounds are most commonly detected during the period between late June and early August when recreational boat use on Horsetooth Reservoir is high.

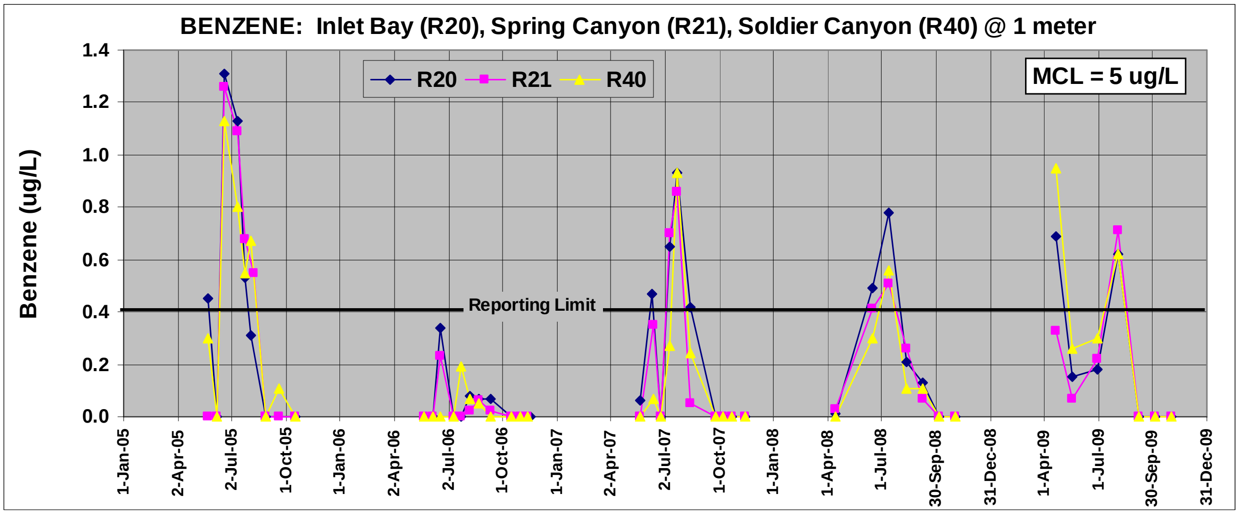


Figure 4-28. 2005 - 2009 Benzene concentrations in 1 meter samples.

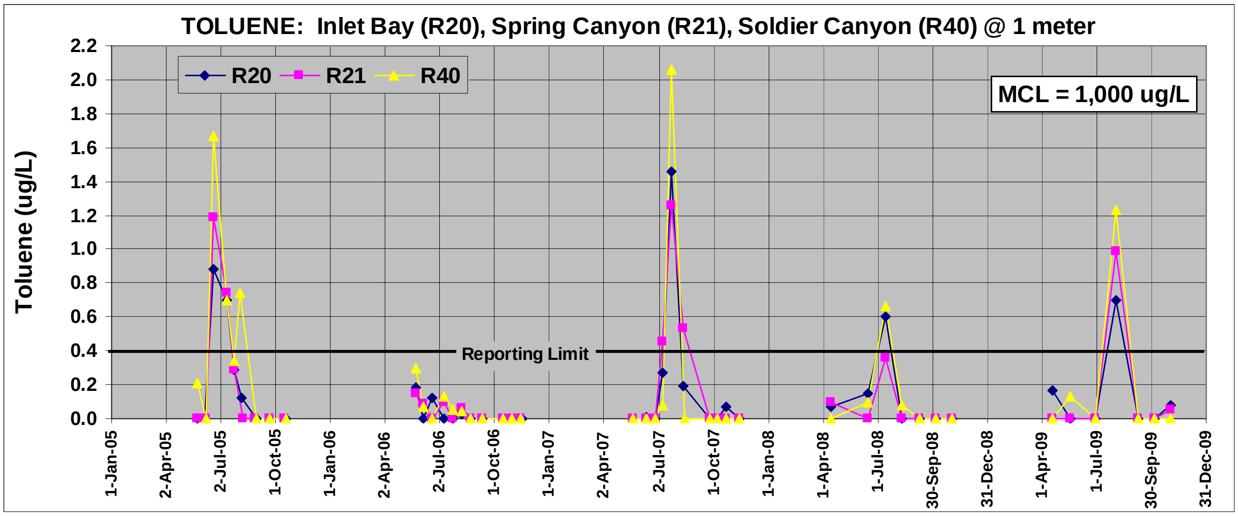


Figure 4-29. 2005 - 2009 Toluene concentrations in 1 meter samples.

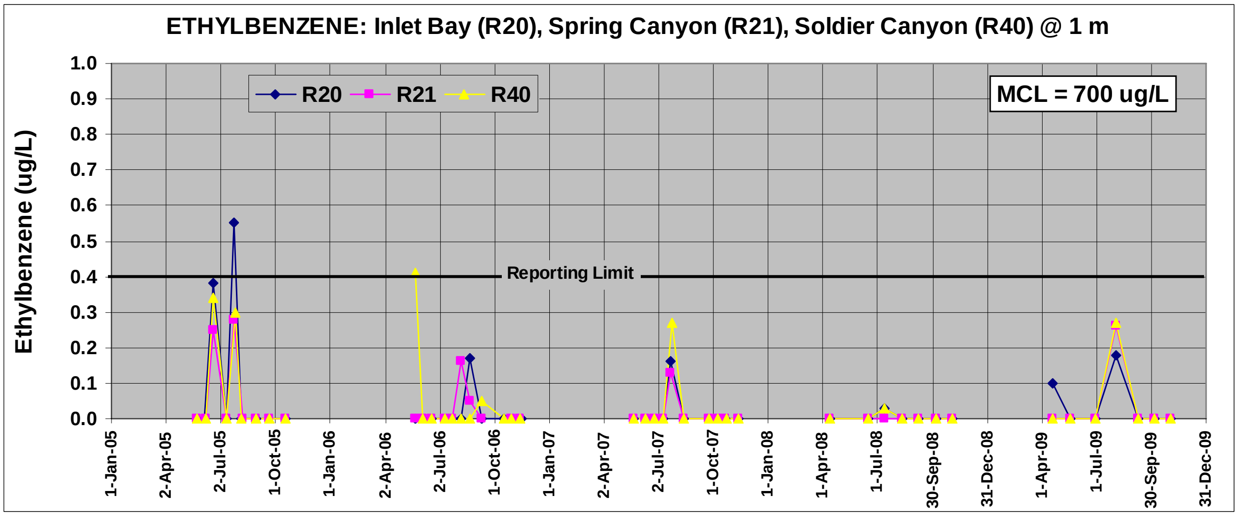


Figure 4-30. 2005 - 2009 Ethylbenzene concentrations in 1 meter samples.

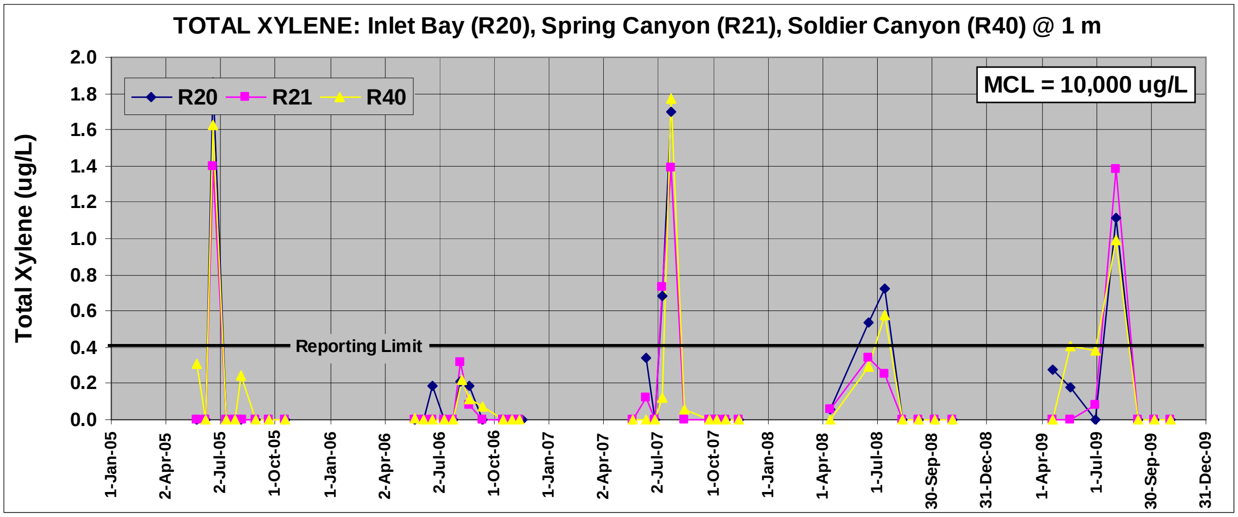


Figure 4-31. 2005 - 2009 Total Xylene concentrations in 1 meter samples.

5.0 OVERVIEW OF SPECIAL STUDIES RELATED TO HORSETOOTH RESERVOIR WATER QUALITY

FCU's source watersheds are under various human and environmental pressures. Mountain pine beetle deforestation, wildfires, climate change, and invasive mussels (zebra and quagga) are all potential sources of future impacts to the quality of the FCU's source waters. CBT Project operational changes, including proposed water supply transfers to Horsetooth Reservoir (i.e., the Northern Integrated Supply Project or NISP) and the possible construction of a second Horsetooth Reservoir outlet structure, are also potential sources of future water quality impacts. The continued routine monitoring of the source watersheds will be important to help the FCU plan for future challenges and is a proactive approach to maintaining the City's high drinking water quality standards. Special studies are designed to address specific long-term issues or new concerns that are outside of the scope of the routine monitoring program. Section 5.0 summarizes the special studies that are currently being conducted, including studies focusing on dissolved organic matter, geosmin, emerging contaminants, and Horsetooth Reservoir water quality modeling.

5.1 Dissolved Organic Matter (DOM) Studies

5.1.1 Background

Dissolved organic matter (commonly measured as TOC, and used interchangeably here with 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 to understand because it affects 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). Studies conducted for the proposed NISP (Glade Reservoir) Project have shown that there is a limited understanding of the nature, sources, and transformations of DOM in Horsetooth Reservoir (INTERA and CH2MHill, 2006) and the implications for treatment and DBP formation potential.

The City of Fort Collins has had a long interest in characterizing the nature of the DOM present in its source waters. Prior to the use of advanced instrumentation, the FCWTF used color as an indicator of TOC for raw and finished water. Routine analysis of water samples for TOC has been conducted by the City of Fort Collins since the early 1990's. A study to characterize the nature of the TOC in raw Horsetooth Reservoir and Poudre River waters was first conducted by the City in 1994 (Carlson, et al, 1994) in order to obtain information to plan for the then upcoming Disinfectants - Disinfection Byproducts Rule. Detailed TOC characterization work was conducted in 2004 (Sharp et al, 2005) on raw Poudre River water samples collected at the FCWTF during the 2004 snowmelt runoff.

A more comprehensive DOM characterization study of both source waters was desired in order to establish a baseline database of information that can be used into the future to help optimize water treatment and to consider the impacts of changing water sources and blends. In addition, as the watershed protection program for the FCWTF, SCFP, and Greeley Bellvue WTP moves into the future, it will be useful to have a better understanding of TOC sources, including potential contributions from algal production in CBT system reservoirs and from events (such as the mountain pine beetle epidemic that can increase pine litter depth as well as the risk of high severity wildfires) that may mobilize watershed DOM into surface waters.

A comprehensive 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 the Upper Cache la Poudre River as well as Horsetooth Reservoir and associated components of the CBT Project. Laboratory analyses for this study included ultraviolet absorbance at a wavelength of 254 nm (UV_{254}), fluorescence, ultrafiltration for size characterization, polarity rapid assessment method for polarity characterization, and trihalomethane formation potential. The final report for this study has been significantly delayed, but is expected to be completed in late 2010.

A new study that builds 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 includes the same study area as the UCLA project, but is focusing on the use of fluorescence parameters to develop relationships between DOM characteristics in the watershed and DBP formation at the FCWTF. The project also used fluorescence to evaluate DOM characteristics and reactivity to chlorine of leachate from pine needles from lodgepole pine trees killed by the ongoing mountain pine beetle epidemic in Colorado. The project used fluorescence data to evaluate the effect of photodegradation (solar radiation) on DOM characteristics in waters from the Hansen Feeder Canal and the Poudre River to assess potential environmental degradation processes. The final report for this project will be completed in 2011. It is expected that together, the results of the UCLA and CU studies will together provide a significant body of information on TOC origin and fate in FCU’s local watersheds and Horsetooth Reservoir, and the potential for this TOC to form disinfection byproducts.

5.1.2 Findings to Date: Preliminary Fluorescence Results

The fluorescence analysis for both projects was conducted at CU and the fluorescence data for the samples collected for the UCLA project (collected in 2008) and for the CU project (collected in 2009) have been analyzed and reported by Beggs (2010). Samples include filtered raw watershed samples collected in 2008 and 2009 at the sites shown on Figure 5-1; treatment plant influent and effluent samples collected in 2008; pine needle leachate, including fresh leachate and laboratory biodegraded leachate from each of three litter ages in pine beetle impacted areas (new litter, recent fall litter, aged litter); chlorinated watershed and pine needle leachate samples; bench-top coagulated (with 20 mg/L alum) watershed and pine needle leachate samples; and bench-top coagulated *and* chlorinated watershed and pine needle leachate samples.

Details of the fluorescence analysis and other methods used in the studies are presented in Beggs (2010) and are not repeated here. Briefly, three-dimensional fluorescence excitation and emission matrices (EEM) were obtained for the samples along with data for TOC, UV_{254}, total trihalomethanes (TTHM), haloacetic acids (HAA5), and chlorine residual. An example of an

EEM showing regions of the EEM 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 5-2. The results of the 2008 and 2009 sampling and analysis were used to explore how watershed DOM characteristics vary spatially and temporally, assess DOM origin, examine the treatability of the DOM, develop relationships between DBP formation and DOM quantity and quality measures, and determine what fluorescent components may be part of the manageable DOM fraction as related to chlorine demand and DBP formation.

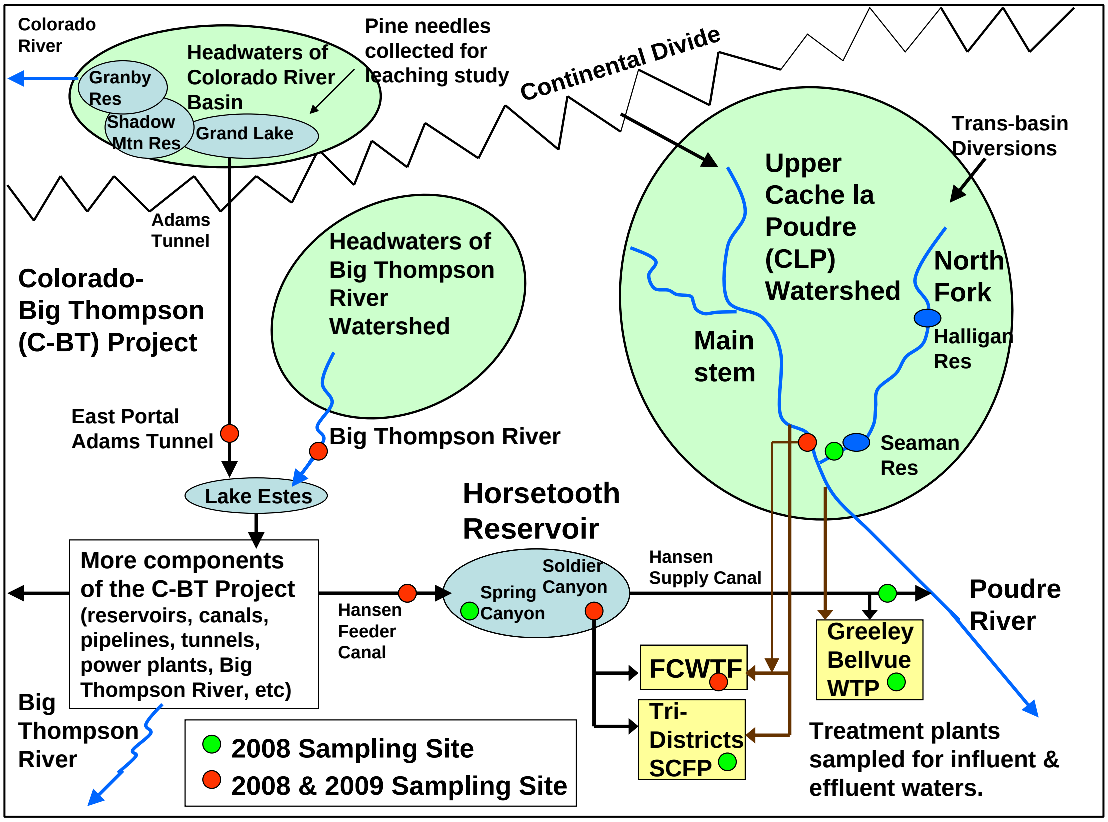


Figure 5-1. 2008 and 2009 sampling locations for DOM projects.

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.

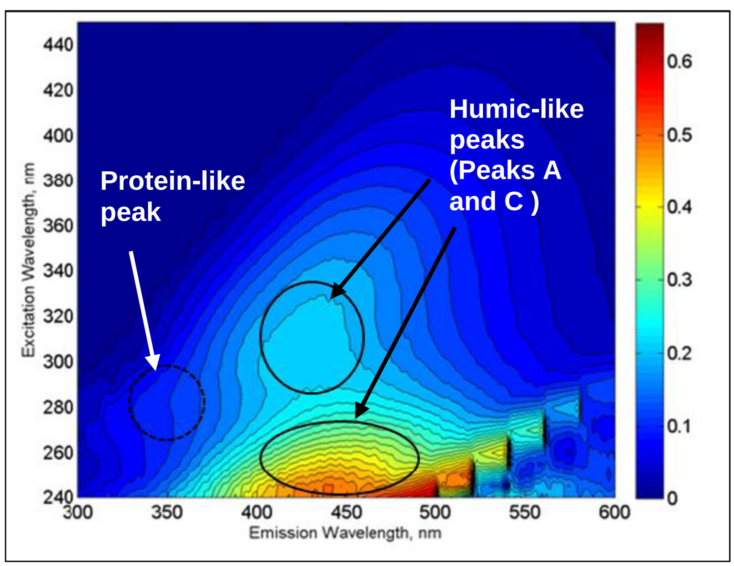


Figure 5-2. Example of a fluorescence excitation and emission matrix (EEM) with primary peaks (from Beggs,

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, 38 samples from the solar simulation study, and 73 pine litter leachate (fresh and biodegraded) samples. The EEMS were together used to develop a watershed-specific six component PARAFAC model (Figure 5-3). 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). The significant findings from Beggs (2010) for the FCWTF, SCFP, and the Greeley Bellvue WTP are summarized below.

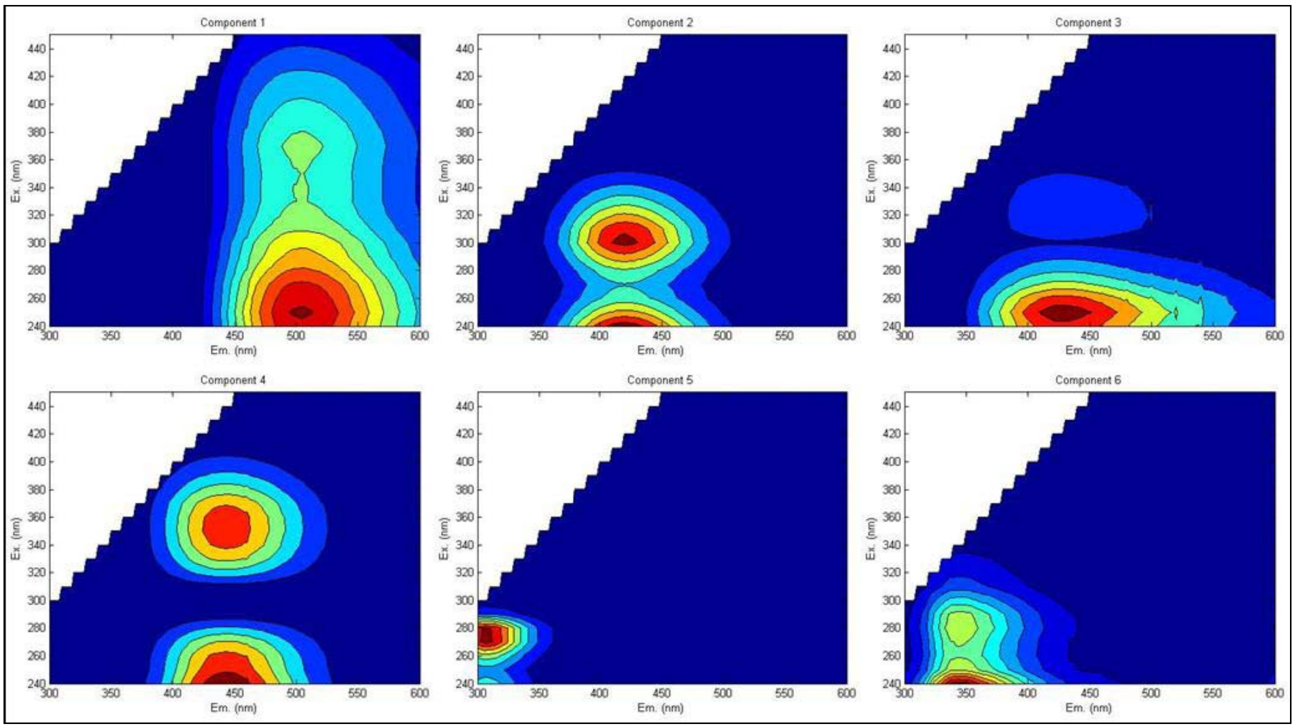


Figure 5-3. Components from the six component PARAFAC model developed for the Upper CLP, Horsetooth Reservoir, and the CBT system upstream of Horsetooth Reservoir. Components 1-4 appear to be humic-like in nature while Component 5 is polyphenolic/tyrosine-like, and Component 6 appears to be tryptophan (protein)-like (from Beggs, 2010).

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.

- 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. 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. 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 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).

- 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. 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. 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.

- 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 170).

Pine Litter Leachate Findings

- Laboratory leaching of pine litter produced leachate with a considerable amount of DOC. Leachates contained humic-like, polyphenolic-like, and protein-like (tyrosine-like and tryptophan-like) material (note that tyrosine and tryptophan are amino acids).

- Fresh pine litter leachates had significant contributions from the polyphenolic/tyrosine-like component (Component 5 of the six-component model shown in Figure 5-3). The fluorophores that contribute to this component vary depending on the age of the litter, but may include polyphenolic compounds such as tannins and lignins that leach from dead plant material, and relatively recalcitrant proteinaceous compounds. Laboratory biodegradation of the pine litter leachate resulted in a dramatic reduction in the contribution of the polyphenolic/tyrosine-like component.

- The contribution of humic-like components increased during laboratory biodegradation of the pine litter leachate. The residual DOM and/or the DOM created during biodegradation appear more aromatic and humic-like than before degradation.

- The humic-like components were positively correlated to TTHM and HAA5 concentrations, but were well removed by coagulation.

- The protein-like (tryptophan-like) component was removed by coagulation and did not show a correlation to DBP concentrations or chlorine demand.

- The polyphenolic/tyrosine-like component was poorly removed by coagulation, but was not correlated to DBP concentrations. While this non-coagulatable portion of the DOM did not appear to serve as a source of DBP precursors, the presence of this component at significant concentrations may have the potential to cause treatment plants to be in non-compliance with percent TOC removal requirements.

Photodegradation Findings

- Based on solar simulator studies performed on water samples from Horsetooth Reservoir, the Hansen Feeder Canal (at the Horsetooth Inlet), and the Poudre River (above the North Fork), photodegradation alone is not a key process for DOM transformation in the FCU's source waters.

- Data suggest a combination of photodegradation and microbial degradation are occurring within the natural systems.

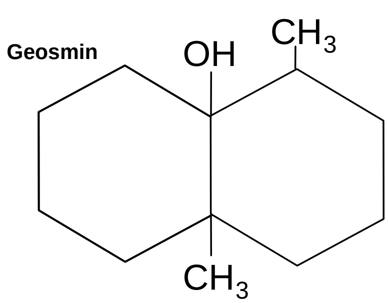
Findings from 2008 Treatment Plant Samples

- The three treatment plants (FCWTF, SCFP, and Greeley Bellvue WTP) had similar DOM quality characteristics for their influent flows despite differences in their blending ratios.

- Treatment at all three plants successfully removed or oxidized the hydrophobic, aromatic TTHM precursor material. TOC removal efficiencies averaged near 50%, with higher efficiency during spring runoff when the DOM had more aromatic character. With conventional treatment processes, allochthonous (terrestrial) DOM is typically more easily removed than autochthonous (microbial) DOM.

5.2 Evaluation of Geosmin Occurrence and Sources 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). When these organisms die and decompose, geosmin is released into the water. 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 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. This high geosmin episode resulted in taste and odor complaints to the City of Fort Collins. The City responded by increasing the powdered activated carbon (PAC) dose for geosmin removal and minimizing the amount of Horsetooth Reservoir water treated at the plant.

Geosmin is one of the most difficult taste and odor compounds to remove during water treatment. It is not removed by conventional treatment processes, but can be partially removed by adsorption onto PAC. The FCWTF upgraded its PAC feed system in 2006 to provide for PAC dosages of up to 10 mg/L. However, the ability to achieve significant removal of geosmin with the upgraded PAC feed system is unknown for raw water geosmin concentrations greater than about 20 ppt.

FCU staff conducted watershed geosmin sampling in 2008 and 2009 to help determine geosmin occurrence and production sites. The 2009 monitoring was also designed to provide for a better "early warning" system. Watershed geosmin sampling included the Horsetooth Reservoir routine sampling sites (in 2008 and 2009), Hansen Feeder Canal sites (in 2009), Big Thompson River above the Dille Tunnel (in 2009), and the east Portal Adams Tunnel (in 2009). The results of the 2008 and 2009 sampling efforts are presented in Billica, Oropeza, Elmund (2010), included in Appendix B.

Watershed geosmin sampling will continue in 2010 as more data are required in order to clarify issues related to geosmin occurrence, transport, fate, and potential production sites.

5.3 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

Snyder et al (2008) recently completed a document for the Water Research Foundation on the "State of Knowledge of Endocrine Disruptors and Pharmaceuticals in Drinking Water." Effluent from wastewater treatment plants is considered to be the major source of PCPs, pharmaceuticals, and EDCs to surface waters. Other sources can include septic systems, leaky sewers, urban runoff, agricultural runoff, and direct release from humans during recreational activities.

The water in Horsetooth Reservoir comes primarily from the headwaters of the Colorado River. Compared to water sources in less pristine environments, the detection of emerging contaminants in water from Horsetooth Reservoir or in upstream components of the CBT system would generally not be expected. However, due to the national media attention focused on emerging contaminants, there was local interest in determining the occurrence of these compounds in waters of the CBT system.

In 2008, Northern Water initiated a collaborative study to determine the presence of emerging contaminants in waters of the CBT system. Collaborators in this study include Northern Water, the Cities of Boulder, Fort Collins, Greeley, Longmont, and Loveland, and the Town of Estes Park. The group decided that each Utility would only report the findings that are directly related to their specific source waters. Therefore, only information for waters of direct interest to the City of Fort Collins is reported here.

Sampling Locations. The sampling sites are located at various points within the CBT Project. The monitoring program includes sites that are upstream of Horsetooth Reservoir (Windy Gap Reservoir, East Portal Adams Tunnel, Upper Thompson Sanitation District Effluent, and Big Thompson River upstream of the Dille Tunnel) and sites that are not hydraulically connected to Horsetooth Reservoir (including Saint Vrain Supply Canal, Boulder Feeder Canal, and Boulder Reservoir). Windy Gap Reservoir, a mix of Colorado River and Fraser River water that is pumped to Granby Reservoir, is included in the monitoring program due to the potential impact of four municipal wastewater treatment plants that discharge in the Fraser River Watershed. At the request of the City of Fort Collins and the City of Greeley, the mainstem Poudre River above the North Fork, and the North Fork Poudre below Seaman Reservoir were added to the monitoring program. The sampling sites of direct interest to the City of Fort Collins are shown on Figure 5-4.

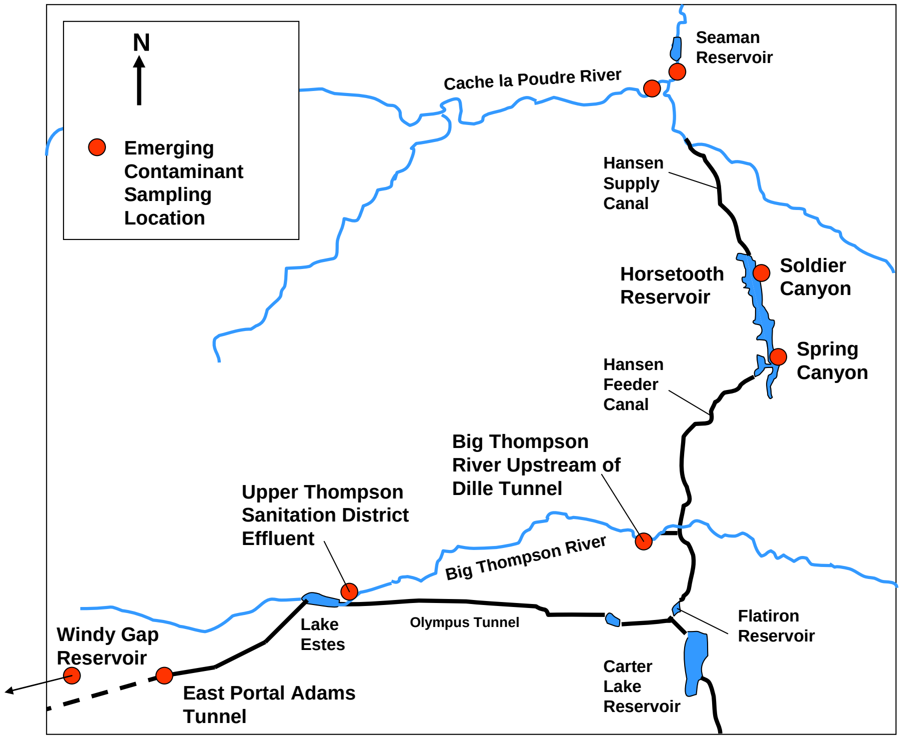


Figure 5-4. Sampling sites for Northern Water Emerging Contaminant Study.

Laboratory Analysis. Samples are submitted to the Center for Environmental Mass Spectrometry Laboratory (at the University of Colorado at Boulder) for analysis of 51 pharmaceuticals and 103 pesticides. Beginning with the June 2009 sampling event, samples are also submitted to Underwriters Laboratories, Inc. for analysis of estrogens and other hormones (9 compounds), and phenolic endocrine disrupting chemicals (8 compounds including bisphenol A).

Sampling Dates through 2010. Sampling dates for the Northern Water emerging contaminant study are outlined on Table 5-1. The study will continue through 2010 (and possibly beyond) with FCU providing financial support and sample collection. Seasonal variability may exist in levels of some emerging contaminants such as pesticides and personal care products due to seasonal changes in agricultural and recreational activities, respectively. Because of this, 2010 will include sampling in late spring (June) and as well as late summer (August), plus additional depths and locations in Horsetooth Reservoir. In 2010, top, middle and bottom samples will be collected at Spring Canyon Dam and Soldier Canyon Dam.

Results through 2009. The results obtained from the Nov/Dec 2008 and June 2009 samples are summarized on Table 5-2 (the method reporting limits (MRL) are indicated in parentheses next to results). The Upper Thompson Sanitation District effluent sample was the only sample that was clearly impacted by PPCPs. For the other sampling locations, DEET was detected at the MRL during one of the Horsetooth Reservoir sampling events, and progesterone was detected at or near the MRL during the June 2009 sampling at Windy Gap Reservoir, Big Thompson River above Dille Tunnel, and Poudre River above North Fork. Note that the detected concentrations of these compounds are in the parts per trillion (nanogram/L) or lower range and caution must be exercised in terms of assigning importance to results near the MRL at such extremely low values.

Table 5-1. Sampling dates through 2010 for the Northern Water Emerging Contaminant Study

Sampling Location	Nov/Dec 2008	June 2009	June 2010	Aug 2010
Windy Gap Reservoir		X	X	
East Portal Adams Tunnel	X	X	X	X
Upper Thompson San. District Effluent		X		
Big Thompson River upstream of Dille Tunnel		X	X	X
Horsetooth Reservoir at Spring Canyon Dam			Top, middle & bottom samples	Top, middle, & bottom samples
Horsetooth Reservoir at Soldier Canyon Dam	1 meter sample	1 meter sample	Top, middle & bottom samples	Top, middle, & bottom samples
Poudre River upstream of North Fork		X	X	X
North Fork Poudre below Seaman Res		X	X	

Table 5-2. Results through 2009 - Northern Water Collaborative Emerging Contaminant Study (method reporting limits (MRL) are indicated in parentheses next to results)

Sampling Location	Nov/Dec 2008	June 2009
Windy Gap Reservoir	Not sampled	Progesterone = 0.2 ng/L (0.1 ng/L)
East Portal Adams Tunnel	No compounds detected.	No compounds detected.
Big Thompson River upstream of Dille Tunnel	Not sampled	Progesterone = 0.1 ng/L (0.1 ng/L)
Horsetooth Reservoir at Soldier Canyon Dam (@ 1 meter)	DEET = 5 ng/L (5 ng/L)	No compounds detected.
Poudre River upstream of North Fork	Not sampled	Progesterone = 0.1 ng/L (0.1 ng/L)
North Fork Poudre below Seaman Reservoir	Not sampled	No compounds detected.

Upper Thompson Sanitation District Effluent - June 2009 Sampling Event - Detected Compounds:

Compound	Use	Concentration	Compound	Use	Concentration
Atenolol	Beta Blocker	Identified	Clarithromycin	Antibiotic	172 ng/L (10 ng/L)
Metoprolol	Beta Blocker	Identified	Diphenhydramine	Antihistamine (Benadryl)	70 ng/L (2 ng/L)
Propranolol	Beta Blocker	Identified	DEET	Insect repellant	20 ng/L (5 ng/L)
Carbamazepine	Anti-convulsant	14 ng/L (5 ng/L)	Carbendazim	Pesticide (fungicide)	193 ng/L (0.8 ng/L)
Lamotrigine	Anti-convulsant	Identified	Diazinon	Insecticide	6 ng/L (0.05 ng/L)
Diltiazem	Heart/blood pressure drug	153 ng/L (5 ng/L)	Nonylphenol	Phenolic Endocrine Disruptor	0.9 ng/L (0.5 ng/L)
Trimethoprim	Antibiotic	429 ng/L (5 ng/L)	Phenylphenol	Phenolic Endocrine Disruptor	0.1 ng/L (0.1 ng/L)
Sulfamethoxazole	Antibiotic	53 ng/L (5 ng/L)	17 alpha-Estradiol	Hormone	0.8 ng/L (0.5 ng/L)
Erthromycin Anhydrate	Antibiotic	1,200 ng/L (5 ng/L)	Estrone	Hormone	12 ng/L (0.5 ng/L)

5.4 Northern Water Collaborative Horsetooth Reservoir Water Quality Modeling Study

The Horsetooth Reservoir Water Quality Study Technical Committee (Committee) was formed in 2008 as a subcommittee of Northern Water's Nutrient Project Technical Advisory Team. Participants on the Committee include Northern Water, City of Greeley, City of Fort Collins, Soldier Canyon Filter Plant, Colorado Division of Wildlife, U.S. Bureau of Reclamation, Big Thompson Watershed Forum, and Coleman Ecological. The purpose of the Committee is to oversee water quality studies conducted of Horsetooth Reservoir.

A Draft Scope of Work was put together by Northern Water (with input from the Committee) in December 2008 that outlined tasks and special studies to address the causes of the recurring low dissolved oxygen levels in the metalimnion of Horsetooth Reservoir. Broader assessments and tasks were also proposed that would directly or indirectly address other water quality issues that had been identified in Horsetooth Reservoir (i.e., low dissolved oxygen at the reservoir bottom, manganese release from sediments, the occurrence of taste and odor compounds, increasing levels of TOC, potential for algal toxins, etc). The development of a Horsetooth Reservoir hydrodynamic water quality model was part of the 2008 Draft Scope of Work.

In Summer 2009, Northern Water initiated a special monitoring program to collect data in the metalimnion. The purpose of this data collection effort was to help identify the processes that are responsible for the low metalimnetic dissolved oxygen values, prior to the development of a water quality model. In Fall 2009, Northern Water received cash contributions from the City of Greeley, the City of Fort Collins, and Soldier Canyon Filter Plant to hire a consultant to analyze the 2009 metalimnion data and develop a hydrodynamic water quality model. The collaborators subsequently selected Jean Marie Boyer and Blair Hanna (both now with Hydros Consulting Inc.) to conduct this project which will begin in June 2010 and is expected to be completed by May 2011.

There are a number of reasons why the development of a hydrodynamic water quality model for Horsetooth Reservoir is important. Such a model will help us evaluate a whole range of water quality issues (D.O., TOC, nutrients, water quality transport issues related to a potential future multi-level outlet and the proposed Glade to Horsetooth pipeline, etc) under situations that include interflow from the Hansen Feeder Canal and seasonal thermal stratification within the 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.

The modeling capabilities are expected to include the following:

- Provide for the evaluation of the effect of reservoir operation (time varying inflows/outflows/water levels) and structural changes (inlet/outlet locations) on water quality transport and fate.

- Simulate processes and constituents associated with the nutrient-food chain including temperature, dissolved oxygen, algae, the nitrogen and phosphorus species, and organic matter.

- Simulate interflow, density gradients, and thermal stratification as demonstrated by the existing reservoir profiles for temperature and conductivity.

- The predictive capability of the model for reproducing dissolved oxygen profiles should receive particular attention, including the ability to accurately simulate both metalimnetic and hypolimnetic dissolved oxygen concentrations.

- Although beyond the current scope of this work, the model must have the capability to add new inflow and outflow points in the future.

- Dimensions: A two-dimensional model will be developed to simulate flow and water quality changes in the vertical and longitudinal directions, with averaging occurring in the lateral direction (assumption of lateral homogeneity). It is uncertain if a two-dimensional model will adequately simulate reservoir hydrodynamics and water quality transport, so consideration will be given during 2-D model development to the possible development of a quasi-3-D or fully 3-D hydrodynamic model.

- The model must be capable of evaluating changes in TOC concentrations at the Reservoir outlets (inflows to water treatment facilities) that may occur due to changing inflow mass loads, flow paths, and operational conditions. The model must incorporate parameters/coefficients to simulate the production, fate (including biodegradation and photodegradation) and transport of TOC within the reservoir.

6.0 SUMMARY

The 2009 Horsetooth Reservoir Water Quality Monitoring Program Report documents information and data collected through 2009 for Horsetooth Reservoir and the influent flows from the Hansen Feeder Canal. Specifically, the 2009 Report includes information and data on regulatory issues, reservoir hydrology, Hansen Feeder Canal water quality and mass loads, Horsetooth Reservoir water quality, relevant special studies, 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 CDPH&E Water Quality Control Division (WQCD) has proposed changes to Footnote 9 of Regulation 31 (Assessing Dissolved Oxygen in Lakes and Reservoirs) that, once adopted, may again change Horsetooth Reservoir's status with regard to the M&E List and 303(d) List for dissolved oxygen.
- WQCD is in the process of developing a nutrient standard (or chlorophyll-a standard) to support a new High-Quality Water Supply Reservoirs sub-classification to the existing Water Supply use classification.
- WQCD is conducting a study in 2010 to better understand the relationship of disinfection byproducts with nutrients, phytoplankton, chlorophyll, and organic carbon in Colorado reservoirs to support nutrient criteria development for Water Supply Reservoirs. Fort Collins Utilities is participating in this study by conducting intensive sampling of Horsetooth Reservoir.

Horsetooth Reservoir Hydrology

- The estimated hydraulic residence time for 2009 is 0.98 years, and ranged from 0.82 to 1.1 years for the five year period of 2005 through 2009.
- 2009 inflow to Horsetooth Reservoir from the Hansen Feeder Canal totaled 107,100 ac-ft.
- 2009 annual outflow to the Hansen Supply Canal (74,000 ac-ft) was roughly three times the 2009 annual outflow at Soldier Canyon Dam (24,900 ac-ft).

- 2009 Horsetooth Reservoir water surface elevations fluctuated a total of 42.85 feet, between the reservoir high water level and reservoir low water level.

- 2009 Horsetooth Reservoir annual average volume was 100,480 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.

- Metals that have been routinely detected above their respective reporting limits in Hansen Feeder Canal water include aluminum, barium, copper, iron, and manganese. Lead, cadmium, and chromium have each been detected once at concentrations above their respective reporting limits (but below their respective MCLs) over the period of 2005 through 2009.

- Dissolved copper concentrations dropped below the reporting limit in 2008 after Northern Water stopped using copper sulfate to control algal growth in the Hansen Feeder Canal.

- The calculated annual mass loads of nutrients and TOC from the Hansen Feeder Canal to Horsetooth Reservoir generally track the annual discharge; i.e., the higher the annual Hansen Feeder Canal flow, the higher the annual mass load. Over the five year period of 2005-2009, the highest annual mass loads of nutrients and TOC occurred in 2007, the year with the highest Hansen Feeder Canal flows to Horsetooth Reservoir.

Horsetooth Reservoir Water Quality

- **Sampling Events.** In 2009, there were seven routine Horsetooth Reservoir sampling events: April 20, May 18, June 29, August 3, September 8, October 5, and November 2. There were also two special sampling events (August 17 and September 21) associated with obtaining additional information to evaluate potential geosmin sources and production sites; sampling was conducted for only a subset of the routine parameters during these special events.

- **Temperature Profiles.** The 2009 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 May 18 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 will plunge 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 occurrence of a minimum in specific conductance in the Horsetooth Reservoir profiles 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 late spring and summer and can therefore be used as a tracer of the interflow process. The specific conductance profiles collected at Inlet Bay, Spring Canyon, Dixon Canyon, and Soldier Canyon show the presence of a specific conductance minima in the metalimnion of all of the profiles collected on June 29, 2009, August 3, 2009, and September 8, 2009, indicating the occurrence of interflow all the way to Soldier Canyon.

- **Total Organic Carbon (TOC).** Annual flow-weighted TOC concentrations for the Hansen Feeder Canal (at the Horsetooth inlet) were compared to the annual average TOC concentrations at the FCWTF (calculated from weekly data) for the 2005-2009 time period and 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.

- **Calcium.** Calcium concentrations in Horsetooth Reservoir are below 12 mg/L, a threshold used to identify water bodies at very low risk for invasion by zebra and quagga mussels.

- **Phosphorous.** Total phosphorous 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.

  Ortho-phosphate concentrations near the reservoir surface are low 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.

- **Chlorophyll-a.** Mean chlorophyll-a concentrations for Horsetooth Reservoir fall into the mesotrophic range.

- **Phytoplankton.** By density (number of cells/mL), Cyanophytes (blue-green algae) and Chlorophytes (green algae) were the dominant contributors to the total phytoplankton composition in 2009 (1-meter samples). The Cyanophytes were dominant through September, while the Chlorophytes were dominant in October and November.

The predominant blue-green algae species identified in the 2009 Horsetooth Reservoir one meter water samples included *Aphanothece smithii, Cyanodictyon plantonium, and Merismopedia tenuissima*. None of these species produce geosmin. Geosmin-producing species comprised a small fraction of the total phytoplankton count in 2009, generally 5 percent or less of the total density. Identified geosmin-producing species included *Anabaena lemmermannii*.

- **Manganese.** Total and dissolved manganese concentrations are both significantly higher for the reservoir bottom samples than for the near surface samples. Dissolved manganese concentrations are higher at the bottom (bottom + 1 meter) of Spring Canyon than at the bottom of Soldier Canyon because of the more significant depletion of dissolved oxygen that occurs at the bottom of Spring Canyon. The median dissolved manganese concentration at the bottom of Soldier Canyon over the 2005-2009 five-year time period was 3.2 ug/L, compared to 13.7 ug/L at the bottom of Spring Canyon. The 2008 and 2009 September and October dissolved manganese concentrations at the bottom of Soldier Canyon were below the FCWTF treated water target of 5 ug/L.

- **Benzene, Toluene, Ethylbenzene, and Xylene (BTEX).** These organic contaminants (indicators of contamination by petroleum-based fuels) are occasionally detected in Horsetooth Reservoir 1-meter samples at concentrations above the 0.4 ug/L reporting limit, but far below their respective MCLs. The data show that these compounds are most commonly detected during the period between late June and early August when recreational boat use on Horsetooth Reservoir is high.

Relevant Special Studies

- **Dissolved Organic Matter (DOM) Studies**. Two DOM studies have been recently conducted that include characterization of Horsetooth Reservoir and upstream CBT TOC: the UCLA study (data collection in 2008) and the Water Research Foundation Tailored Collaboration Study (data collection in 2009). The final report for the UCLA study has been significantly delayed and may be available in 2010. The final report for the Water Research Foundation project (Project 04282) will be completed in 2011.

  Fluorescence analysis was conducted at the University of Colorado (Boulder) for both studies. The significant relevant findings based on the preliminary/ongoing analysis of the fluorescence data include the following:

  - 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 the DOM in the source waters of the 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.

  - Coagulation is effective at removing the material associated with DBP 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.

- **Evaluation of Geosmin Occurrence and Sources**. Findings from the 2009 geosmin monitoring program indicate the following:

  - Significant spatial and temporal variation in geosmin concentrations exist within Horsetooth Reservoir and within upstream components of the CBT Project.

  - Concentrations are highest in the epilimnion (as measured by the 1 meter samples).

  - Significant geosmin concentrations can exist at the bottom of the reservoir even when the reservoir is stably stratified.

  - Geosmin concentrations measured at the FCWTF intake (bottom of Soldier Canyon) are not representative of concentrations found at other locations within the reservoir.

  - Data suggest that geosmin is both transported into the reservoir via the Hansen Feeder Canal and produced within Horsetooth Reservoir

  - Geosmin is transported from the west slope CBT reservoirs through the Adams Tunnel to the east slope CBT system.

  - No correlation exists between geosmin concentrations and chlorophyll-a concentrations or the algal cell density of the potentially geosmin producing genera.

  - More periphyton sampling of the Hansen Feeder Canal will be required to evaluate the canal as a geosmin production site.

- Numerical modeling will be required to fully understand the flow patterns in Horsetooth Reservoir and the impact of Hansen Feeder Canal interflow on geosmin transport.

The data suggest a very complex system with respect to geosmin, and varying levels of geosmin production, transport, and degradation throughout the system. Many questions remain and it is expected that several years of monitoring will be required to more fully understand geosmin sources, transport, and fate.

- **Northern Water Collaborative Emerging Contaminant Study**. The results obtained from the Nov/Dec 2008 and June 2009 sampling events showed that DEET was detected at the method reporting limit (MRL) at Horsetooth Reservoir during the Nov/Dec 2008 sampling event, and progesterone was detected at or near the MRL during the June 2009 sampling event at Windy Gap Reservoir and the Big Thompson River above the Dille Tunnel. The Upper Thompson Sanitation District effluent sample collected in June 2009 was the only sample that was clearly impacted by pharmaceuticals and personal care products.

- **Northern Water Collaborative Horsetooth Reservoir Water Quality Modeling Study**. A financial commitment was made by FCU in 2009 to participate in a collaborative Horsetooth Reservoir hydrodynamic water quality modeling project with Northern Water, the City of Greeley, and Soldier Canyon Filter Plant.

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.

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APPENDIX A

FCU HORSETOOTH RESERVOIR
WATER QUALITY MONITORING PROGRAM

2009 PHYTOPLANKTON DATA

(analysis by Mr. Richard Dufford, consultant)

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina
Site Code	GEOSMIN	C50	C50	C50	C50	C50	R20	R20	R20	R20	R20	R20	R20	R20	R20	R20
Sample Date	PRODUCER?	29-Jun	4-Aug	9-Sep	6-Oct	3-Nov	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov
Depth							1M	1M	1M	1M	5M	10M	15M	1M	5M	10M
DIVISION CYANOPHYTA (blue-green algae)																
Anabaena lemmermannii	*yes*			6.4					171.0			2.4				
Anabaena planctonica	*?*			88.0					1.2							
Anabaena sp.	*yes*			3.6												
Aphanizomenon gracile	*yes*							2.4								
Aphanocapsa delicatissima			1133.0		11.2				2,060			136.0		140.0	40.0	
Aphanocapsa incerta											600.0					
Aphanothece clathrata							5,253									
Aphanothece smithii				2,781	2,369	52	1,030	28,375	4,738		3,250		103	610		3,500
Cyanobium sp.				103.0	18.0											
Cyanodictyon planctonicum									4,841	3,250	3,438					
Dactylococcopsis sp.		4.5	18.0			0.2		0.4	9.0				9.0			
Geitlerinema sp.																
Merismopedia sp.											3.2					
Merismopedia tenuissima						309.0		9,750			1,000					
Planktolyngbya limnetica																
Planktothrix agardhii	*yes*															
Pseudanabaena limnetica	*?*												4.0			
Rhabdogloea scenedesmoides									18.0		140.0					
Synechococcus capitatus	*?*			144.0	45.0				515.0	120.0	80.0		27.0	60.0	180.0	20.0
Synechococcus sp.	*yes*								0.2							
Synechocystis sp.																
Woronichinia karelica									6.0			40.0				
DIVISION CHRYSOPHYTA (golden-brown algae)																
Bicosoeca sp.																
Chromulina sp.				1,597					18.0							
Chrysococcus minutus		4.5														
Dinobryon cylindricum var. *alpinum*						0.1										
Dinobryon divergens							8.2	9.2								
Mallomonas akrokomos									9.0	20.0	1.6	0.4	54.0	40.0	80.0	60.0
Ochromonas sp.			9.0	51.5												
Synura petersenii								14.4								
DIVISION XANTHOPHYTA																
Gloeobotrys limneticus								3.2								
Merismogloea polychloris																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina
Site Code	GEOSMIN	C50	C50	C50	C50	C50	R20	R20	R20	R20	R20	R20	R20	R20	R20	R20
Sample Date	PRODUCER?	29-Jun	4-Aug	9-Sep	6-Oct	3-Nov	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov
Depth							1M	1M	1M	1M	5M	10M	15M	1M	5M	10M
DIVISION BACILLARIOPHYTA (diatoms)																
Achnanthidium deflexum					0.4											
Asterionella formosa							19.2	1.4	0.4	165.6	184.0	162.2	161.2	36.2	39.0	37.6
Aulacoseira ambigua			4.0	18.0	9.2	12.6				1.6	43.2	23.6	27.2	13.2	34.6	28.8
Aulacoseira granulata var. *angustissima*												6.6	5.2			
Aulacoseira italica													4.0			
Aulacoseira italica var. *tenuissima*		0.9														
Cyclostephanos sp.		0.2														
Cyclotella distinguenda																
Cymbella mexicana		0.1														
Cymbella subturgidula						2.2										
Diatoma anceps		0.1														
Diatoma tenuis					0.8	1.6										
Discostella pseudostelligera					18.0											
Encyonema latens			0.2													
Encyonema minutum						4.0										
Encyonema silesiacum					0.2	1.4										
Fragilaria crotonensis				5.6	62.4	3.2	11.2	4.4		34.4	14.8	11.2	31.8			
Fragilaria vaucheriae				0.4	4.6	0.4										
Hannaea arcus		0.6		0.4	12.0	4.0										
Melosira varians				5.2	16.8	0.4						9.4	0.8	3.6		
Navicula caterva				0.4	0.6											
Navicula cryptotenella					0.2											
Navicula sp.					0.4											
Navicula tripunctata					0.2											
Nitzschia archibaldii																
Nitzschia dissipata		0.4														
Nitzschia draveillensis				0.4	0.8											
Nitzschia fonticola					0.6											
Nitzschia gracilis																
Nitzschia linearis				0.2												
Nitzschia sp.													0.2			
Puncticulata bodanica				0.6			52.2	120.0	0.8	0.8	1.2	0.4	0.2			
Staurosira construens		11.0		14.8	5.2								5.6			
Staurosirella pinnata		4.6		3.6												
Stephanodiscus niagarae										2.0	0.8	1.8	3.0	0.8	0.2	0.4
Stephanodiscus parvus				0.8												

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina
Site Code	GEOSMIN	C50	C50	C50	C50	C50	R20	R20	R20	R20	R20	R20	R20	R20	R20	R20
Sample Date	PRODUCER?	29-Jun	4-Aug	9-Sep	6-Oct	3-Nov	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov
Depth							1M	1M	1M	1M	5M	10M	15M	1M	5M	10M
Stephanodiscus sp.																
Synedra cyclopum																
Synedra delicatissima var. *angustissima*				0.1												
Synedra rumpens var. *familiaris*				11.6	12.6	0.2		0.4					0.2			
Synedra rumpens var. *fragilarioides*				0.4	5.4					0.4		0.2	0.2			
Synedra rumpens																
Synedra ulna var. *chaseana*					0.2											
Synedra ulna var. *contracta*					6.6											
Synedra ulna var. *danica*				0.1	0.2											
Synedra ulna var. *subaequalis*					2.8	2.2										
Synedra ulna		0.2		0.6	19.8	64.6							0.4	0.2		
Tabellaria fenestrata							16.6	4.6								
Tabellaria flocculosa				0.6												
Urosolenia eriensis													90.0			
HAPTOPHYTA																
Chrysochromulina parva									9.0	160.0	320.0	120.0	135.0			10.0
DIVISION CRYPTOPHYTA																
Chroomonas coerulea					0.2			10.0					9.0			
Cryptomonas borealis				1.2	2.2	1.0		8.8		5.6	2.8	2.0	4.2	1.4	3.2	2.6
Cryptomonas curvata				0.8	0.2					0.2	2.0	0.4	1.2	0.4	0.8	1.4
Cryptomonas erosa																
Cryptomonas marsonii								2.0	0.2						0.2	0.2
Kathablepharis ovalis																
Komma caudata				9.0		27.0		60.0	63.0	680.0	740.0	240.0	378.0	70.0	160.0	80.0
Plagioselmis nannoplanctica				0.4				80.0		120.0	60.0	80.0	36.0	30.0	10.0	10.0
DIVISION DINOPHYTA																
Ceratium hirundinella								0.4	0.5	0.4			0.4			
Gymnodinium fuscum																
Woloszynskia coronata				1.0			0.1									
DIVISION EUGLENOPHYTA																
Colacium vesiculosum fo. *cyclopicola*																
Phacus longicauda																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina
Site Code	GEOSMIN	C50	C50	C50	C50	C50	R20	R20	R20	R20	R20	R20	R20	R20	R20	R20
Sample Date	PRODUCER?	29-Jun	4-Aug	9-Sep	6-Oct	3-Nov	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov
Depth							1M	1M	1M	1M	5M	10M	15M	1M	5M	10M
PRASINOPHYTA																
Scourfieldia sp.																
DIVISION CHLOROPHYTA (green algae)																
Ankistrodesmus falcatus													0.8			
Ankyra judayi								10.0	18.0	80.0	160.0	20.0	117.0	30.0	40.0	20.0
Botryococcus braunii																
Chlamydomonas sp.					54.0	27.0			154.5							
Chlorella minutissima		2,678	309	773	1,185	2,472	670	875	412	8,625	10,815	6,375	5,305	7,000	13,000	11,500
Closterium macilentum var. *substriatum*				0.2												
Closterium moniliferum						0.4										
Coelastrum microporum				1.6												
Coenochloris fottii				9.2	1.6			6.4					7.2			
Cosmarium candianum var. *candianum* f. *minutum*				0.6												
Cosmarium contractum								0.4	1.0							
Cosmarium orthostichum var. *orthostichum* f. *orthostichum*						0.2										
Cosmarium orthostichum var. *pumilum*					0.2											
Cosmarium phaseolus var. *phaseolus* f. *minus*					0.4							1.0				
Crucigenia tetrapedia																
Elakatothrix gelatinosa				1.6												
Elakatothrix viridis				0.4												
Eremosphaera gigas								0.4								
Eudorina elegans																
Heimansia pusilla										0.4	2.0	1.4	0.8			
Keratococcus sp.																
Kirchneriella obesa				0.2												
Lagerheimia genevensis					0.4	4.5										
Monoraphidium contortum				0.4	0.4	1.2					0.4					
Monoraphidium sp.									9.0							
Mougeotia sp.																
Oedogonium sp.					5.2											
Oocystis apiculata									0.2		4.0	1.6				
Oocystis borgei																
Oocystis parva																
Oocystis pusilla								0.8					9.0			
Pandorina smithii								2.4								

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Canal	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina	Inlet Bay Marina
Site Code	GEOSMIN	C50	C50	C50	C50	C50	R20	R20	R20	R20	R20	R20	R20	R20	R20	R20
Sample Date	PRODUCER?	29-Jun	4-Aug	9-Sep	6-Oct	3-Nov	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov
Depth							1M	1M	1M	1M	5M	10M	15M	1M	5M	10M
Pediastrum boryanum				4.4									7.2			
Pseudodicytosphaerium elegans						0.8										
Pseudodicytosphaerium sp.		309.0				630.0				360.0	160.0					16.0
Scenedesmus arcuatus var. *gracilis*								1.6								
Scenedesmus bicaudatus				0.4												
Scenedesmus communis				0.8	0.8	0.8										
Scenedesmus obliquus					1.6											
Spirogyra sp.					0.1											
Spondylosium planum				1.6												
Staurastrum boreale				0.2												
Staurastrum hexacerum					1.4	0.2										
Staurastrum lapponicum						0.8					0.2					
Staurastrum lunatum var. *planctonicum*																
Staurastrum planctonicum							0.1	0.4								
Staurodesmus mucronatus																
Staurodesmus orientalis																
Staurodesmus sp.								0.2								
Stichococcus subtilis					1.6											
Volvox tertius								3.6								
TOTAL DENSITY (cells/mL)		**3,014**	**1,473**	**5,644**	**3,878**	**3,624**	**7,060**	**39,348**	**13,055**	**13,626**	**21,023**	**7,236**	**6,537**	**8,036**	**13,588**	**15,287**

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam
Site Code	GEOSMIN	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
DIVISION CYANOPHYTA (blue-green algae)																
Anabaena lemmermannii	*yes*			348.8												
Anabaena planctonica	*?*								0.8							
Anabaena sp.	*yes*															
Aphanizomenon gracile	*yes*															
Aphanocapsa delicatissima						1,250	64.0	207.0					600.0			
Aphanocapsa incerta																
Aphanothece clathrata																
Aphanothece smithii		1,700	7,957	9,750	4,750	625	250	412	1,545	824	520	1,500	1,438	515		721
Cyanobium sp.										154.5				51.5		
Cyanodictyon planctonicum				5,250	2,500				309	927						
Dactylococcopsis sp.			4.5	10.0	20.0		20.0	9.0								
Geitlerinema sp.																
Merismopedia sp.																
Merismopedia tenuissima			4274.5													
Planktolyngbya limnetica															3.6	
Planktothrix agardhii	*yes*															
Pseudanabaena limnetica	*?*									2.0						
Rhabdogloea scenedesmoides			27.0													
Synechococcus capitatus	*?*			250.0	180.0	300.0	100.0	225.0	144.0	13.0	125.0	125.0	125.0	18.0		9.0
Synechococcus sp.	*yes*									3.0						
Synechocystis sp.										51.5						
Woronichinia karelica																
DIVISION CHRYSOPHYTA (golden-brown algae)																
Bicosoeca sp.																
Chromulina sp.						40.0				10						
Chrysococcus minutus																
Dinobryon cylindricum var. *alpinum*																
Dinobryon divergens		14.85	7.6													
Mallomonas akrokomos					2.4	20.0	1.2	9.0	0.2		50.0	10.0	20.0	18.0	4.5	
Ochromonas sp.									9.0	2						
Synura petersenii			4.8													
DIVISION XANTHOPHYTA																
Gloeobotrys limneticus			3.8													
Merismogloea polychloris					4.8											

City of Fort Collins Watershed Program

2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam
Site Code	GEOSMIN	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
DIVISION BACILLARIOPHYTA (diatoms)																
Achnanthidium deflexum																
Asterionella formosa		42.0	0.4		91.2	356.8	102.4	142.2	144.8		29.4	22.6	46.6	21.4	12.0	19.2
Aulacoseira ambigua					12.0	8.2	9.0	39.9	22.0		0.6	27.2	57.0	31.1	29.4	10.6
Aulacoseira granulata var. *angustissima*							18.2									
Aulacoseira italica			1.0													
Aulacoseira italica var. *tenuissima*			0.6													
Cyclostephanos sp.																
Cyclotella distinguenda			9.0													
Cymbella mexicana																
Cymbella subturgidula																
Diatoma anceps																
Diatoma tenuis																
Discostella pseudostelligera																
Encyonema latens																
Encyonema minutum																
Encyonema silesiacum																
Fragilaria crotonensis		13.2	32.1		43.2	10.0	10.4	9.9	23.8				6.0	2.2		
Fragilaria vaucheriae																
Hannaea arcus																
Melosira varians					1.6		8.0		1.6							
Navicula caterva																
Navicula cryptotenella																
Navicula sp.																
Navicula tripunctata																
Nitzschia archibaldii								0.1	0.2							
Nitzschia dissipata																
Nitzschia draveillensis				1.2	0.4	0.4	0.4	0.1								
Nitzschia fonticola					0.8				0.2							
Nitzschia gracilis								0.1								
Nitzschia linearis							0.2				0.2					
Nitzschia sp.							0.4									
Puncticulata bodanica		31.95	85.5	0.4	0.8		0.2	0.9	1.2			0.4		0.2		
Staurosira construens																
Staurosirella pinnata																
Stephanodiscus niagarae					1.2	2.0	1.8	1.4	1.8		0.6	0.6	1.0	0.3	0.2	0.4
Stephanodiscus parvus																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam
Site Code	GEOSMIN	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
Stephanodiscus sp.									0.8							
Synedra cyclopum									1.0							
Synedra delicatissima var. *angustissima*																
Synedra rumpens var. *familiaris*			0.1	6.0	0.8		0.8	0.3	0.4							
Synedra rumpens var. *fragilarioides*				2.0		1.8	0.6	0.6	1.6							
Synedra rumpens									0.1							
Synedra ulna var. *chaseana*																
Synedra ulna var. *contracta*																
Synedra ulna var. *danica*																
Synedra ulna var. *subaequalis*																
Synedra ulna							0.6	0.1							0.2	
Tabellaria fenestrata		30.0	1.2													
Tabellaria flocculosa																
Urosolenia eriensis								9.0	27.0		40.0					
HAPTOPHYTA																
Chrysochromulina parva					120.0	160.0	280.0	234.0	207.0					9.0	4.5	
DIVISION CRYPTOPHYTA																
Chroomonas coerulea			5.0			0.2										
Cryptomonas borealis			0.6		1.2	1.0	1.6	2.8			1.8	2.0	1.6	1.0	0.2	
Cryptomonas curvata					0.8	0.6	2.4	2.0			0.8	0.4		0.7		
Cryptomonas erosa								0.8								
Cryptomonas marsonii								0.1			0.2					
Kathablepharis ovalis																
Komma caudata			396.0		400.0	300.0	220.0	342.0	18.0		70.0	60.0	10.0	9.0		
Plagioselmis nannoplanctica			9.0		20.0	10.0	80.0	63.0	9.0		10.0	10.0		18.0		
DIVISION DINOPHYTA																
Ceratium hirundinella			1.2	0.4	0.2	0.2	0.2	0.4								
Gymnodinium fuscum										0.3						
Woloszynskia coronata																
DIVISION EUGLENOPHYTA																
Colacium vesiculosum fo. *cyclopicola*																
Phacus longicauda									0.1							

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam
Site Code	GEOSMIN	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
PRASINOPHYTA																
Scourfieldia sp.																
DIVISION CHLOROPHYTA (green algae)																
Ankistrodesmus falcatus			0.2													
Ankyra judayi			27.0	5.0	100.0	40.0	160.0	81.0	126.0		40.0	20.0	20.0	9.0	13.5	18.0
Botryococcus braunii			0.7							1.4						
Chlamydomonas sp.									0.4							
Chlorella minutissima		2,369	1,236	4,000	7,625	3,750	5,875	2,833	9,270	5,150	6,875	16,000	15,375	4,275	2,678	3,863
Closterium macilentum var. *substriatum*																
Closterium moniliferum																
Coelastrum microporum																
Coenochloris fottii			7.8				5.2		6.8							
Cosmarium candianum var. *candianum* f. *minutum*																
Cosmarium contractum			0.5					1.1								
Cosmarium orthostichum var. *orthostichum* f. *orthostichum*																
Cosmarium orthostichum var. *pumilum*																
Cosmarium phaseolus var. *phaseolus* f. *minus*							1.0									
Crucigenia tetrapedia						1.6	0.8		36.0							
Elakatothrix gelatinosa			0.8													
Elakatothrix viridis						1.0		0.4						0.2		
Eremosphaera gigas																
Eudorina elegans																
Heimansia pusilla					0.4	1.0		0.8	0.8	0.3	0.4					
Keratococcus sp.																
Kirchneriella obesa																
Lagerheimia genevensis																
Monoraphidium contortum					0.4			0.1								
Monoraphidium sp.																
Mougeotia sp.								1.8								
Oedogonium sp.																
Oocystis apiculata							2.8	1.0	3.2							
Oocystis borgei			0.5													
Oocystis parva								0.4								
Oocystis pusilla			0.8													
Pandorina smithii			12.4													

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam	Spring Canyon Dam
Site Code	GEOSMIN	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21	R21
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
Pediastrum boryanum																
Pseudodicytosphaerium elegans																
Pseudodicytosphaerium sp.			180.0		1500.0			450.0	108.0		100.0	280.0			1030.0	
Scenedesmus arcuatus var. *gracilis*			0.8													
Scenedesmus bicaudatus																
Scenedesmus communis																
Scenedesmus obliquus																
Spirogyra sp.																
Spondylosium planum																
Staurastrum boreale																
Staurastrum hexacerum																
Staurastrum lapponicum									0.2							
Staurastrum lunatum var. *planctonicum*								0.1	0.1							
Staurastrum planctonicum		0.6	0.3													
Staurodesmus mucronatus				0.2										0.1		
Staurodesmus orientalis																
Staurodesmus sp.			0.3													
Stichococcus subtilis																
Volvox tertius																
TOTAL DENSITY (cells/mL)		**4,201**	**14,289**	**19,624**	**17,377**	**6,880**	**7,217**	**5,081**	**12,020**	**7,139**	**7,864**	**18,058**	**17,700**	**4,979**	**3,776**	**4,641**

City of Fort Collins Watershed Program

2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam
Site Code	GEOSMIN	R30	R30	R30	R30
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct
Depth		1M	1M	1M	1M
DIVISION CYANOPHYTA (blue-green algae)					
Anabaena lemmermannii	*yes*			830.4	
Anabaena planctonica	*?*			3.2	
Anabaena sp.	*yes*				
Aphanizomenon gracile	*yes*				
Aphanocapsa delicatissima				1,375	
Aphanocapsa incerta					
Aphanothece clathrata					
Aphanothece smithii		5,000	4,875	3,125	5,000
Cyanobium sp.					
Cyanodictyon planctonicum				750.0	44.0
Dactylococcopsis sp.			1.0	10.0	
Geitlerinema sp.					
Merismopedia sp.					
Merismopedia tenuissima			4,750		
Planktolyngbya limnetica					
Planktothrix agardhii	*yes*				
Pseudanabaena limnetica	*?*				
Rhabdogloea scenedesmoides					120.0
Synechococcus capitatus	*?*			120.0	340.0
Synechococcus sp.	*yes*				
Synechocystis sp.					
Woronichinia karelica					
DIVISION CHRYSOPHYTA (golden-brown algae)					
Bicosoeca sp.					
Chromulina sp.					
Chrysococcus minutus					
Dinobryon cylindricum var. *alpinum*					
Dinobryon divergens		180.0	16.8		
Mallomonas akrokomos					0.6
Ochromonas sp.					
Synura petersenii					
DIVISION XANTHOPHYTA					
Gloeobotrys limneticus			12.2		
Merismogloea polychloris					

City of Fort Collins Watershed Program

2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam
Site Code	GEOSMIN	R30	R30	R30	R30
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct
Depth		1M	1M	1M	1M
DIVISION BACILLARIOPHYTA (diatoms)					
Achnanthidium deflexum					
Asterionella formosa		84.8	4.8	2.8	132.8
Aulacoseira ambigua					23.2
Aulacoseira granulata var. *angustissima*					
Aulacoseira italica					
Aulacoseira italica var. *tenuissima*					0.4
Cyclostephanos sp.					
Cyclotella distinguenda					
Cymbella mexicana					
Cymbella subturgidula					
Diatoma anceps					
Diatoma tenuis					
Discostella pseudostelligera					
Encyonema latens					
Encyonema minutum					
Encyonema silesiacum					
Fragilaria crotonensis		64.0	13.6	7.2	29.4
Fragilaria vaucheriae					
Hannaea arcus					
Melosira varians					
Navicula caterva					
Navicula cryptotenella					
Navicula sp.					
Navicula tripunctata					
Nitzschia archibaldii					
Nitzschia dissipata					
Nitzschia draveillensis					
Nitzschia fonticola					
Nitzschia gracilis					
Nitzschia linearis					
Nitzschia sp.					
Puncticulata bodanica		200.0	77.5	0.8	0.4
Staurosira construens					
Staurosirella pinnata					
Stephanodiscus niagarae					
Stephanodiscus parvus					

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam
Site Code	GEOSMIN	R30	R30	R30	R30
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct
Depth		1M	1M	1M	1M
Stephanodiscus sp.					
Synedra cyclopum					
Synedra delicatissima var. *angustissima*					
Synedra rumpens var. *familiaris*				13.2	
Synedra rumpens var. *fragilarioides*		0.8		4.0	0.2
Synedra rumpens					
Synedra ulna var. *chaseana*					
Synedra ulna var. *contracta*					
Synedra ulna var. *danica*					
Synedra ulna var. *subaequalis*					
Synedra ulna					
Tabellaria fenestrata		39.2	17.6	0.2	
Tabellaria flocculosa					
Urosolenia eriensis				20.0	
HAPTOPHYTA					
Chrysochromulina parva					340.0
DIVISION CRYPTOPHYTA					
Chroomonas coerulea					
Cryptomonas borealis			2.4		3.6
Cryptomonas curvata					0.2
Cryptomonas erosa					
Cryptomonas marsonii					0.2
Kathablepharis ovalis					
Komma caudata			230.0		440.0
Plagioselmis nannoplanctica					
DIVISION DINOPHYTA					
Ceratium hirundinella			0.6	0.6	0.2
Gymnodinium fuscum				2.4	0.4
Woloszynskia coronata					
DIVISION EUGLENOPHYTA					
Colacium vesiculosum fo. *cyclopicola*			0.4		
Phacus longicauda					

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam
Site Code	GEOSMIN	R30	R30	R30	R30
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct
Depth		1M	1M	1M	1M
PRASINOPHYTA					
Scourfieldia sp.					
DIVISION CHLOROPHYTA (green algae)					
Ankistrodesmus falcatus					
Ankyra judayi			10.0		60.0
Botryococcus braunii			1.6		
Chlamydomonas sp.					20.0
Chlorella minutissima		2,625	875	3,500	23,750
Closterium macilentum var. *substriatum*					
Closterium moniliferum					
Coelastrum microporum					
Coenochloris fottii			3.2	0.8	5.2
Cosmarium candianum var. *candianum* f. *minutum*					
Cosmarium contractum			0.6	0.4	1.2
Cosmarium orthostichum var. *orthostichum* f. *orthostichum*					
Cosmarium orthostichum var. *pumilum*					
Cosmarium phaseolus var. *phaseolus* f. *minus*					
Crucigenia tetrapedia					
Elakatothrix gelatinosa					
Elakatothrix viridis					
Eremosphaera gigas					
Eudorina elegans					
Heimansia pusilla					
Keratococcus sp.			2.0		
Kirchneriella obesa					
Lagerheimia genevensis					
Monoraphidium contortum					
Monoraphidium sp.					
Mougeotia sp.					
Oedogonium sp.					
Oocystis apiculata		20.0	0.4		0.8
Oocystis borgei					
Oocystis parva					
Oocystis pusilla					
Pandorina smithii			6.8		

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam	Dixon Canyon Dam
Site Code	GEOSMIN	R30	R30	R30	R30
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct
Depth		1M	1M	1M	1M
Pediastrum boryanum					
Pseudodicytosphaerium elegans					
Pseudodicytosphaerium sp.				500.0	1000.0
Scenedesmus arcuatus var. *gracilis*					
Scenedesmus bicaudatus					
Scenedesmus communis					
Scenedesmus obliquus					
Spirogyra sp.					
Spondylosium planum					
Staurastrum boreale					
Staurastrum hexacerum					
Staurastrum lapponicum					
Staurastrum lunatum var. *planctonicum*					
Staurastrum planctonicum		0.6			
Staurodesmus mucronatus					0.4
Staurodesmus orientalis					
Staurodesmus sp.					
Stichococcus subtilis					
Volvox tertius					
TOTAL DENSITY (cells/mL)		**8,214**	**10,902**	**10,266**	**31,313**

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam
Site Code	GEOSMIN	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
DIVISION CYANOPHYTA (blue-green algae)																
Anabaena lemmermannii	*yes*			775.2												
Anabaena planctonica	*?*															
Anabaena sp.	*yes*															
Aphanizomenon gracile	*yes*															
Aphanocapsa delicatissima					1,000						80.0	2000.0	72.0	51.5	700.0	80.0
Aphanocapsa incerta					120.0	62.0			540.0							
Aphanothece clathrata																
Aphanothece smithii		13,500	1,580	2,875	11,625	10,125	320	2,266	2,112	3,605	1,133	5,000	6,750	4,893	1,030	2,318
Cyanobium sp.						1,250	51.5	309.0	154.5	25.8						
Cyanodictyon planctonicum				250.0	148.0			783.0			20.4					
Dactylococcopsis sp.				20.0				9.0	9.0		9.0				9.0	
Geitlerinema sp.								1.0								
Merismopedia sp.																
Merismopedia tenuissima			8,875					412.0								54.0
Planktolyngbya limnetica																
Planktothrix agardhii	*yes*							1.8								
Pseudanabaena limnetica	*?*															10.8
Rhabdogloea scenedesmoides				40.0	120.0	60.0	80.0	108.0								
Synechococcus capitatus	*?*				375.0	1,250	500.0	154.5	495.0		117.0	240.0	125.0	154.5	51.5	9.0
Synechococcus sp.	*yes*							27.0	9.0	309						
Synechocystis sp.																
Woronichinia karelica																
DIVISION CHRYSOPHYTA (golden-brown algae)																
Bicosoeca sp.								4.5						9.0		
Chromulina sp.				12.5		250.0	25.8	51.5								
Chrysococcus minutus																
Dinobryon cylindricum var. *alpinum*																
Dinobryon divergens		8.0	4.0													
Mallomonas akrokomos					0.4	0.4	0.2	2.0			63	40.0	20.0		54.0	18.0
Ochromonas sp.																
Synura petersenii			8.4													
DIVISION XANTHOPHYTA																
Gloeobotrys limneticus							0.4									
Merismogloea polychloris																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam
Site Code	GEOSMIN	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
DIVISION BACILLARIOPHYTA (diatoms)																
Achnanthidium deflexum																
Asterionella formosa		41.6	1.6		104.0	132.8	96.0	96.0	66.4	4.0	140.4	274.4	292.0	734.8	101.2	250.6
Aulacoseira ambigua						12.8					159.4	149.6	154.4	96.8	39.2	235.8
Aulacoseira granulata var. *angustissima*											3.6					
Aulacoseira italica					8.8		2.4	10.6	16.4		10.6					
Aulacoseira italica var. *tenuissima*					7.2	17.6	13.6	14.8	13.6							
Cyclostephanos sp.							2.0									
Cyclotella distinguenda																
Cymbella mexicana																
Cymbella subturgidula																
Diatoma anceps																
Diatoma tenuis																
Discostella pseudostelligera																
Encyonema latens																
Encyonema minutum																
Encyonema silesiacum																
Fragilaria crotonensis			8.0	0.4	3.2	53.6	7.2	4.4	14.0	0.6		8.8	36.4		0.4	39.0
Fragilaria vaucheriae																
Hannaea arcus																
Melosira varians																
Navicula caterva																
Navicula cryptotenella																
Navicula sp.																
Navicula tripunctata																
Nitzschia archibaldii																
Nitzschia dissipata																
Nitzschia draveillensis													0.2		0.2	
Nitzschia fonticola																
Nitzschia gracilis																
Nitzschia linearis																
Nitzschia sp.																
Puncticulata bodanica		70.8	140.0	0.4	0.8	0.8	0.4	0.1	0.4	0.2		0.8			0.4	0.2
Staurosira construens																
Staurosirella pinnata																
Stephanodiscus niagarae					1.6	0.8	0.4	0.8	0.2	0.1	1.4	5.2	7.2	6.2	4.8	4.0
Stephanodiscus parvus																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam
Site Code	GEOSMIN	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
Stephanodiscus sp.																
Synedra cyclopum		0.4	0.2												0.2	
Synedra delicatissima var. *angustissima*																
Synedra rumpens var. *familiaris*				12.0											0.6	
Synedra rumpens var. *fragilarioides*				1.6	0.4	0.4	0.4	0.2	0.2							
Synedra rumpens																
Synedra ulna var. *chaseana*																
Synedra ulna var. *contracta*																
Synedra ulna var. *danica*																
Synedra ulna var. *subaequalis*																
Synedra ulna																
Tabellaria fenestrata		5.2	1.2													
Tabellaria flocculosa																
Urosolenia eriensis				10.0		40.0										
HAPTOPHYTA																
Chrysochromulina parva					140.0	300.0	320.0	495.0	423.0	9.0	72.0	40.0	20.0	360.0	180.0	198.0
DIVISION CRYPTOPHYTA																
Chroomonas coerulea			10.0											0.2		
Cryptomonas borealis			3.6		10.0	4.0	2.2	1.6	0.6		7.6	11.6	12.0	1.4	6.0	0.2
Cryptomonas curvata									0.2		2.0	8.4	5.2	0.6	3.0	
Cryptomonas erosa																
Cryptomonas marsonii					1.2	0.4	0.2						0.8			
Kathablepharis ovalis						20.0										
Komma caudata			120.0	20.0	520.0	560.0	300.0	378.0	270.0		486.0	200.0	380.0	36.0	360.0	36.0
Plagioselmis nannoplanctica			10.0		140.0	120.0	10.0	4.5	9.0		90.0	40.0	40.0	18.0	18.0	
DIVISION DINOPHYTA																
Ceratium hirundinella			0.2	2.8	0.4			0.1	0.1				0.2			
Gymnodinium fuscum				1.2	0.2					0.3	0.1	0.2	0.2	0.1	0.1	
Woloszynskia coronata										0.3						
DIVISION EUGLENOPHYTA																
Colacium vesiculosum fo. *cyclopicola*																
Phacus longicauda																

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam
Site Code	GEOSMIN	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
PRASINOPHYTA																
Scourfieldia sp.						10.0										
DIVISION CHLOROPHYTA (green algae)																
Ankistrodesmus falcatus																
Ankyra judayi			30.0		20.0	100.0	60.0	45.0	27.0		9.0	20.0	20.0	27.0	36.0	
Botryococcus braunii			3.6					4.2								
Chlamydomonas sp.																
Chlorella minutissima		2,250	625	1,875	11,125	25,125	20,875	12,566	9,785	206	1,751	8,750	10,500	2,987	2,833	1,288
Closterium macilentum var. *substriatum*																
Closterium moniliferum																
Coelastrum microporum																
Coenochloris fottii		3.2	1.6			8.0	3.6									
Cosmarium candianum var. *candianum* f. *minutum*																
Cosmarium contractum			10.0		0.4		0.8	0.4								
Cosmarium orthostichum var. *orthostichum* f. *orthostichum*																
Cosmarium orthostichum var. *pumilum*																
Cosmarium phaseolus var. *phaseolus* f. *minus*																
Crucigenia tetrapedia						16.0										
Elakatothrix gelatinosa																
Elakatothrix viridis						4.0	2.6		1.6							
Eremosphaera gigas																
Eudorina elegans			10.0													
Heimansia pusilla																
Keratococcus sp.																
Kirchneriella obesa																
Lagerheimia genevensis																
Monoraphidium contortum																
Monoraphidium sp.					0.8											
Mougeotia sp.																
Oedogonium sp.																
Oocystis apiculata		1.6									1.2				0.2	
Oocystis borgei																
Oocystis parva																
Oocystis pusilla						80.0				4.5						
Pandorina smithii			5.0													

City of Fort Collins Watershed Program
2009 Horsetooth Reservoir Phytoplankton Data (cells/mL)

Site Name	POSSIBLE	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam	Soldier Canyon Dam
Site Code	GEOSMIN	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40	R40
Sample Date	PRODUCER?	29-Jun	3-Aug	8-Sep	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	5-Oct	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov	2-Nov
Depth		1M	1M	1M	1M	5M	10M	15M	20M	25M	1M	5M	10M	15M	20M	25M
Pediastrum boryanum														2.8		
Pseudodicytosphaerium elegans																
Pseudodicytosphaerium sp.			120.0		80.0	380.0	1000.0	103.0			594.0	120.0	320.0	252.0	1030.0	207.0
Scenedesmus arcuatus var. *gracilis*																
Scenedesmus bicaudatus																
Scenedesmus communis																
Scenedesmus obliquus																
Spirogyra sp.																
Spondylosium planum																
Staurastrum boreale																
Staurastrum hexacerum																
Staurastrum lapponicum																
Staurastrum lunatum var. *planctonicum*																
Staurastrum planctonicum		0.8														
Staurodesmus mucronatus							0.6	0.2	0.1						0.2	
Staurodesmus orientalis									0.1							
Staurodesmus sp.																
Stichococcus subtilis																
Volvox tertius																
TOTAL DENSITY (cells/mL)		**15,882**	**11,567**	**5,896**	**25,552**	**39,984**	**23,675**	**17,854**	**13,947**	**4,165**	**4,751**	**16,909**	**18,756**	**9,630**	**6,458**	**4,748**

APPENDIX B

FCU HORSETOOTH RESERVOIR WATER QUALITY MONITORING PROGRAM

2010 Geosmin Paper

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).

Monitoring to Determine Geosmin Sources and Concentrations in a Northern Colorado Reservoir

Judith A. Billica, Jill Oropeza, G. Keith Elmund

City of Fort Collins Utilities, Fort Collins, Colorado, United States

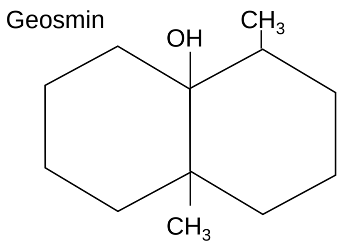
ABSTRACT

Geosmin is a naturally occurring organic compound produced by some species of cyanobacteria and actinomycetes that imparts an earthy odor to water when present at extremely low concentrations (<5 nanograms/L). In October 2008, a significant geosmin outbreak occurred in Horsetooth Reservoir, a reservoir that supplies water to northern Colorado communities served by three drinking water treatment plants, including the City of Fort Collins Water Treatment Facility (FCWTF). A geosmin outbreak in raw drinking water supplies presents special challenges for traditional water quality monitoring programs because the sources and events leading up to an outbreak are not well understood or easily monitored. The City of Fort Collins initiated geosmin monitoring within Horsetooth Reservoir and upstream components of the Colorado-Big Thompson (CBT) Project in direct response to the 2008 outbreak. This paper outlines the geosmin monitoring program used by the FCWTF and highlights some of the key findings to date and factors that affect the success of the program. The reconnaissance monitoring conducted in 2008 revealed high geosmin concentrations throughout Horsetooth Reservoir, but geosmin production sites could not be determined. The expanded monitoring program in 2009 showed significant spatial and temporal variation in geosmin concentrations in the reservoir and in the upstream components of the CBT Project. The data suggest a very complex system with respect to geosmin, and varying levels of geosmin production, transport, and degradation throughout the system. Many questions remain and it is expected that several years of monitoring will be required to fully understand geosmin sources, transport, and fate, and to identify geosmin occurrence patterns.

BACKGROUND

In October 2008, a significant geosmin outbreak occurred in Horsetooth Reservoir, a reservoir that supplies water to northern Colorado Front Range communities served by three drinking water treatment plants, including the City of Fort Collins Water Treatment Facility (FCWTF). The event produced a record high geosmin concentration of 25 nanograms per liter (ng/L) at the FCWTF raw water supply intake. Customer complaints increased and the FCWTF responded by adjusting their treatment process for taste and odor control (including changing the raw water blend and feeding powdered activated carbon) and by initiating a monitoring program for Horsetooth Reservoir to determine the spatial distribution of high geosmin concentrations.

Geosmin is one of the most common, naturally occurring, taste and odor (T&O) producing organic compounds found in drinking water supplies. It imparts an earthy odor to water that can be detected by the most sensitive people when present at extremely low concentrations (<5 ng/L, or <5 parts per trillion (ppt)). The City of Fort Collins Utilities can expect “earthy” odor complaints if geosmin levels are above 4.0 ng/L in its finished water. Geosmin is produced by some species of cyanobacteria (blue-green algae) and actinomycetes (a filamentous bacteria). It is released after cell lysis and death and, depending on the species, it may also be actively excreted by healthy cells into the water column (e.g., Graham et al, 2008).



Geosmin does not pose a public health risk, but its detectible presence in treated drinking water can cause serious concerns in the eyes of the public about the aesthetic quality of the water supply. Utilities around the country receive high numbers of customer complaints whenever a geosmin outbreak occurs in their water supply. Geosmin is one of the most difficult T&O compounds to remove during water treatment.

The Fort Collins Utilities has a long-term water quality monitoring program for Horsetooth Reservoir. In most water quality monitoring programs, including the Fort Collins program, geosmin is not a routine monitoring parameter. Recent publications (i.e., Taylor et al, 2006; Juttner and Watson, 2007; Graham et al, 2008) provide guidance for the design of reservoir monitoring programs to assess the spatial and temporal occurrence of geosmin produced by cyanobacteria. Studies conducted on U.S. reservoirs provide further guidance on monitoring approaches and data analysis tools related to understanding and predicting geosmin outbreaks (Christensen et al, 2006; Journey and Abrahamsen, 2008; Pan et al, 2002; Smith et al, 2002).

Juttner and Watson (2007) suggest that three zones in lakes should be investigated as possible sources of geosmin: 1) the epilimnetic water and associated plankton; 2) the hypolimnetic water (oxic or anoxic), and 3) the benthic littoral zone (i.e., shallow, near shore bottom regions). Taylor et al (2006) emphasize that geosmin producing species are frequently hard-to-find minor components of the aquatic community and, therefore, geosmin will usually be detected analytically before a T&O producer will be observed microscopically. Geosmin production is often strain specific, and phytoplankton data showing the occurrence of known geosmin producing cyanobacteria species or genera does not prove causation. Dissolved geosmin is relatively stable to chemical and biological degradation and can persist for significant periods of time depending on environmental conditions (water temperature, oxygen levels, etc); this must be considered when trying to understand and track the distribution, transport, and fate of geosmin in aquatic systems (Juttner and Watson, 2007).

SITE DESCRIPTION

Horsetooth Reservoir (elevation 5430 ft, length 6.7 miles, width 0.9 miles) is located directly west of the City of Fort Collins, Colorado. At maximum capacity, Horsetooth Reservoir has a storage volume of 156,735 acre-feet, a mean depth of approximately 80 feet (24 m), and a maximum depth of 188 feet (57 m). The reservoir was created by the construction of four dams in the 1940's by the U.S. Bureau of Reclamation as part of the Colorado-Big Thompson (CBT) Project. The CBT Project is operated and maintained by the Northern Colorado Water Conservancy District. Horsetooth Reservoir is a terminal reservoir on the CBT Project and stores water prior to being released for municipal, industrial, and agricultural uses. The hydraulic residence time of Horsetooth Reservoir is generally in the range of 1 to 1.5 years, depending on reservoir operations.

The CBT Project transports water from the upper Colorado River on the west slope of the continental divide to the east slope of the continental divide (Figure 1) through a series of reservoirs, canals, and pipelines. The CBT Project watershed area covers over 1,000 square miles compared to the natural local Horsetooth Reservoir watershed area of approximately 17 square miles. The CBT Project watershed area is primarily forested and includes national forest lands, Rocky Mountain National Park, and the towns of Winter Park, Granby, and Estes Park.

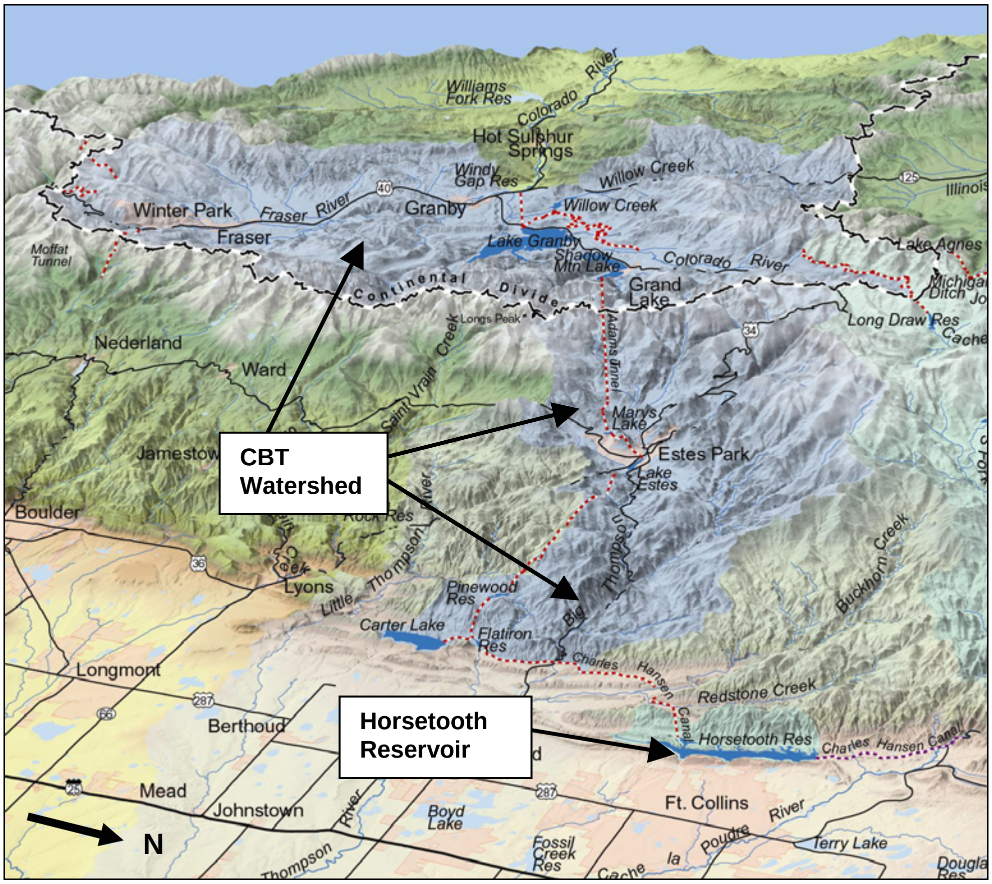


Figure 1. Horsetooth Reservoir and the Colorado-Big Thompson (CBT) Project watershed.

Water enters Horsetooth Reservoir at its south end via the CBT Project Charles Hansen Feeder Canal. Water entering Horsetooth via this canal is a mixture of water from the east slope Big Thompson River and water from the Colorado River headwaters (and associated reservoirs) that is transported through the continental divide via the Adams Tunnel. The travel time from the west portal of the Adams Tunnel to the inlet of Horsetooth Reservoir is on the order of about one week, depending on flow rates.

The Fort Collins Utilities long-term water quality monitoring program has provided information on the general limnological characteristics of Horsetooth Reservoir. Chlorophyll-a, total phosphorus, and Secchi disk transparency data all indicate that the tropic status of the reservoir is generally in the mesotrophic range. Horsetooth Reservoir is a dimictic reservoir, characterized by two mixing periods each year – one in the spring and one in the fall. Thermal stratification develops in the spring and strengthens throughout the summer and into the fall. Fall turnover occurs in October or November. However, due to the presence of pools behind each of the dams, the reservoir does not uniformly mix at the same time. During the period of thermal stratification, water entering the reservoir from the Hansen Feeder Canal is generally of a colder temperature than the epilimnion. As a result, a density current forms and temperature and specific conductance data indicate that an interflow exists within the metalimnion.

Horsetooth Reservoir Operations. Water quality in Horsetooth Reservoir is impacted by CBT system operation due to its influence on reservoir hydraulic residence times, water levels, and influent flow rates. The primary in-flow to Horsetooth Reservoir is the CBT Project Charles Hansen Feeder Canal. There are two outlets from Horsetooth Reservoir: the Charles Hansen Supply Canal at Horsetooth Dam, and the Soldier Canyon Dam Outlet. The Soldier Canyon Dam outlet structure is located near the bottom of the reservoir and provides a continuous (year round) supply of raw water to the FCWTF.

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 Outlet and to the Hansen Supply Canal. Water levels are lowest in the late fall after the end of the irrigation season and rise over the winter during the reservoir filling period. The annual drop in Horsetooth Reservoir water level results in large areas of exposed sediments. The sediments of rivers, lakes, and reservoirs have been reported as potential sites of geosmin production by actinomycetes (Wood et al, 1983). Although actinomycetes may be found in large numbers in sediments covered by water, they are likely relatively inactive in that environment due to the lack of oxygen. The aerobic conditions required for the production of geosmin prevail only when the sediment is exposed and dried during a drop in the water level (Wood et al, 1983). The sediments could then become a source of geosmin, particularly when the water level rises or fluctuates. In Horsetooth Reservoir, it is possible that geosmin is produced within the exposed sediments as the water level drops, and then subsequently enters the reservoir as the water level rises. No actinomycetes data have been collected for Horsetooth Reservoir sediments. However, water levels in Horsetooth Reservoir begin rising each fall *after* the on-set of seasonal taste and odor events, so it could be concluded that actinomycetes present in the sediments are likely not a significant source of geosmin.

GEOSMIN MONITORING PROGRAM

Geosmin monitoring within Horsetooth Reservoir began in Fall 2008 in direct response to the record high geosmin levels measured at the FCWTF intake. The initial monitoring program was a reconnaissance study to evaluate spatial distributions and concentrations of geosmin within the reservoir. Because the 2008 sampling plan was initiated after the on-set of the geosmin episode, sampling did not provide data to address the location of production sites and fate of this compound. In 2009, sampling efforts were expanded to meet the following long-term objectives:

- Provide for a better understanding of the spatial and temporal distributions, concentrations, and potential production sites of geosmin within the reservoir and the canal inflow, considering the impacts of reservoir stratification, interflow, and CBT system operations.
- Improve early-warning capabilities by sampling earlier, more often, and at more key sites within the CBT system.

- Evaluate the physical, chemical, and biological factors affecting geosmin occurrence, transport, and fate in Horsetooth Reservoir.

Since cyanobacteria are considered to be the chief source of geosmin in aquatic systems where photosynthetic growth is possible (Juttner and Watson, 2007), the monitoring program currently assumes that the geosmin detected in Horsetooth Reservoir and the upstream components of the CBT system is due to the presence of cyanobacteria (phytoplankton and/or periphyton). However, this working hypothesis will be re-evaluated as data collection and analysis progresses over time.

Sampling Locations. The geosmin sampling locations are established sampling sites in long-term water quality monitoring programs conducted by the City of Fort Collins, the Big Thompson Watershed Forum, the Northern Colorado Water Conservancy District, and/or the U.S. Geological Survey. The geosmin sampling locations (Figure 2) include four sites within Horsetooth Reservoir (R20, R21, R30, and R40), three sites along the 13 mile length of the Hansen Feeder Canal (C30, C40, and C50), one site at the east portal of the Adams Tunnel (C10), and one site on the Big Thompson River (M70) where diversions from the river to the Hansen Feeder Canal can occur. Geosmin samples are also collected of raw Horsetooth Reservoir water at the FCWTF. The intake is located at the bottom of Horsetooth Reservoir at Soldier Canyon Dam (R40) so samples of raw Horsetooth Reservoir water at the FCWTF are representative of hypolimnetic conditions at Soldier Canyon Dam.

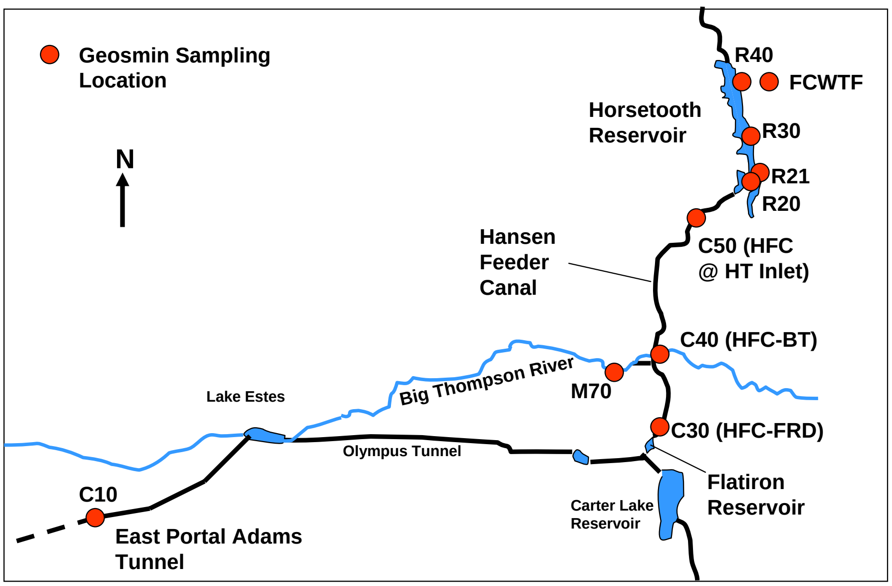
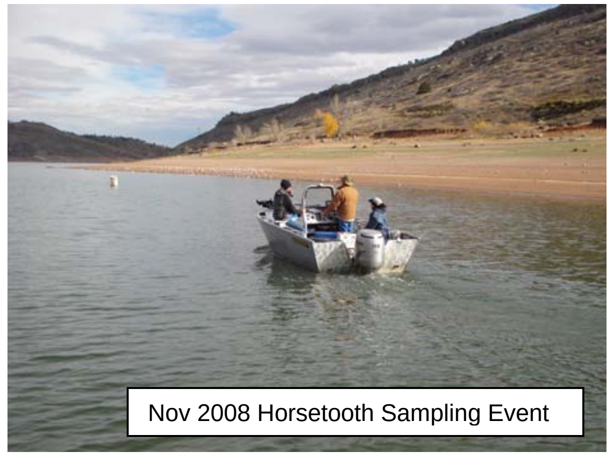


Figure 2. Geosmin Monitoring Program Sampling Locations.

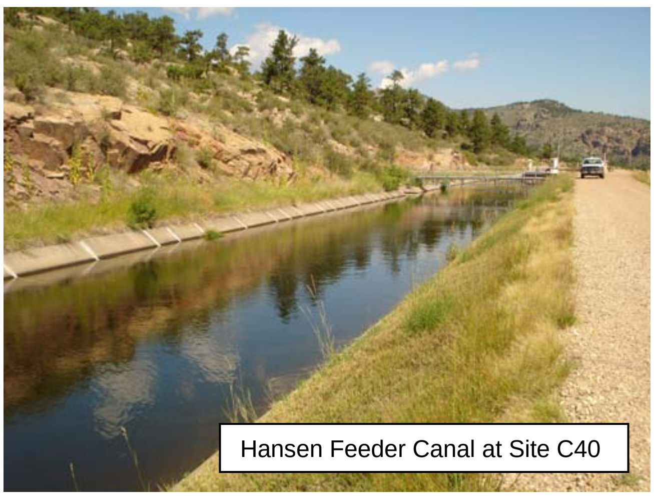
Field sampling methods. All geosmin samples were collected by City of Fort Collins Utilities staff. The reservoir sample sites were accessed using the City of Fort Collins sampling boat. All reservoir samples were discrete depth grab samples collected using a Van Dorn sampler. Each collected sample was immediately transferred to an amber glass bottle and placed on ice in sample coolers. Reservoir water column grab samples were generally collected at two depths: a near surface sample at a depth of 1 meter, and a bottom sample at 1 meter above the reservoir bottom. Because data analysis indicated the occurrence of interflow from the Hansen Feeder

Canal, grab samples were also collected from the metalimnion as the 2009 sampling season progressed. The canal, river, and Adams Tunnel grab samples were collected from the center of the main flow with sampling aided by the use of a telescopic pole. The sample volume collected in the bottle attached to the pole was immediately transferred to an amber glass bottle and placed on ice in sample coolers.



Nov 2008 Horsetooth Sampling Event

Geosmin Sampling Frequency. Reservoir geosmin sampling began in Fall 2008 with one sampling event in November and one in December; the 2008 sampling did not include the sites upstream of Horsetooth Reservoir. In 2009, the geosmin monitoring program was expanded to improve early-warning capabilities by sampling earlier, more often, and at more locations. The 2009 sampling frequency was reviewed and modified as the season progressed based on the results of the most recent sampling event. Both the sampling locations and frequencies had to be carefully optimized such that program objectives could be met within reasonable budget and time constraints.



Hansen Feeder Canal at Site C40

Horsetooth Reservoir geosmin sampling in 2009 was conducted twice in August, twice in September, once in October, and once in November. Sampling of the sites upstream of Horsetooth Reservoir was conducted beginning in August 2009, and conducted twice a month in August through November. Sampling of raw Horsetooth Reservoir water at the FCWTF (representative of conditions in the hypolimnion at Soldier Canyon Dam R40) was conducted once a week. This is the water that the treatment plant operators must respond to and treat to meet regulatory requirements and customer expectations for aesthetically pleasing water.

Geosmin Analysis. Geosmin occurs in surface waters as cellular (cell-bound) and dissolved fractions (Juttner and Watson, 2007). For the Fort Collins monitoring program, samples are not filtered prior to analysis so analysis is conducted for total concentrations. However, protein-bound geosmin may be underestimated using current extraction techniques (Juttner and Watson, 2007). Geosmin analysis is conducted by the City of Fort Collins Water Quality Laboratory using solid phase microextraction as per Standard Method 6040D (2005), and gas chromatography/mass spectrometry. Geosmin data are generally available within two days of sample collection. The high quality data, short turn-around times, and scheduling flexibility provided by the Fort Collins Water Quality Laboratory are key elements to the success of the Fort Collins geosmin monitoring program.

Routine sampling program. The reservoir geosmin samples were generally collected at the same time that the routine samples were collected. Data collected as part of the routine Horsetooth Reservoir monitoring program include Secchi depth, profiles for temperature, dissolved oxygen, and specific conductance, and water column discrete depth and composite samples for nutrients, chlorophyll-a, phytoplankton, total organic carbon, major ions, and metals. The field and laboratory methods for the routine monitoring program are outlined in Billica and Oropeza (2009). Data collected as part of the routine monitoring program provide for the evaluation of the physical, chemical, and biological factors affecting geosmin.

Phytoplankton analysis. As part of the routine Fort Collins program, samples are collected for phytoplankton enumeration (cells/mL) and identification within Horsetooth Reservoir (at a depth of one meter) and at the Hansen Feeder Canal at the inlet to Horsetooth Reservoir (C50). The routine monitoring program has historically included phytoplankton identification and enumeration to the *genus* level. However, since geosmin production is species (and sometimes strain) specific (Juttner and Watson, 2007; Taylor et al, 2006), the routine monitoring program was modified in 2009 to conduct phytoplankton enumeration and identification to the *species* level (when possible). Speciation was conducted by Richard Dufford (private consultant in Fort Collins) as outlined in Billica and Oropeza (2009).

RESULTS

Geosmin Data at the FCWTF. A plot of geosmin data for Horsetooth Reservoir samples collected at the FCWTF raw water sample tap is shown on Figure 3 for the period of record (October 2003 to December 2010). The FCWTF customer odor threshold for geosmin (4 ng/L) was exceeded in raw Horsetooth Reservoir water at the FCWTF in Oct-Nov 2003, Nov-Dec 2005, Oct 2006-Jan 2007, Oct-Dec 2007, and Oct 2008-March 2009. Although the data indicate the presence of recurring seasonal geosmin episodes, it wasn't until 2008, when the record high geosmin concentration of nearly 25 ng/L was measured in raw Horsetooth Reservoir water at the FCWTF, that the Fort Collins Utilities initiated their geosmin sampling program within the reservoir.

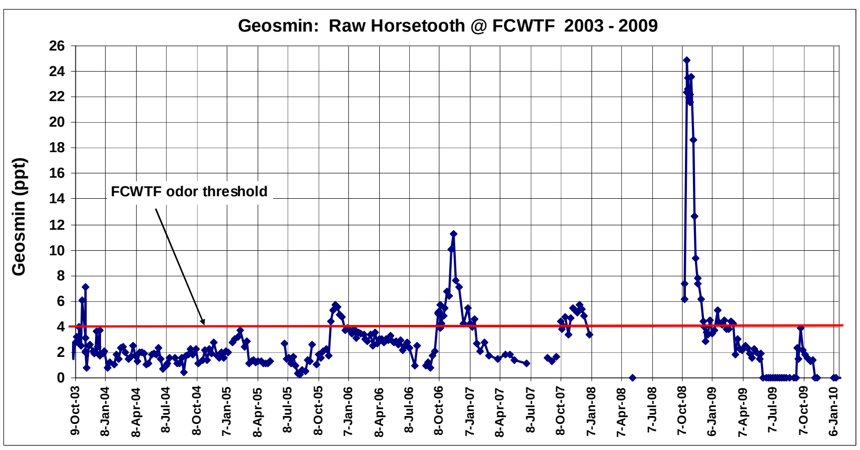


Figure 3. Horsetooth Reservoir geosmin concentrations at the FCWTF raw water intake.

2008 Horsetooth Reservoir Geosmin Data. Geosmin concentrations measured in samples collected within Horsetooth Reservoir are plotted on Figure 4. The geosmin concentrations in the November 4, 2008 Horsetooth Reservoir samples were the highest on record. The peak concentration was 53 ng/L, collected at 1 meter below surface in the pool at Spring Canyon Dam (R21). The samples collected on Nov. 4, 2008 do not show a clear geosmin gradient from upstream (R20, Inlet Bay Marina) to downstream (R40, Soldier Canyon Dam) in the top and bottom samples (Figure 4). However, the samples collected on Dec. 2, 2008 do show a gradient with the highest concentrations at the upstream (R20) end of the reservoir and the lowest concentrations at the downstream (R40) end of the reservoir.

A. TOP SAMPLES

B. BOTTOM SAMPLES

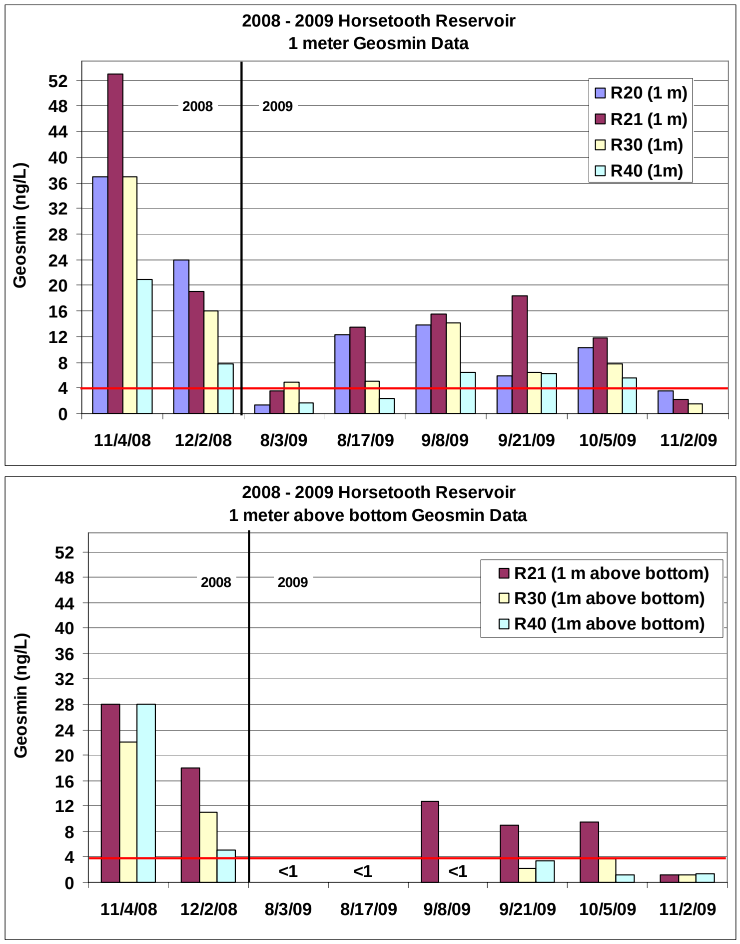


Figure 4. Geosmin concentrations measured within Horsetooth Reservoir in 2008 and 2009 at: A) a depth of a meter below the surface, and B) a depth of 1 meter above the reservoir bottom.

The pools at Spring Canyon and Dixon Canyon Dams were still weakly stratified on the Nov. 4, 2008 sampling date, resulting in significantly different top and bottom geosmin concentrations. By the December 2008 sampling date, the reservoir was completely mixed. The bottom geosmin concentrations (at depths of 32 m to 35 m) measured on Nov. 4, 2008 were all surprisingly high. High geosmin concentrations at the bottom of the reservoir prior to turnover is likely due to the settling of organic particulate matter that contains cell-bound geosmin (Juttner and Watson, 2007). Microbial digestion of this settled organic particulate matter in the hypolimnion results in the transfer of cell-bound geosmin into dissolved geosmin.

2009 Horsetooth Reservoir Geosmin Data. In 2009, the geosmin sampling season was begun early enough to follow the progression of increasing geosmin concentrations at various locations within the reservoir. The peak 2009 geosmin concentration of 18.4 ng/L, measured on 9/21 in the surface sample from Spring Canyon (R21), was significantly less than the 2008 peak

(Figure 4). The highest geosmin concentrations were measured at Spring Canyon (R21) top and bottom throughout the 2009 sampling season. Geosmin concentrations at the reservoir bottom at Spring Canyon (at depths of 35 to 40 meters) were also relatively high. During 2009, it was particularly revealing to observe that low concentrations can exist throughout the season at the FCWTF intake (all values were < 4 ng/L) while potentially problematic concentrations developed at various locations within the reservoir. Geosmin concentrations measured at the FCWTF intake are not representative of concentrations found within the reservoir.

2009 CBT System Geosmin Data. Geosmin concentrations measured in CBT Project components upstream of Horsetooth Reservoir are plotted on Figure 5. Geosmin concentrations at the Horsetooth Inlet (C50) indicate that geosmin is transported to the reservoir from upstream sources. Potential upstream sources include phytoplankton in the west slope reservoirs, phytoplankton in Flatiron Reservoir, and periphyton in the Hanson Feeder Canal. Large blooms of cyanobacteria are known to be present at times in August and September in the west slope Grand Lake and Shadow Mountain Reservoir (Lieberman, 2008).

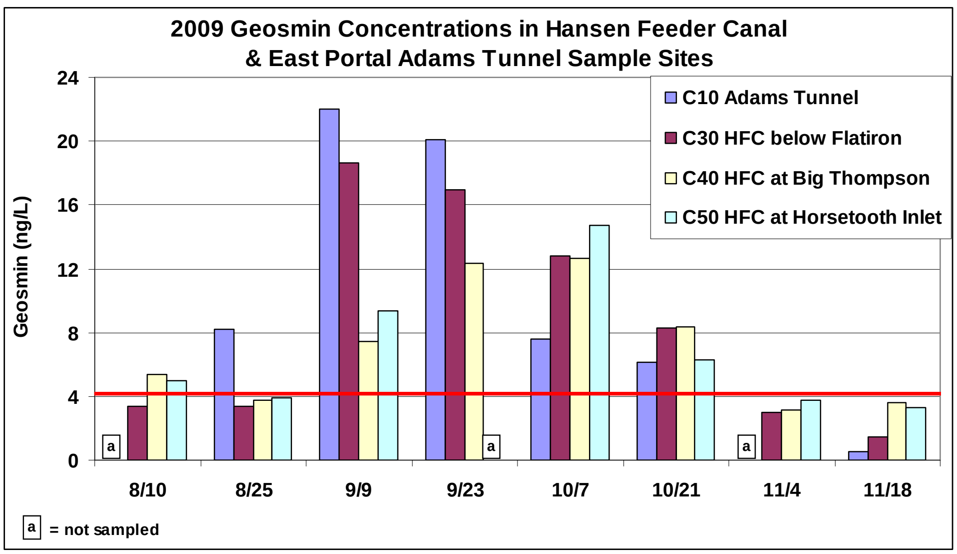


Figure 5. 2009 Geosmin concentrations in CBT Project components upstream of Horsetooth Reservoir.

The data plotted on Figure 5 suggest that at different times of the season, each of the possible geosmin sources may be more significant. Processes such as volatilization and biodegradation are also occurring at the same time and can cause net decreases in concentration from upstream sites to downstream sites. Finally, transport and fate is complicated by operation and maintenance of the various CBT Project components; in 2009 the Hansen Feeder Canal from C40 to C50 was off for maintenance from September 11 to 25, while flow through the Adams Tunnel was off or very low from August 13 to 26, and November 2 to 17. In addition to significant temporal variability, the monitoring program conducted to date has revealed wide spatial variability in geosmin concentrations as shown on Figure 6 for the September 8-9 sampling event.

Figure 7 compares geosmin concentrations in water flowing into Horsetooth Reservoir (C50) with reservoir water closest to the influent end (R20 Inlet Bay and R21 Spring Canyon). Concentrations at Inlet Bay (R20) and Spring Canyon (R21) are higher than the influent water

(C50) until early October. This indicates that at least a portion of the geosmin in Horsetooth Reservoir is being produced in Horsetooth Reservoir. Alternatively, cell-bound geosmin (not separately measured by the laboratory analysis) may be transported to Horsetooth Reservoir where it is subsequently released during microbial digestion. When the Hansen Feeder Canal was off (Sept. 11 to 25), the geosmin concentration at Inlet Bay decreased while the geosmin concentration at Spring Canyon increased. It is postulated that geosmin concentrations at the Inlet Bay are generally being sustained by the inflowing waters, and without that source, geosmin degradation exceeded geosmin production resulting in the drop in concentration. At Spring Canyon, geosmin production occurred independent of the inflow allowing geosmin concentrations to increase during this time.

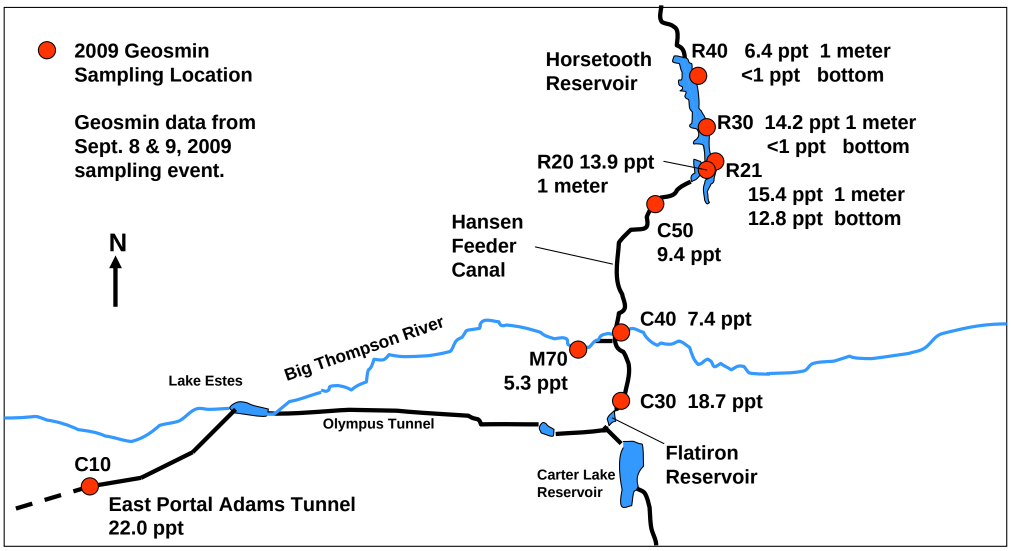


Figure 6. September 2009 geosmin concentrations in sampling sites upstream of Horsetooth Reservoir and sampling sites within Horsetooth Reservoir.

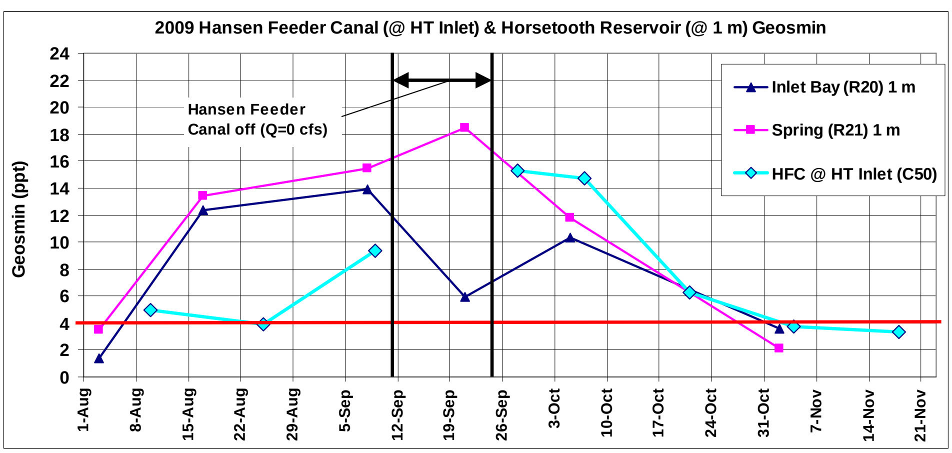


Figure 7. Comparison of geosmin inflow concentrations (C50) with concentrations at the upstream end of Horsetooth Reservoir.

Temperature data indicate that Hansen Feeder Canal water exists as an interflow in the metalimnion of Horsetooth Reservoir. Because of this, metalimnion samples were also collected for geosmin analysis beginning in late September. The reservoir geosmin data from the October 7 sampling event are shown on Figure 8. The geosmin concentrations within the bottom half of R20 (Inlet Bay) were higher than the surface due to the cold Hansen Feeder Canal water (with a geosmin concentration of 14.8 ng/L) plunging to the bottom of the relatively shallow (19 m) Inlet Bay. Some amount of mixing and entrainment of ambient Inlet Bay water into the Hansen Feeder Canal inlet water occurs when the canal water plunges below the surface of the reservoir. This results in intermediate geosmin concentrations and water temperatures at the bottom half the Inlet Bay water column (compared to those measured in the Hansen Feeder Canal and the top half of the Inlet Bay water column). It is postulated that this interflow continues moving through the reservoir metalimnion, with additional entrainment of ambient reservoir water causing the geosmin concentration in the metalimnion to decrease as the interflow proceeds downstream. Numerical modeling will be required to better understand the flow patterns in Horsetooth Reservoir and the impact of Hansen Feeder Canal interflow on geosmin transport.

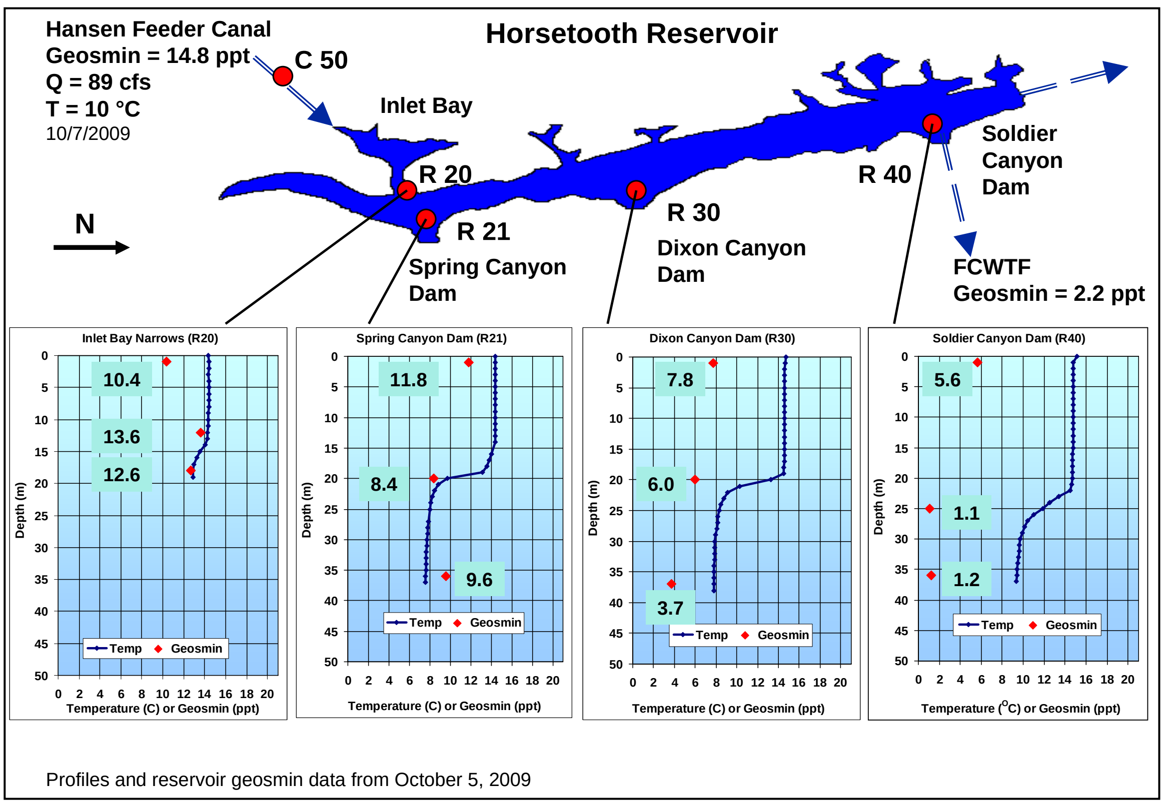


Figure 8. Temperature profiles and geosmin concentrations at sampling sites within Horsetooth Reservoir (collected October 5, 2009).

Chlorophyll-a and phytoplankton. Most monitoring programs attempt to establish correlations between geosmin concentrations and cyanobacteria densities and chlorophyll-a concentrations. In 2009, the total phytoplankton densities ranged from 4,201 to 39,348 cells per milliliter (cells/mL) in the 1 meter samples collected from Horsetooth Reservoir. The geosmin producing genera of cyanobacteria generally made up 5 percent or less of the total density. The most common cyanobacteria genera found in Horsetooth that include species of geosmin producers were *Anabaena* and *Synechococus*, with *Aphanizomenon* and *Pseudanabaena* making up very minor amounts of the total densities. *Synechococcus* are very small (bacterial dimensions) unicellular cyanobacteria that can be overlooked (Taylor et al 2006). Geosmin producing species identified in the 2009 samples include *Anabaena lemmermannii* and *Aphanizomenon gracile* (Juttner and Watson, 2007). The 2008 phytoplankton data indicated lower total densities within the reservoir, and lower densities of geosmin producing genera. Although the densities of potential geosmin producers was low in both years, it has been observed by others that the geosmin source may not be the predominant organism, but rather a minor or inconspicuous component (Taylor et al, 2006).

The 2008 and 2009 chlorophyll-a concentrations for the reservoir sites at a depth of one meter are summarized on Table 1. The data show that the August through November average chlorophyll-a concentrations in the reservoir in 2008 were higher than in 2009, indicating that conditions in the reservoir were different during the two years. However, observing this difference does not provide the necessary information to determine the cause(s) of the record setting high geosmin concentrations in 2008. The site with the highest 1 meter geosmin concentrations in both 2008 and 2009 - Spring Canyon (R21) - did not have the highest chlorophyll-a concentrations. Soldier Canyon (R40), which consistently had the lowest 1 meter geosmin concentrations in 2008 and 2009, had some of the higher chlorophyll-a concentrations in fall 2008 and 2009.

Table 1. Average of August through November chlorophyll-a data

Site	2008 Avg (ug/L)	2009 Avg (ug/L)
R20 Inlet Bay	3.6	2.2
R21 Spring Canyon Dam	2.9	2.2
R30 Dixon Canyon Dam	4.5	2.0
R40 Soldier Canyon Dam	4.2	2.6

Chlorophyll-a density is only a good predictor of geosmin if the geosmin-producing species make up a significant portion of the total algal biomass (Taylor et al, 2006). Since geosmin-producing genera were only minor contributors to the total phytoplankton density, the direct relationship between the 2008 and 2009 one-meter geosmin and chlorophyll-a data is poor as shown on Figure 9.

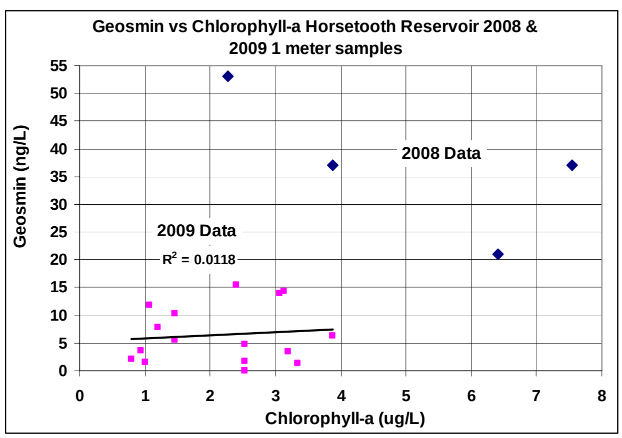


Figure 9. Geosmin versus chlorophyll-a (all Horsetooth Reservoir 2008-2009 1 meter samples).

Periphyton Data. Periphyton (attached algae) sampling was conducted in 2008 and 2009 by the Northern Colorado Water Conservancy District at the three locations on the Hansen Feeder Canal where geosmin sampling has been conducted (C30, C40, and C50 shown on Figure 2). One sample was collected at each site in each of the months of September 2008, June 2009, and August 2009. Algae speciation was conducted by Richard Dufford. The attached cyanobacteria

Phormidium autumnale made up 100 percent of the biomass at C30 (downstream of Flatiron Reservoir) in September 2008, and 45% of the biomass at C30 in August 2009. Attached cyanobacteria were not observed at the other two Hansen Feeder Canal locations. Several species of the genus *Phormidium* have been shown to produce geosmin. However, *Phormidium autumnale* has not been identified as a geosmin producer. Additional periphyton sampling will be required before it can be ruled out as a possible geosmin source.

FINDINGS AND CONCLUSIONS

A geosmin outbreak in raw drinking water supplies presents special challenges for traditional water quality monitoring programs because the sources and events leading up to an outbreak are not well understood or easily monitored. Without an adequate early warning system for geosmin in source waters, water treatment plant operators have little time to respond, resulting in an increase in customer T&O complaints and a negative perception of treated drinking water quality. And without an understanding of temporal and spatial variability, concentrations, production sites, transport, and fate of geosmin within source watersheds, watershed managers are unable to identify potential control strategies.

This paper outlined the geosmin monitoring program used by the FCWTF and highlights some of the key findings to date and factors that affect the success of the program. The reconnaissance monitoring conducted in 2008 revealed high geosmin concentrations throughout Horsetooth Reservoir, but geosmin production sites could not be determined. The expanded monitoring program in 2009 showed significant spatial and temporal variation in geosmin concentrations in the reservoir and in the upstream components of the CBT Project. The data suggest a very complex system with respect to geosmin. The watershed that makes up the study area is large and includes natural and constructed hydrologic features subject to biological, physical, and hydrodynamic processes and varying operational controls. The monitoring conducted to date indicates varying levels of geosmin production, transport, and degradation throughout the system.

Many questions remain and it is expected that several years of monitoring will be required to more fully understand geosmin sources, transport, and fate, and to identify geosmin occurrence patterns. Future monitoring will build upon the following findings of the geosmin monitoring program conducted to date:

- Significant spatial variation in geosmin concentrations exists within the reservoir and within upstream water bodies.
- Concentrations are highest in the epilimnion (as measured by the 1 meter samples).
- Significant geosmin concentrations can exist at the bottom of the reservoir even when the reservoir is stably stratified.
- Data suggest that geosmin is both transported into the reservoir via the Hansen Feeder Canal and produced within Horsetooth Reservoir
- Geosmin concentrations measured at the FCWTF intake are not representative of concentrations found within the reservoir.
- No correlation exists between geosmin concentrations and chlorophyll-a concentrations or the algal cell density of the potentially geosmin producing genera.

- More periphyton sampling of the canal will be required to evaluate the canal as a geosmin production site.
- A better understanding of geosmin transport and fate will require separate analysis of the dissolved and cell-bound fractions.
- Numerical modeling will be required to fully understand the flow patterns in Horsetooth Reservoir and the impact of Hansen Feeder Canal interflow on geosmin transport.

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