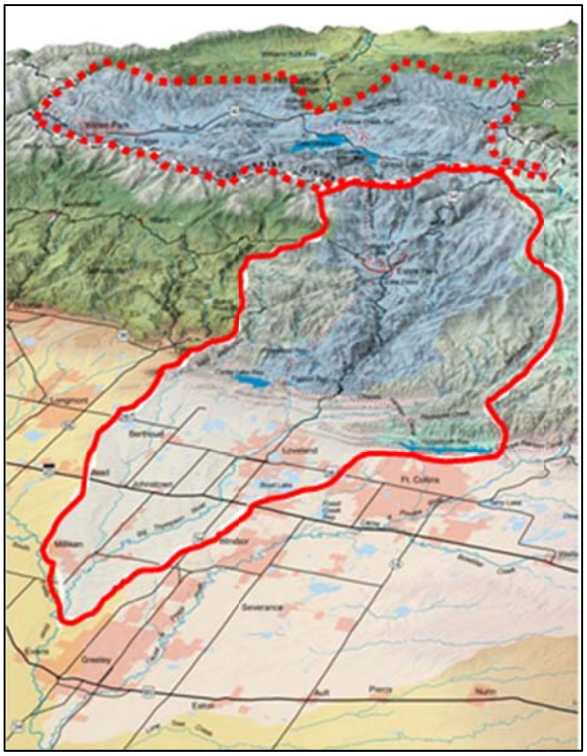
BIG THOMPSON STATE OF THE WATERSHED
2021 Final Report



Prepared for:

BIG THOMPSON
WATERSHED
FORUM

1044 West Drake Road, Suite 201
Fort Collins, CO 80526

Prepared by:

Christine Hawley and Nicolás Rodríguez-Jeangros

Hydros
Consulting
1628 Walnut St.
Boulder, CO 80302

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ACRONYMS AND ABBREVIATIONS

AF/yr	Acre-feet per year
As	Arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
C-BT	Colorado-Big Thompson
Ca	Calcium
CDOT	Colorado Department of Transportation
cfs	Cubic feet per second
COOP	Cooperative Sampling Program
Cu	Copper
CWCB	Colorado Water Conservation Board
DBP	Disinfection By-products
E. coli	Escherichia Coliforms
EPA	U.S. Environmental Protection Agency
Fe	Iron
HBND	High-biasing non-detect
Hg	Mercury
IQR	Inter-quartile range
JFA	Joint Funding Agreement
M&E	Monitoring and Evaluation
Mg	Magnesium
mg/L	Milligrams per liter
Mn	Manganese
NWCG	National Wildfire Coordinating Group
NWQL	National Water Quality Lab
ND	Non-detect
NH_3	Ammonia
NO_3	Nitrate
Se	Selenium
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TOC	Total Organic Carbon
TSS	Total Suspended Solids
ug/L	Micrograms per liter
USGS	U.S. Geological Survey
WQCC	Water Quality Control Commission
WWTF	Wastewater Treatment Facility
WWTP	Wastewater Treatment Plant
WY	Water Year
Zn	Zinc

ACKNOWLEDGEMENTS

Hydros Consulting would like to thank the Big Thompson Watershed Forum for the opportunity to develop this report, with specific thanks to Richard Thorp of the City of Fort Collins and Curtis Hartenstein of Northern Water for guidance throughout the scoping and development of the report. Additionally, we would like to thank Jen Stephenson of Northern Water and Kelly Close of Leonard Rice Engineers for their excellent efforts in developing and refining the database that provided the basis for this work. Overall, we commend the Forum and its members for their commitment to not only thoughtful data collection, but to the study of those data to inform management and protection of the watershed.

Cover Images:

Left: Relief Map showing the Big Thompson Watershed (outlined in red) and the West-Slope Watershed Joined to the Big Thompson through the Colorado Big-Thompson Project (Dashed Red Outline)

Top Right: Repairs to Highway 34 - Image shows crews conducting innovative soil-cement mixing as part of extensive post-flood repairs to Highway 34 from 2015-2018.

- Photo by Kiewit Infrastructure Company, as presented in Engineering News Record (https://www.enr.com/articles/46455-project-of-the-year-best-highwaybridge-us-34-permanent-repairs-project).

Bottom Right: Cameron Peak Fire, Image from August 13, 2020

- Photo credit: CBS (from: https://denver.cbslocal.com/2020/08/13/cameron-peak-fire-larimer-county-chambers-lake-evacuations/)

EXECUTIVE SUMMARY

This report presents the data analysis conducted to determine the current state of the watershed for the Big Thompson River and its tributaries. The assessment was sponsored by the Big Thompson Watershed Forum (the Forum), a nonprofit stakeholder organization founded in 1997 and dedicated to protecting and improving water quality in the Big Thompson watershed. This report meets the Forum's mission and program goals by summarizing current water-quality conditions, evaluating changes in water quality over time, and comparing Forum data to applicable Colorado water-quality standards.

Based on the analysis, the current state of the Big Thompson watershed varies spatially. The upper watershed is generally in good condition, though there is an imminent threat to water quality in both the upper and lower watersheds from the major fires in the fall of 2020. Conditions in the lower watershed are considered fair, with improving conditions on the mainstem but deteriorating conditions on the Little Thompson River.

ES-1. SITE DESCRIPTION

Colorado's Big Thompson watershed, located approximately 50 miles northwest of Denver, is a large, complex hydrologic system covering more than 900 square miles east of the Continental Divide. The watershed varies widely in terms of terrain and land use. The watershed is part of Colorado's largest trans-basin water diversion, the Colorado-Big Thompson (C-BT) Project. The C-BT project brings water from Grand Lake to the eastern slope through the Adams Tunnel to provide for a growing population on Colorado's Front Range. Figure ES-1 shows the Big Thompson River watershed (solid red outline) as well as the watershed on the west side of the Continental Divide feeding the Adams Tunnel (dashed red outline).

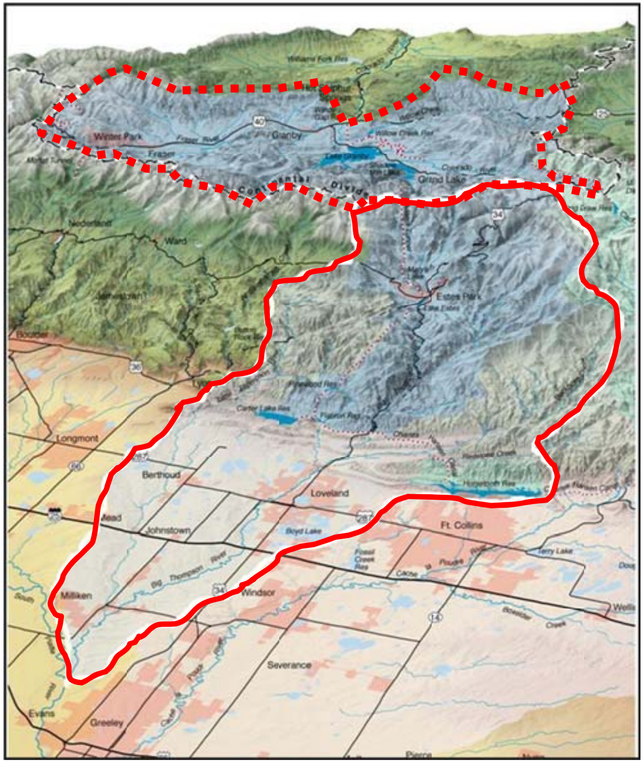

Figure ES-1. Big Thompson Watershed

Flow in much of the Big Thompson River is highly regulated and managed through numerous diversions, returns, and reservoirs. In addition to the water management effects, spatially-varying geology, land-use, and population density affect water quality in the Big Thompson watershed. The upper watershed, including the mountains and foothills, is generally characterized by granitic geology, forested land-use, and low population density. In contrast, the lower watershed, extending to the South Platte River, is characterized by increasing alluvial groundwater, sedimentary rock including Pierre shale, agricultural and urban land use (e.g., Figure ES-2), and increasing population density.

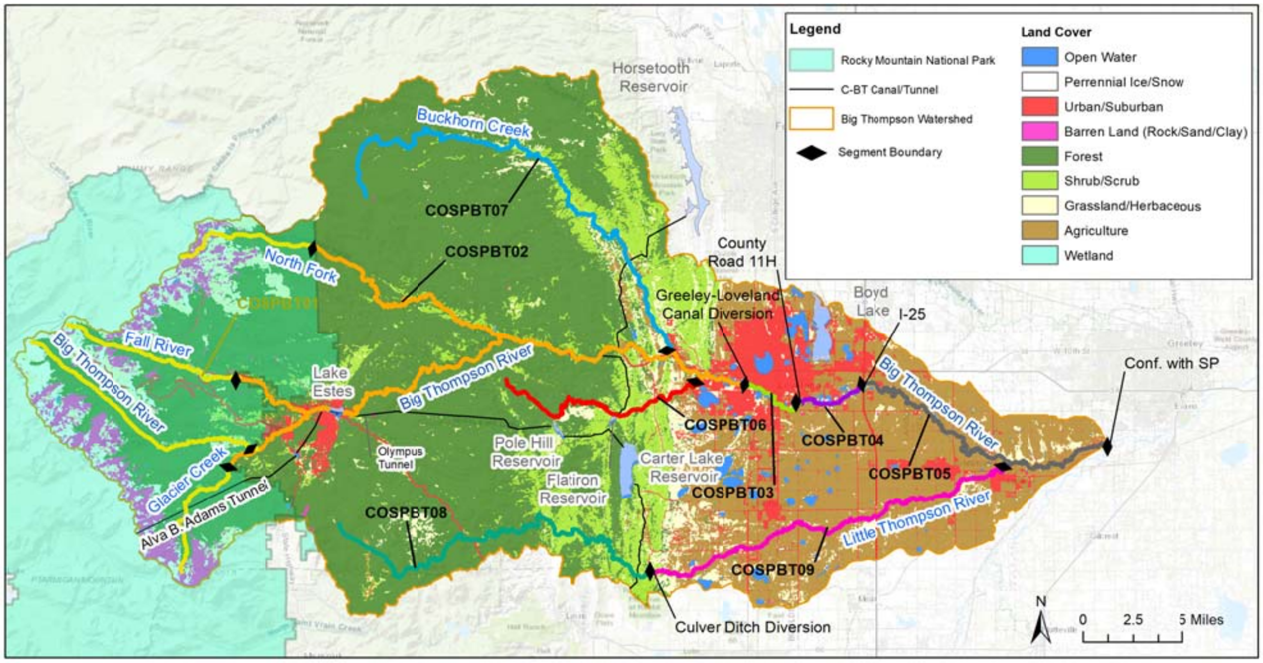

Figure ES-2. Current Land Use Map for the Big Thompson Watershed

Water-quality concerns in the Big Thompson watershed include nutrients (phosphorus and nitrogen), as noted in previous studies. In addition, various segments of the Big Thompson River and its tributaries are on Colorado's current 303(d) List[1] of impaired waters. The current listed parameters are arsenic, copper, iron, manganese, mercury, selenium, zinc, nitrate, Escherichia coli (*E. coli*), pH, macro-invertebrates, and temperature. The watershed has also faced wildfires, a major flood, extensive road reconstruction, and rapidly growing population over the study period, all of which can affect water-quality.

ES-2. DESCRIPTION OF THE ASSESSMENT

This assessment builds on four previous State of the Watershed reports evaluating data from the flowing water sites: Jassby and Goldman (2003), Haby and Loftis (2007), and Hydros (2011 and 2015). This report attempts to define the current state of the Big Thompson Watershed through review of spatial, seasonal, and long-term patterns in the water-quality dataset. The

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[1] The 303(d) List identifies those water bodies where there are exceedances of water-quality standards or non-attainment of uses.

results of a comparison of observed data to applicable State of Colorado water-quality standards and interim nutrient criteria are also considered. Finally, recommendations generated during the data review regarding refinement of data collection and future data analysis are provided.

The Forum's database for rivers and streams in the Big Thompson watershed from water year (WY)[2] 2006 through WY 2020 provided the water-quality data for this 15-year assessment. The assessment focused on flow rates, select metals, general parameters, nutrients, and microbiological parameters. In total, flow rates and 24 water-quality parameters were assessed at 20 sampling stations across the watershed (Figure ES-3). Of the 20 sampling locations, 15 are currently sampled by the USGS, and five are currently sampled by Northern Water.

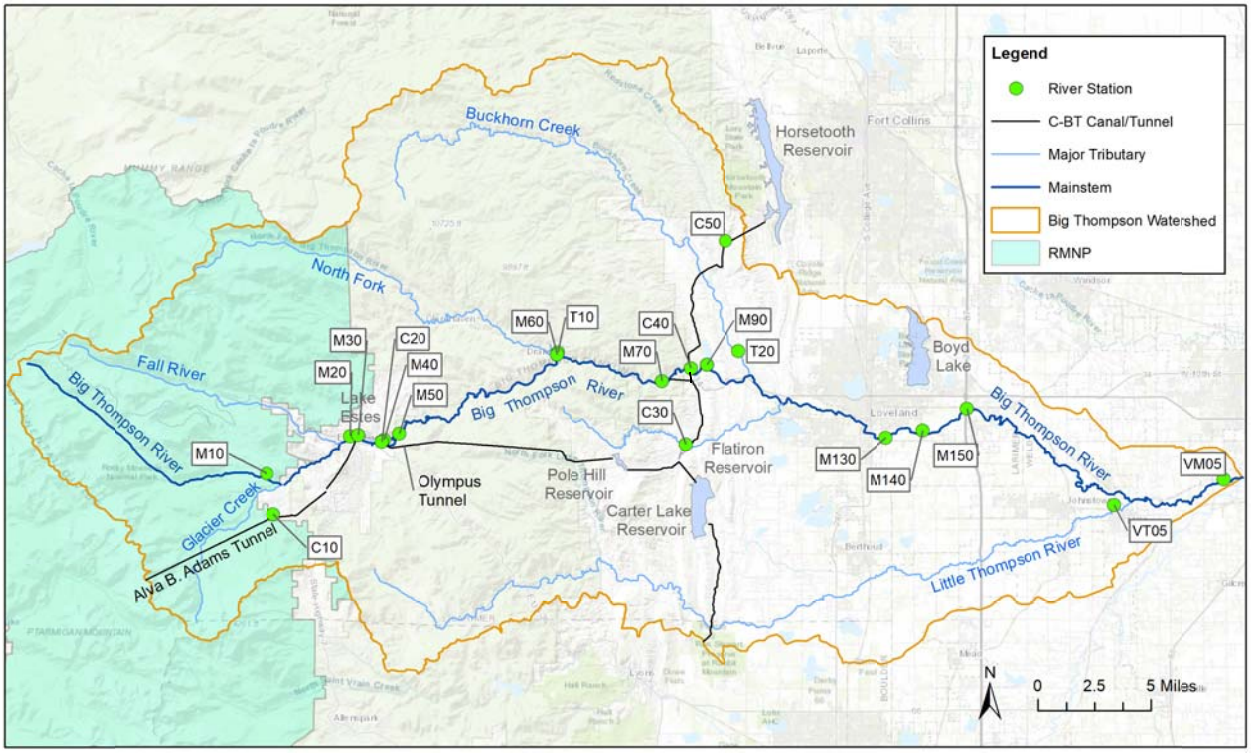

Figure ES-3. Sampling Station Locations

ES-3 ANALYSIS OF RESULTS

The basis for the state of the watershed conclusions are summarized in the following subsections in terms of spatial and seasonal patterns, long-term trends, responses to events, and compliance issues.

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[2] A water year, as defined here, begins in October of the previous calendar year and extends through September (e.g., WY 2000 covers the period from October 1, 1999 through September 30, 2000).

ES-3.1 Flow and Water-Quality Patterns

Detailed review and analysis of flow and water-quality data from canals, rivers, and tributaries in the Big Thompson watershed reveal some consistent spatial and temporal water-quality patterns for the upper watershed, lower watershed, C-BT canals, major tributaries, and below Wastewater Treatment Facilities (WWTFs):

Upper Watershed:

- Flow: Flow rates in the upper watershed follow a seasonal snowmelt hydrograph pattern, with peaks between May and June, and the lowest flows occur in winter months. Below Lake Estes, the snowmelt hydrograph peaks are still apparent, but can be diminished in some years by C-BT diversions to the Olympus Tunnel.
- Water Quality: The upper watershed is generally characterized by good water quality. This reflects the igneous and metamorphic rock of the subsurface geology, low population density, and natural runoff patterns (dominated by the annual snowmelt runoff hydrograph). Concentrations of dissolved solids, metals, nutrients, TOC, suspended solids, and coliforms all tend to be low, especially relative to the lower watershed (e.g., Figure ES-4).

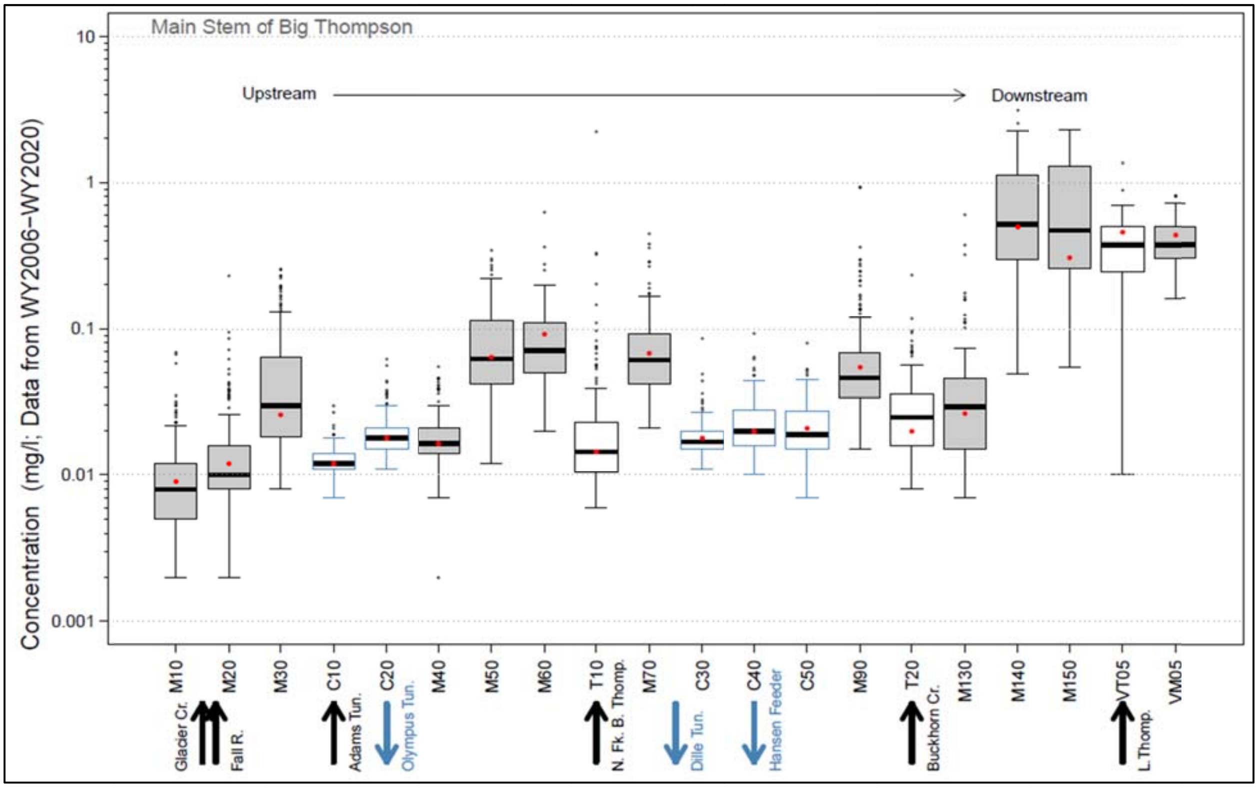


Figure ES-4. Box Plot of Total Phosphorus Concentrations (mg/L) in the Big Thompson River, WY2006-WY2020 (*Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.)*

Lower Watershed:

- Flow: There is a sharp drop in annual flow volumes at the top of the lower watershed. This drop in flow volume, due to major irrigation and municipal water diversions, dampens the annual snowmelt peak in most years. While flow rates are notably lower in spring and summer in the lower watershed as compared to the upper watershed, winter flows tend to be higher at the downstream end of the watershed due to gains from groundwater and wastewater effluent.
- Water Quality: The water quality in the lower watershed is generally fair. It is characterized by higher (and growing) population density, urban development, agriculture, livestock, WWTF effluent, alluvial groundwater gains, and sedimentary subsurface geology, including Pierre shale. Relative to the upper watershed, the lower watershed exhibits notably higher concentrations of dissolved solids, nutrients, TOC, suspended solids, and coliforms, reflecting the land use and geology. The higher concentrations of TOC, nutrients, and some metals reflect the population and corresponding WWTF effluent, as well as land use (e.g., Figure ES-4). Livestock and urbanization likely explain the higher coliform concentrations. Finally, elevated concentrations of selenium (Figure ES-5), arsenic, and sulfate are likely due to the underlying Pierre shale, with concentrations exacerbated by agricultural irrigation.

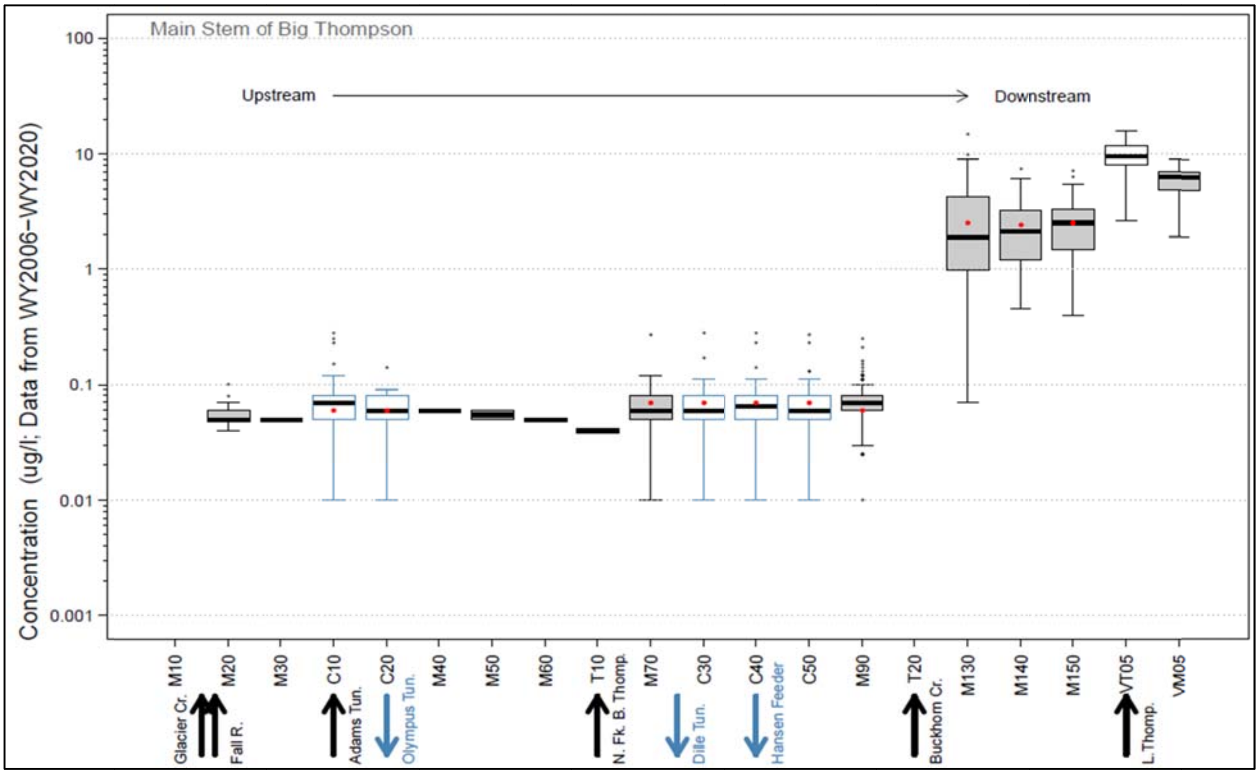
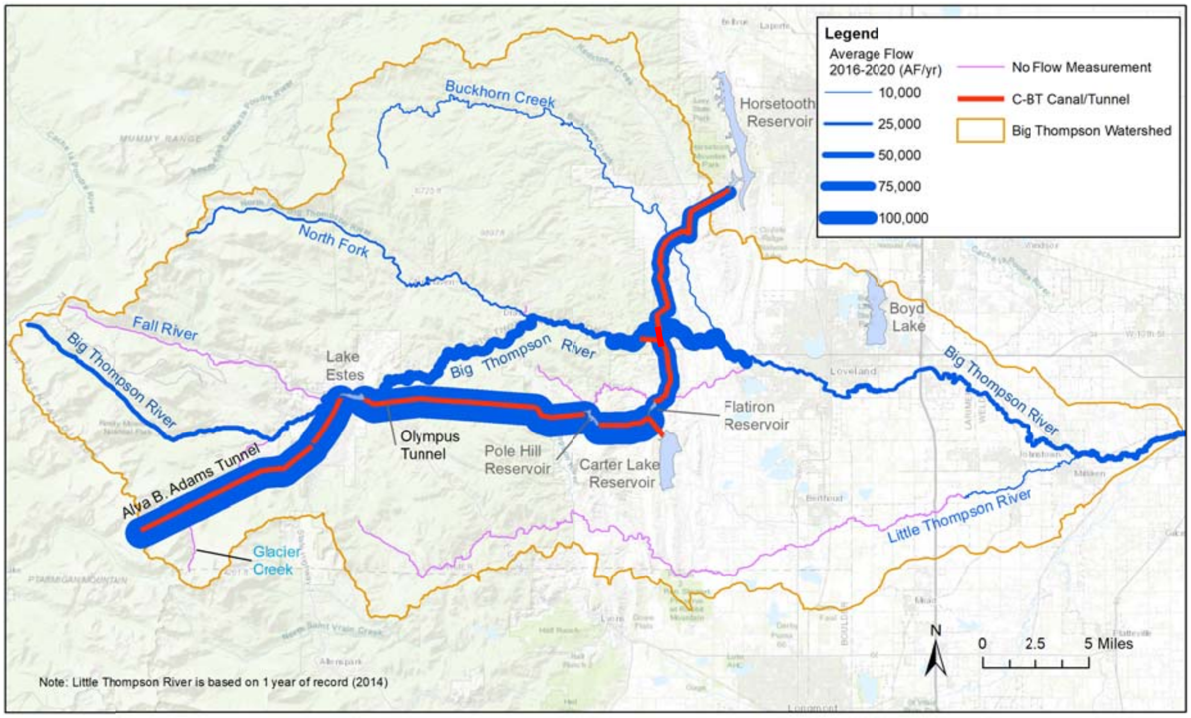


Figure ES-5. Box Plot of Selenium Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020 (*Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.)*

C-BT Canals: The largest average annual flow volumes in the Big Thompson watershed are in the canal and tunnel structures of the C-BT Project (Figure ES-6). Water quality in the C-BT canals is good and reflects the conditions in Grand Lake on the west side of the continental divide. Concentrations from the Adams Tunnel tend to be lower than those in the upper Big Thompson watershed for coliforms, orthophosphate, ammonia, and nitrate, but slightly higher for arsenic, TOC, and dissolved solids (specific conductivity, alkalinity, and hardness). Overall, there is no indication that C-BT water contributes negative impacts to water quality in the Big Thompson River.



Note: Little Thompson River is based on 1 year of record (2014)

Figure ES-6. Diagram Illustrating Average Annual Flows in the Big Thompson Watershed, WY2016-WY2020

Major Tributaries: Major tributaries with sampling data in the Big Thompson watershed for the updated study period include the North Fork, Buckhorn Creek, and the Little Thompson River.

- The North Fork: The North Fork comprises an average of ~20% of the flow in the Big Thompson River at its confluence in the upper watershed. Because it is a generally, high-mountain, granitic watershed with low population and primarily forested land use, water quality from North Fork tends to be good and similar to that of the upper watershed on the mainstem of the Big Thompson River. This includes low concentrations of nutrients, metals, TOC, and dissolved solids, particularly compared to the lower watershed.

- <u>Buckhorn Creek</u>***:*** Buckhorn Creek is defined as an upper sub-watershed and is characterized by low population with primarily forested or shrub/scrub land use. At the downstream end of this tributary, however, Buckhorn Creek crosses transitional sub-surface geology, including the sedimentary sandstones and conglomerates that form the hogbacks. These features include gypsum, which contributes to elevated dissolved solids concentrations in Buckhorn Creek. Due to this subsurface geology, water quality from Buckhorn Creek is similar to that of the lower watershed in terms of alkalinity, hardness, pH, specific conductance, and sulfate. For TOC and nutrients, Buckhorn Creek water quality is more similar to the upper watershed.
- <u>The Little Thompson River</u>***:*** The Little Thompson River contributes roughly 25% of the annual flow in the Big Thompson River at its confluence in the lower watershed. Water quality from the Little Thompson River tends to be comparable to or worse than that in the lower Big Thompson River upstream of its confluence. Increasing population density, urban and agricultural land use, and the underlying Pierre shale contribute to the water quality issues. Temperature, sulfate, TOC, arsenic, lead, coliforms, ammonia, nitrate, dissolved solids, and selenium tend to be higher in the Little Thompson River than in the rest of the lower watershed of the Big Thompson (e.g., See VT05 on Figure ES-7).

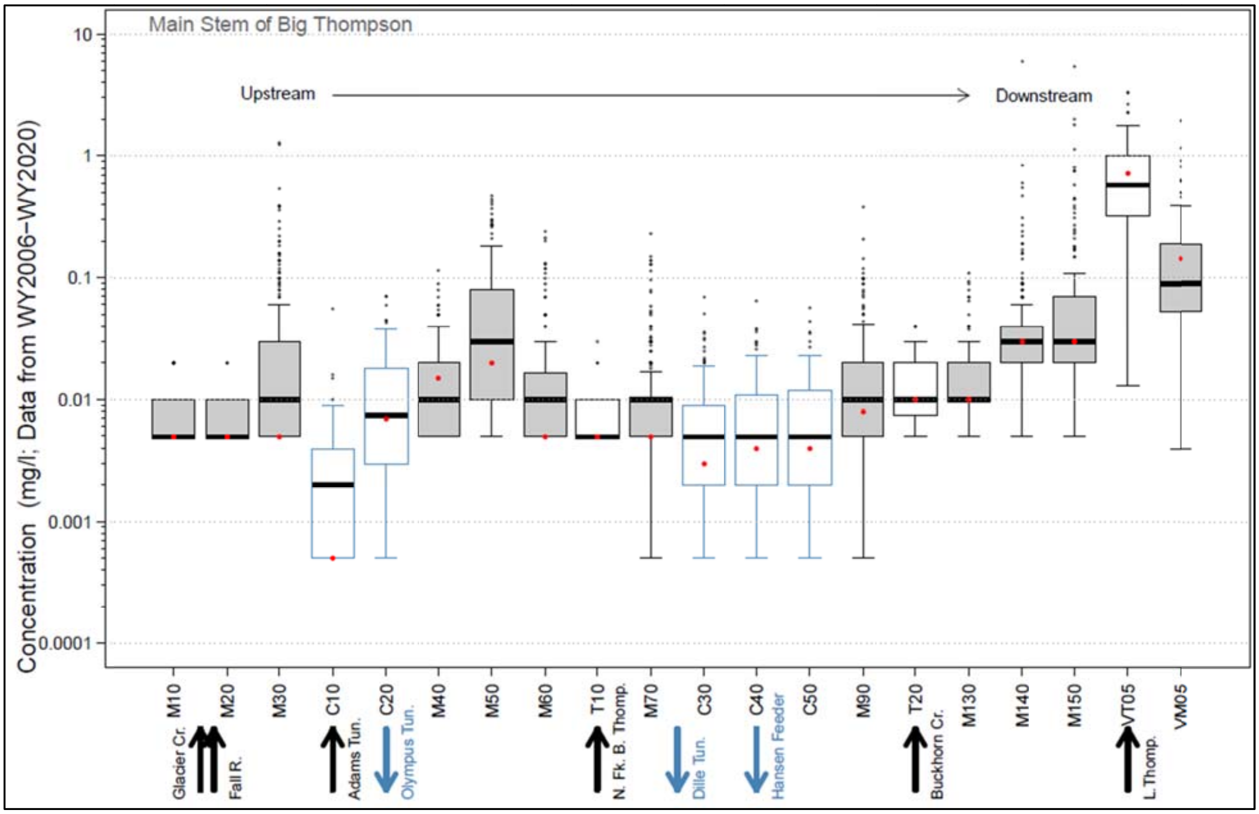


Figure ES-7. Box Plot of Ammonia (mg/L) in the Big Thompson River, WY2006-WY2020 (*Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue* *outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.)*

Below WWTFs: WWTFs serve an important function in the watershed, treating wastewater and returning water to the river. For many rivers, including the Big Thompson, WWTFs represent major point sources for loading of nutrients, organic matter, and sometimes metals. In the Big Thompson watershed, total nitrogen and total phosphorus concentrations increase at sampling stations below each of the major WWTFs in the watershed. These increases largely reflect loading of nitrate and orthophosphate, which are forms of nutrients that are readily available for algae and plant growth. Treatment improvements were noted as apparent in downstream water quality at two WWTFs on the Big Thompson River:

- A pattern of decreasing orthophosphate (as well as total phosphorus) upstream of Lake Estes is attributed to ongoing operational and structural improvements at the Estes Park Sanitation District WWTF.
- A dramatic step change reduction in phosphorus concentrations in the Big Thompson River downstream of the Loveland WWTP reflects upgrades to that facility that went online in 2019 (e.g., Figure ES-8). This improvement at the Loveland WWTP reduced phosphorus concentrations in that part of the lower watershed to values below the interim nutrient criteria value for the first time in the observed record.

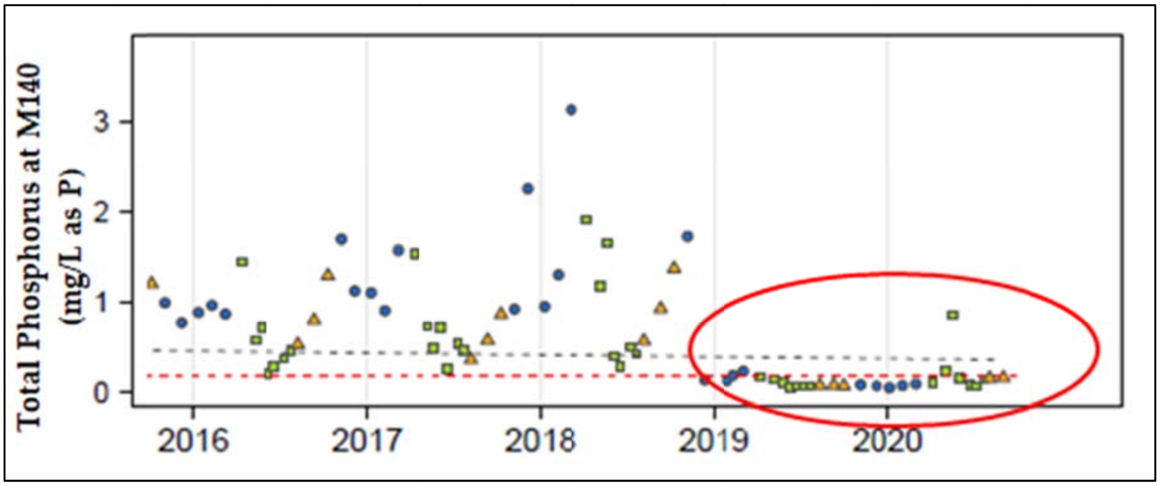


Figure ES-8. Total Phosphorus Concentration Data on the Big Thompson River Downstream of Loveland WWTP, 2016-2020 *(Red Oval Indicates Period of Record Following Loveland WWTP Upgrade)*

ES-3.2 LONG-TERM TRENDS

Testing of the 15-year record for statistically-significant trends revealed two key findings:

Increasing nutrients and TOC in Little Thompson River: Statistically-significant trends of increasing nutrients and TOC were found on the Little Thompson River. Increases were seen across seasons for TOC, total phosphorus (Figure ES-9), orthophosphate, nitrate + nitrite, and total nitrogen. These trends were some of the largest across constituents and sampling locations in terms of rate of increase, including 8% per year for nitrate + nitrite, 15% per year for total phosphorus, and 2% per year for TOC. It is expected that these increasing trends correspond to the rapid population growth rate in the Little Thompson River sub-watershed.

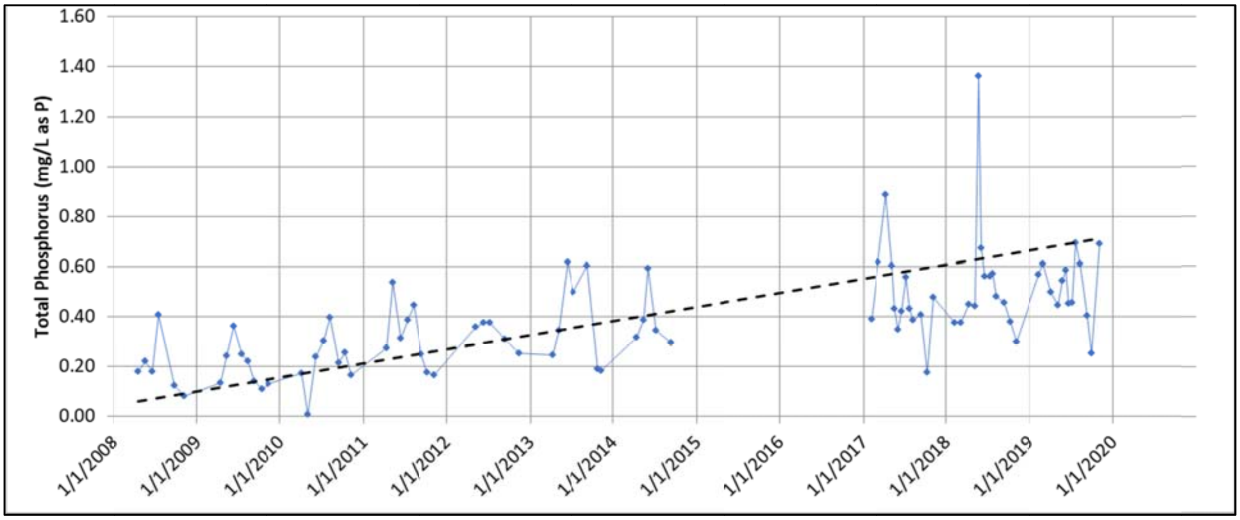


Figure ES-9. Total Phosphorus (mg/L) on the Little Thompson River (Trend slope shown as black dotted line)

<u>**Decreasing TOC in C-BT canals:**</u> In the previous State of the Watershed Report (Hydros, 2015), statistically-significant trends of increasing TOC concentrations were found in the C-BT canal system (C10, C20, C30, C40, and C50) for WY2000-WY2014, as well as in much of the Big Thompson upper watershed mainstem (M20 to M130). The cause of this increase was hypothesized to be the large-scale tree death from the mountain pine beetle epidemic, and it was noted that the trend visually appeared to have leveled off as of ~2008. In this update, there is a statistically-significant trend in the opposite direction of a similar magnitude (a decrease of ~0.03 mg/L TOC per year) across the C-BT canal locations (e.g., Figure ES-10) for the period of WY2006-WY2020. At this time it is uncertain whether the pattern relates to recovery from the Mountain Pine Beetle infestation or is part of another larger cyclical pattern. Either way, it is noteworthy that the increasing trend is no longer apparent.

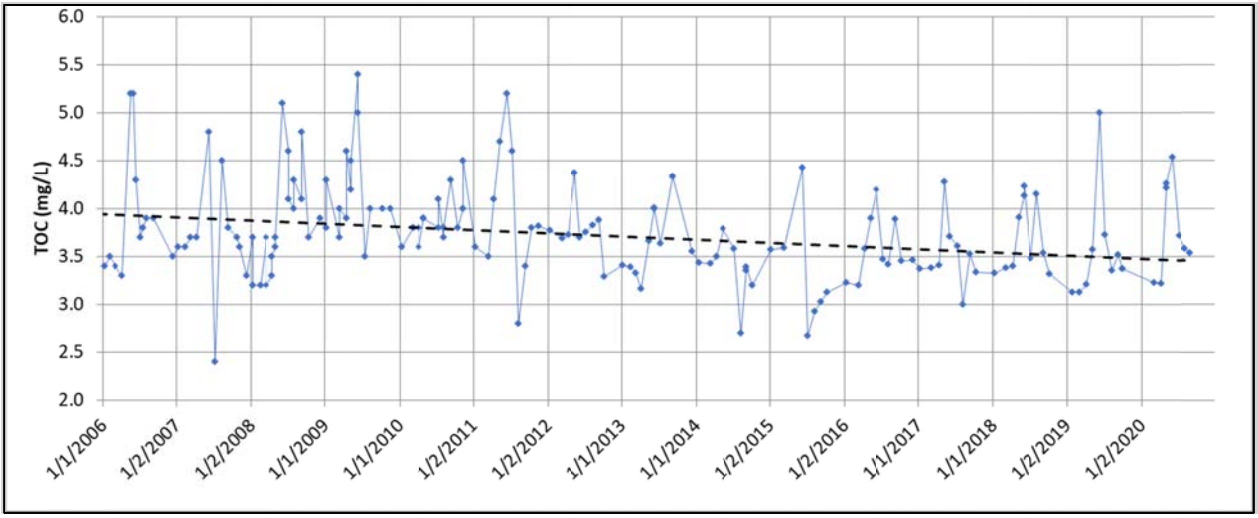


Figure ES-10. TOC (mg/L) from the Adams Tunnel (Trend slope shown as black dotted line)

ES-3.3 COMPLIANCE

Comparison of the Forum's water-quality dataset to relevant standards produced a few noteworthy findings:

Arsenic issues relative to the chronic standard across the watershed: At all sampling stations across the watershed, every detected observation for arsenic is above the 0.02 µg/L chronic standard value (applicable to all Big Thompson segments except Segment 4). Given this pattern across the watershed, from pristine waters in Rocky Mountain National Park (M10) to anthropogenically-influenced waters in the lower watershed, the 0.02 µg/L standard does not appear to be attainable in the Big Thompson watershed. The current 303(d) listings do not include the Little Thompson River or Segment 5; however, based on the observed data, these segments may eventually be listed also under the current chronic standard. Note that there are widespread issues across the state relative to the 0.02 µg/L chronic arsenic standard.

Issue relative to the acute and chronic copper standards at the top of the watershed: There is a high frequency of copper standard exceedances in the upper watershed upstream of Lake Estes. This is not an issue of particularly high copper concentrations. Instead, the naturally low hardness values in this part of the watershed result in very low calculated copper water-quality standards. Based on recent data, it may be appropriate to modify the copper 303(d) listings to exclude Segment 2 downstream of Lake Estes in the future.

Lower watershed issues relative to chronic sulfate and selenium standards: The lower Big Thompson River watershed, including the Little Thompson River, exhibit relatively high frequencies of observations above of the chronic sulfate and selenium standards (Figure ES-11). This reflects the effects of the Pierre shale in this area, exacerbated by irrigation practices.

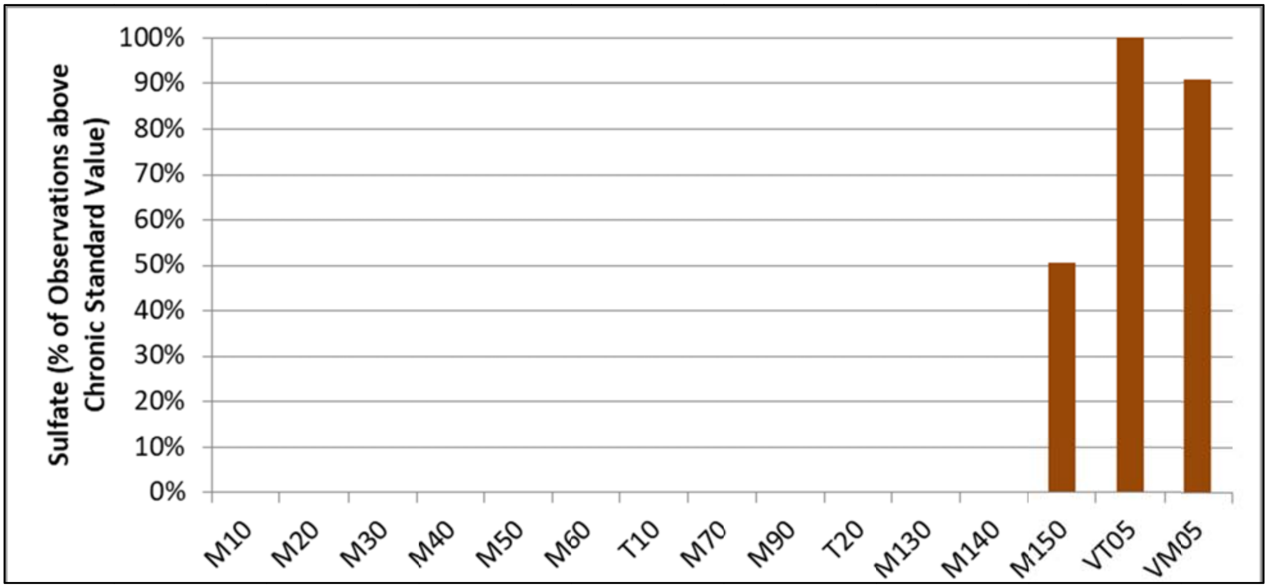


Figure ES-11. Summary of Data Comparison to Chronic Sulfate Standards, 2006-2020

Frequent values above the *E. coli* standard in the lower watershed and Little Thompson River: *E. coli* observations above the standard are infrequent in the upper Big Thompson River. In the lower watershed, beginning with Buckhorn Creek, the frequency of observations above the standard generally increases moving downstream. The most frequent cases are observed on the Little Thompson River and at the downstream end of the Big Thompson River. This may reflect livestock sources of bacteria in these reaches.

Interim Nutrient Criteria review suggests possible future challenges: The interim numeric criteria are only currently applicable in Segment 1 and part of Segment 2 for total phosphorus; however, both total nitrogen and total phosphorus criteria may be considered for adoption as water-quality standards across the watershed prior to or after May 31, 2022, depending on determination by the WQCC. Observed data indicate that the interim criteria would be routinely exceeded in the lower watershed, including the Little Thompson River (Figure ES-12).

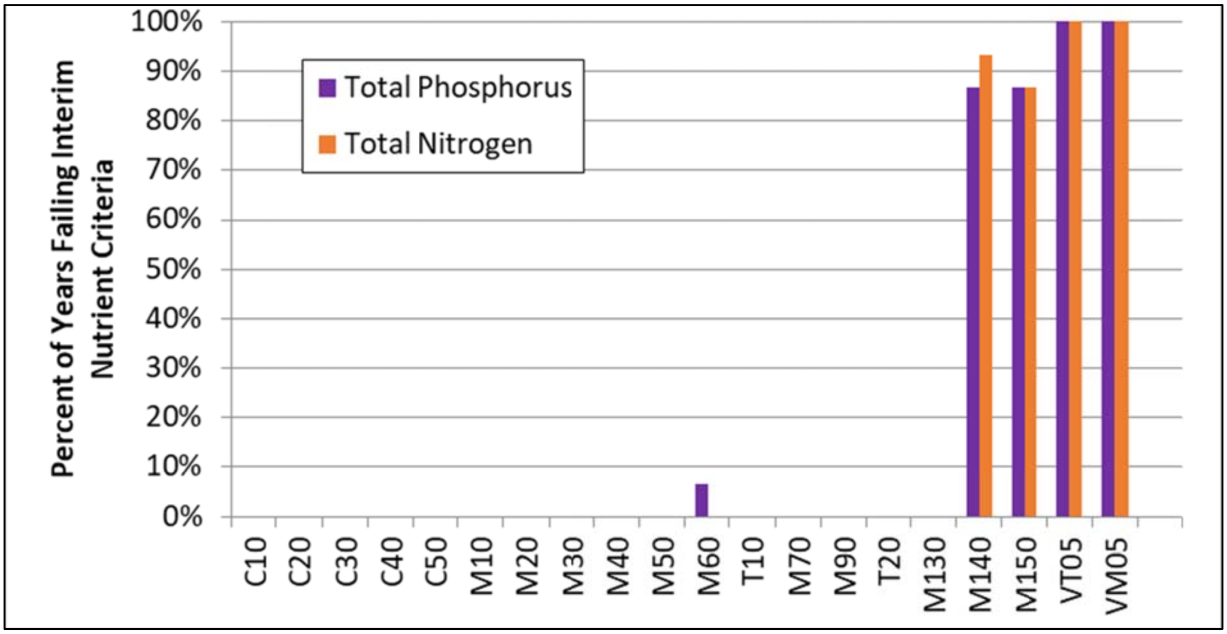


Figure ES-12. Summary of Data Comparison to Interim Nutrient Criteria (Annual Medians Compared to Interim Criteria for Rivers), 2006-2020 *(Note that the Interim Criteria are Only Currently Applicable for Total Phosphorus at M10, M20, M30, and M40.)*

ES-3.4 Response to Major Watershed Events

Major watershed events during the study period included wildfires, a flood, and extensive road reconstruction activities.

Fires: There were six major wildfires entirely or partially within the Big Thompson watershed in recent years (Figure ES-13):

- **Cow Creek Fire:** June 2010 (1,200 acres in the Big Thompson watershed),
- **Crystal Fire:** April 2011 (3,000 acres in the Big Thompson watershed),
- **High Park Fire:** June 2012 (~21,606 acres in the Big Thompson watershed),
- **Fern Lake Fire:** October 2012 (3,500 acres in the Big Thompson watershed),
- **Cameron Peak Fire**: August 2020 (65,162 acres in the Big Thompson watershed), and
- **East Troublesome Fire**: October 2020 (4,894 acres in the Big Thompson watershed).

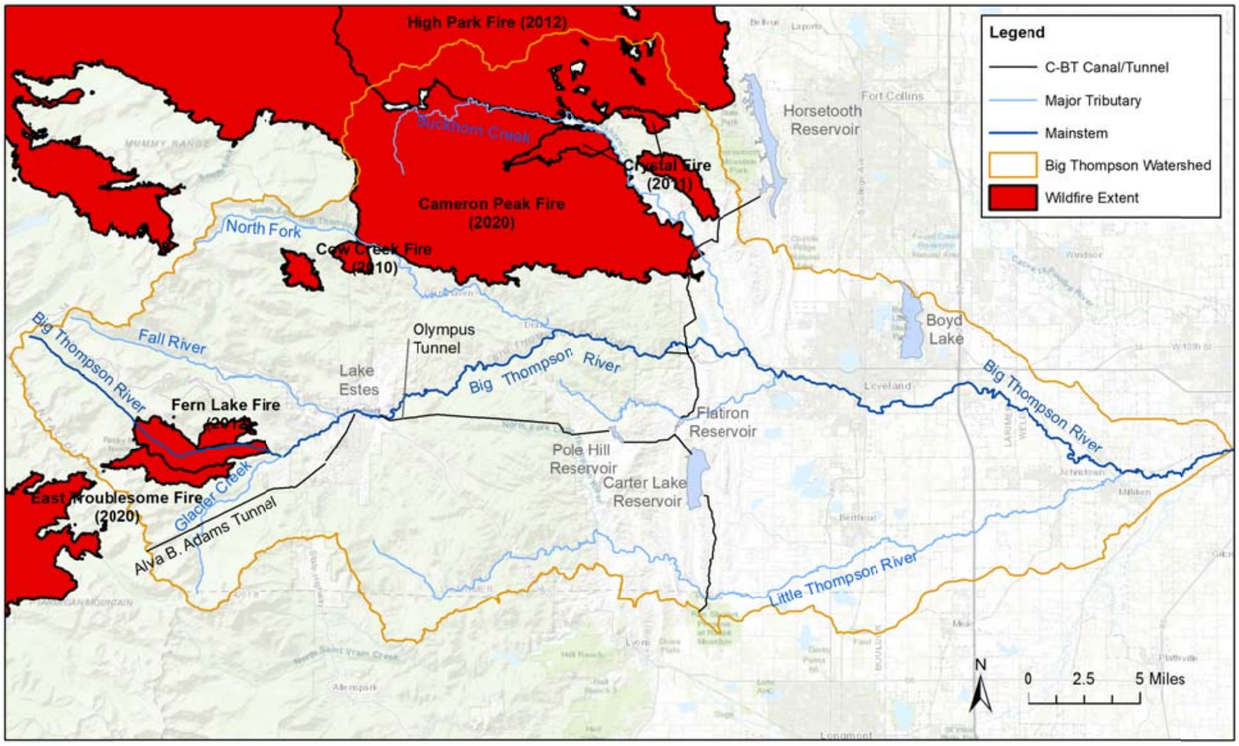


Figure ES-13. Location and Burn Extent of Recent Fires in the Big Thompson Watershed

Of these fires, only the Fern Lake fire shows an apparent water-quality response based on the Forum's database for the study period (WY2006-WY2020), with increased nitrate and dissolved solids concentrations (including alkalinity, hardness, and specific conductivity) observed at one location just below Moraine Park for the three years following the fire. The post-fire effect below Moraine Park may also reflect the combined effect of the 2012 fire and the 2013 flood.

A more significant response may occur following the Cameron Peak Fire (and possibly the East Troublesome Fire) due to its size and intensity. Post-fire water-quality data for these fires are still being collected, with effects expected to be apparent only after the period of record for this study (ends on September 30, 2020); however, there are indications of issues. Specifically, the City of Loveland had to modify its diversion operations from the Big Thompson River at times in 2021 due to ash in the river.

<u>2013 Flood</u>: A week of record-breaking rainfall in September of 2013 resulted in extensive flooding along the Front Range. The flood is estimated to have been a 100- to more than 500-year flood in the Big Thompson and Little Thompson Rivers. Damage from flash flooding and debris flows was extensive.

There was no in-river sampling by the Forum during the 2013 flooding event due to safety and access issues, but some post-flood effects were apparent in the dataset. For two to three years following the September 2013 flood, increased baseflow rates (particularly apparent in winter months) occurred in the lower Big Thompson watershed. The increased baseflow in the lower watershed served to dilute phosphorus and nitrogen from WWTF effluent, lowering concentrations in winter months. Winter concentrations of dissolved solids (alkalinity, hardness, sulfate, and specific conductance) were also lower during those two to three post-flood years. No lasting adverse water-quality impacts of the flood are apparent in the Forum's dataset.

<u>Post-Flood Road Reconstruction Activities</u>: Extensive reconstruction of roads and infrastructure was needed following the September 2013 flood. A multi-year project, led by the Colorado Department of Transportation (CDOT) Flood Recovery Office, was initiated in 2016, including rebuilding of bridges and repair of nearly 23 miles of U.S. 34, mostly between the City of Loveland and Estes Park (e.g., Figure ES-14). The project was largely completed in early 2019, with some minor repairs continuing into 2020.

Figure ES-14. Example Image of Repairs to U.S. 34

While the CDOT-led construction project took all required precautions to protect river water quality during construction, increased erosion often occurs with such large-scale projects. While no clear impacts are apparent in the Forum dataset, separate studies documented construction impacts on the river including increased solids (Fayram, 2018). There was also a well-documented fish kill on the North Fork, due to increased pH from a concrete spill in 2016 related to a bridge reconstruction project that was unaffiliated with the larger CDOT project on U.S. 34. The lack of observed impacts from road construction activities in the Forum dataset likely reflects the transient nature of such impacts, which may easily be missed at the sampling frequency of the Forum's program, which is designed for different purposes. The Forum's dataset does not indicate any long-term impacts from the reconstruction activities.

ES-4. PROGRAM RECOMMENDATIONS

Overall, the Forum monitoring program is well-conceived and well-managed, generating a useful dataset to support evaluation of water quality across the watershed. Through the process of developing this report, several recommendations for sampling program improvements were generated for consideration by the Forum:

- **Add total arsenic**: Total arsenic should be added to 13 stations currently sampled by the USGS, given widespread 303(d) listings.

- **Restart mercury sampling**: Sampling for mercury should be added back into the program across all stations, given widespread 303(d) listings.
- **Add zinc at M10 and M20**: It is recommended that dissolved zinc be added to the analyte list for routine sampling at M10 and M20 to support future analyses, in light of the 303(d) listing.
- **Add manganese sampling in lower watershed**: Recognizing the 303(d) listings, the sampling program should include manganese at VT05, M130, M140, M150, and VM05.
- **Add TSS analyses**: Routine collection of TSS data at all stations is recommended for future sampling. TSS should be added to the analysis list for M30, M40, M50, M60, T10, T20, M130, M140, and M150.
- **Add continuous temperature gages**: Given the importance of water temperature to aquatic life and the variable flow rates in the Big Thompson River due to major diversions, it is recommended that continuous temperature gages be installed across the watershed. Alternatively, if such data are being collected through another program, it is recommended that these data be included in the Forum's next five-year data review.

Additionally, recommendations were generated for modifications to the scope of work for the next five-year review:

- **Discontinue Loading Calculations:** It is recommended that the next report not include analysis in terms of loading for nutrients and TOC.
- **Exclude temperature if continuous data are unavailable:** Unless hourly temperature data collection is initiated in the watershed, analysis of temperature should be excluded from the next five-year review.
- **Update seasons to include spring runoff:** Consider updating season definitions in the next report to attempt to distinguish snowmelt runoff from the "summer" group.
- **Add mercury, iron, and manganese to the list of focus parameters:** Note that the list of metals considered does not include mercury, iron, or manganese, all of which are on the current 303(d) List for flowing sites in the watershed.
- **Include review of 2020 fire effects**: The next five-year review should include a specific objective to evaluate water-quality response to the major fires that occurred in the fall of 2020.

1 INTRODUCTION AND BACKGROUND

The Big Thompson Watershed Forum (Forum) is a nonprofit organization that was formed in 1997 by a group of concerned citizens, stakeholders, and officials with the goal of taking a holistic approach to water-quality assessment and protection in the Big Thompson watershed. The mission of the Forum is to protect and improve water quality in the Big Thompson River Watershed through collaborative monitoring, assessment, education, and restoration projects. Currently, the major funders are the Cities of Loveland, Fort Collins, and Greeley, as well as the Northern Water Conservancy District.

This report, funded by the Forum, presents a review of water-quality data collected in the Big Thompson watershed to determine the current state of the watershed. The assessment considers patterns and trends in the dataset to advance the understanding of the system and identify any developing concerns. Data from the 15-year period from water year (WY)[3] 2006 through WY 2020 are considered, with a particular focus on the recent years of data collected since the previous State of the Watershed Report (Hydros, 2015). This study focuses exclusively on flowing water sites (i.e., rivers, streams, and canals) across the watershed. The assessment and analyses presented in this report directly support the mission and program goals of the Forum.

The following subsections provide background information to offer context for the presentation and evaluation of data in subsequent sections. The background information includes:

- A description of key relevant aspects of the watershed;
- An overview of the regulatory setting and regulatory water-quality concerns;
- Notes on relevant major events in the watershed over the recent decade; and
- The objectives and organization of the report.

1.1 WATERSHED DESCRIPTION

Colorado’s Big Thompson watershed, located approximately 50 miles northwest of Denver, is a large, complex hydrologic system covering more than 900 square miles east of the Continental Divide (Figure 1). The natural headwaters for the Big Thompson River originate in Rocky Mountain National Park (Figure 1), with a maximum elevation of 14,259 ft. The river empties into the South Platte River on the eastern plains at an elevation of 4,670 ft.

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[3] A water year begins in October of the previous calendar year and extends through September (e.g., WY 2000 covers the period from October 1, 1999 through September 30, 2000).

The watershed can be broadly divided into of upper and lower sub-watersheds (Figure 2). The upper watershed includes the upper Big Thompson River, Fall River, upper Little Thompson River, North Fork, and Buckhorn Creek sub-watersheds. The upper Big Thompson sub-watershed contains the Adams Tunnel outfall, the Town of Estes Park, Lake Estes, and the upper end of the Olympus Tunnel. Land use in the upper watershed is primarily forested or tundra, with some urban areas around Estes Park (Figure 4). The lower Big Thompson sub-watershed includes the cities of Loveland, Berthoud, Johnstown, and Milliken. It is comprised of the lower Big Thompson and lower Little Thompson watersheds.

Water that flows through the watershed serves more than 800,000 people, providing residential, industrial, commercial, agricultural, recreational, and wildlife habitat benefits. The watershed faces both natural and anthropogenic stresses on water quality. Natural stresses to water quality in the river include wildfires, floods, drought, forest health issues (including mountain pine beetle infestations), and geologic sources of contaminants (such as selenium from groundwater recharge through Pierre shale in the area). Anthropogenic stresses depend on many factors and are often indicated by land use and population density. Anthropogenic stresses within the Big Thompson watershed include population growth, discharge from wastewater treatment facilities/plants (WWTFs; also in some cases named WWTPs), atmospheric deposition, water management (including diversions, return flows, and trans-basin imports), ranching and agriculture, septic systems, impoundments, and urban/suburban stormwater runoff.

Geology, land use, population density, and water management vary across the watershed with clear transitions occurring between the upper and lower sub-watershed. These patterns are described in the following subsections.

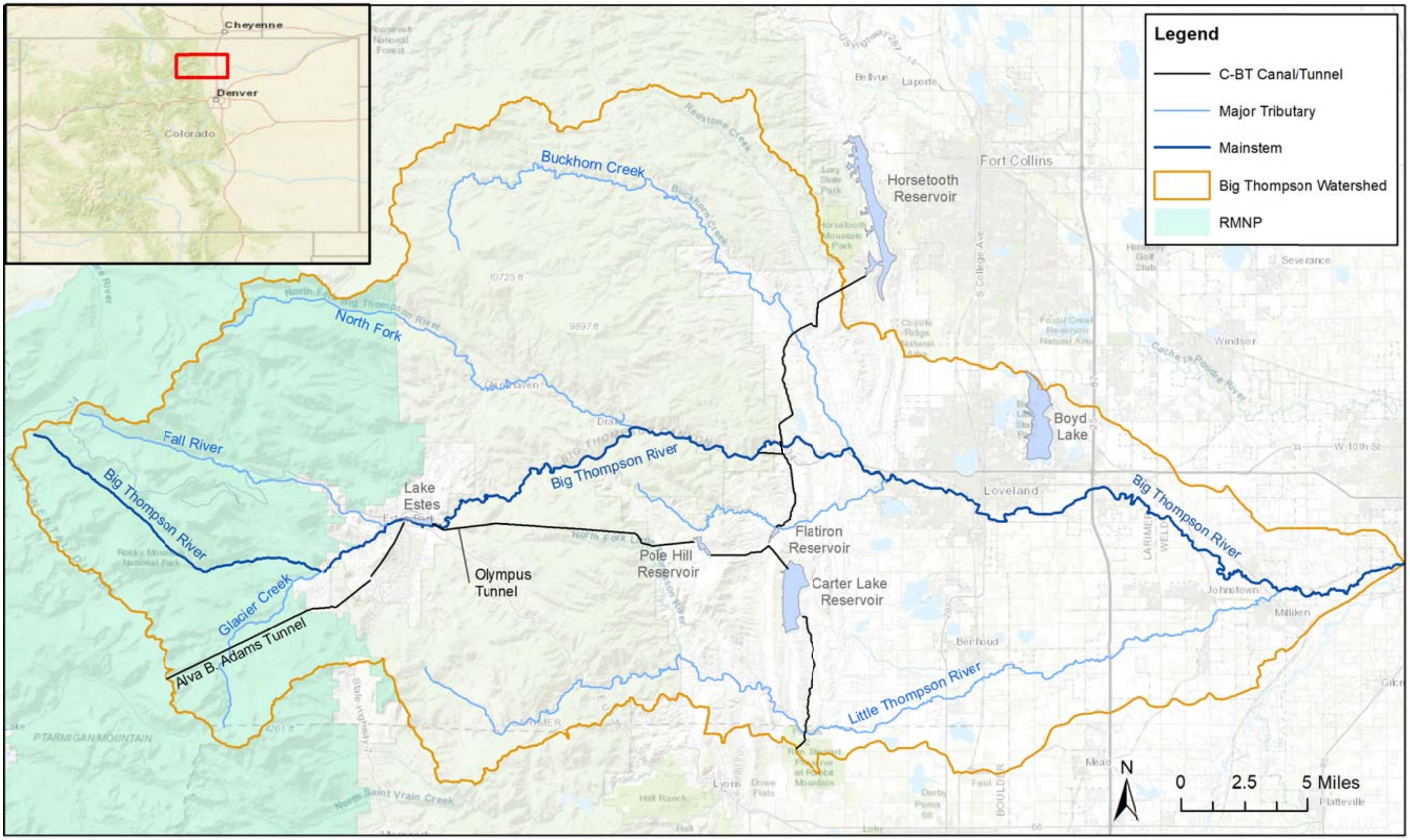

Figure 1. Location of the Big Thompson Watershed

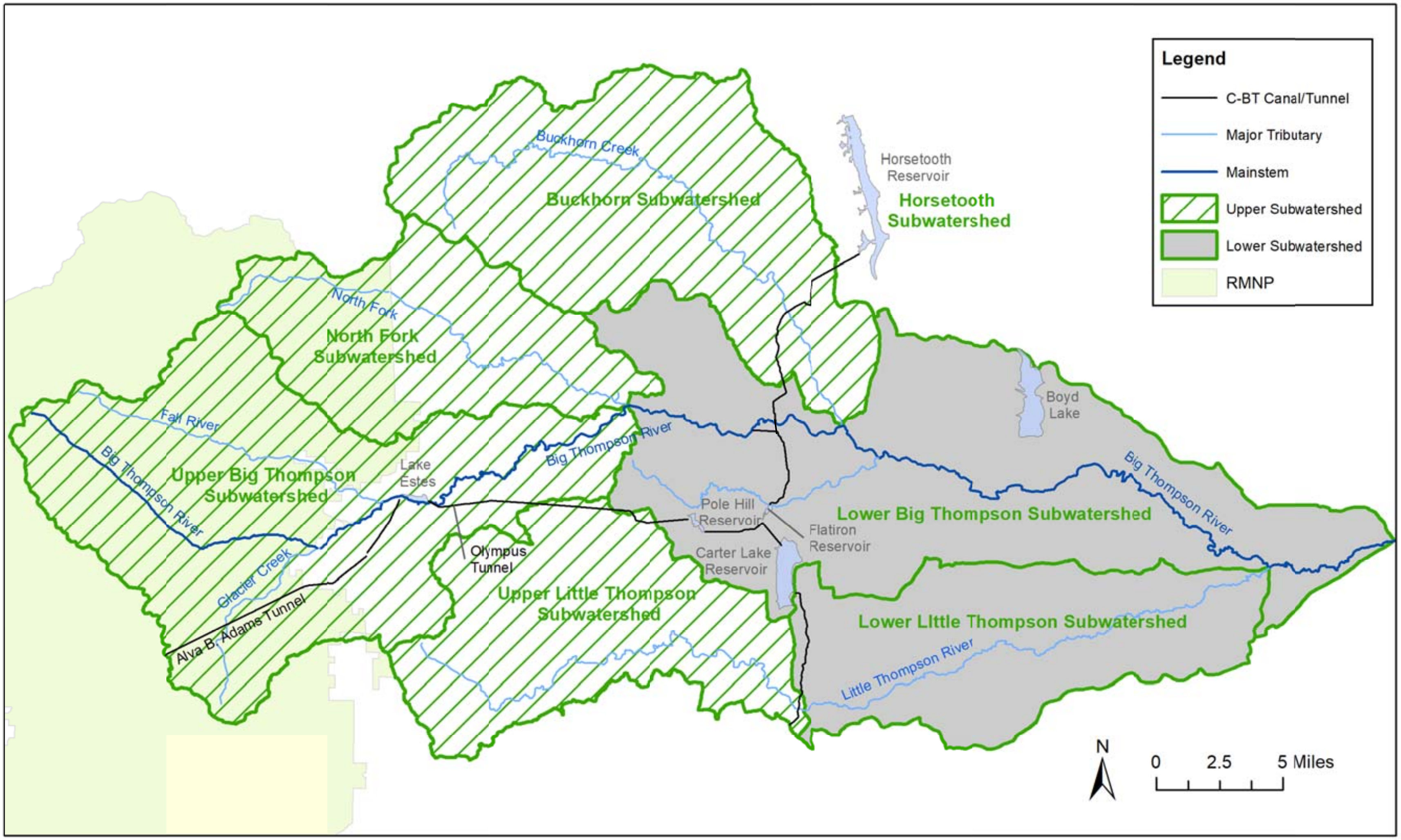

Figure 2. Big Thompson River Sub-Watersheds

1.1.1 Main Stem Geology

The underlying geology of a watershed can affect water-quality in the river. Specifically, chemical and physical weathering of bedrock, and the derived soils and sediments, can be sources of both dissolved and particulate constituents to the river. An understanding of the underlying geology can also provide insights into groundwater interactions and indicate natural transitions across the length of the river.

The upper and lower sub-watersheds of the Big Thompson River (Figure 2) generally fall into two different geologic zones with a transition zone between them (Figure 3). These geologic patterns help, in part, to explain patterns in observed water-quality in the river, as presented and discussed in Section 3.

The upper sub-watershed, from the headwaters to roughly the canyon mouth, is characterized by the metamorphic basement rocks that form the mountains (Figure 3). These hard, crystalline rocks (primarily granites and gneiss) are resistant to weathering. There is also minimal alluvium along the river bed within this zone, reflecting the weathering-resistant surroundings. Note that the Big Thompson watershed is located outside of the Colorado Mineral Belt[4] (the wide zone of mineralization that is associated with most of the historical and current mining in Colorado), so there are no clear concerns with loading of metals from this zone that might exhibit toxicity issues for aquatic life.

Roughly following the boundary between the upper and lower sub-watersheds, there is a band of sedimentary sandstones and conglomerates that form the hogbacks (Figure 3). These bands demarcate the transition between the mountains and the start of the plains in the watershed. This type of geology can provide significant solids to the river; however, contributions from this relatively narrow geological band are expected to be minimal.

The lower sub-watershed, which extends from the mouth of the canyon to the South Platte River, is characterized primarily by Pierre Shale and increasing deposits of alluvial material[5]. Low-permeability Pierre Shale comprises the majority of the bedrock valley through which the Big Thompson River flows in the lower sub-watershed. This is a significant consideration in terms of water quality since Pierre Shale can be a notable source of both sulfate and selenium[6]. The extent of the alluvium increases toward the confluence of the Big Thompson River with the

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[4] The Colorado Mineral Belt is an area of ore deposits that extends from the La Plata Mountains in southwestern Colorado to near the middle of the state, west of Boulder, Colorado.

[5] Alluvial material refers to unconsolidated clay, silt, sand, or gravel that has been deposited by running water. Relatively speaking, alluvial material is geologically young. It can also be rich in organic matter, depending on the upstream watershed conditions.

[6] Elevated sulfate concentrations can pose challenges to treatment of water for drinking water distribution. Selenium is a bioaccumulative toxin to aquatic life, which can cause reproductive impairments (Chapman et al., 2009 and 2010).

South Platte River, and the underlying bedrock transitions to the overlying Fox Hills Sandstone and the Laramie Formation. These sedimentary formations are less resistant to weathering than the Pierre Shale and can therefore be a greater source of both dissolved constituents and particulate material to the river.

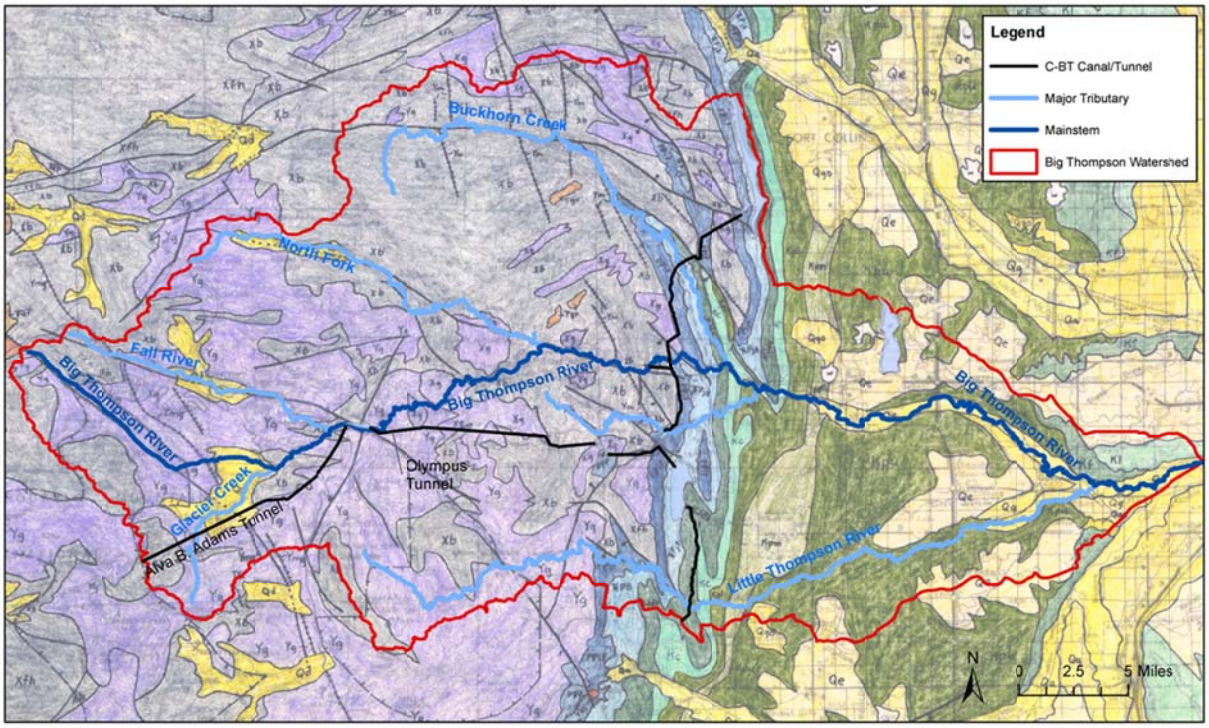


Figure 3. Geologic Map of Big Thompson Watershed; Overlay from Braddock and Cole (1978)

(Purple and grey indicate igneous and metamorphic rock; teal indicates sandstones and conglomerates; dark green indicates Pierre shale, light green indicates Foxhills / Laramie bedrock; beige and yellow indicate alluvial deposits.)

1.1.2 Land Use

Land use can affect both stream water quality and temperature. Developed areas may contribute salts (dissolved solids) in the winter due to road salt. The temperature of runoff can also be higher from impervious surfaces in developed areas. Agricultural return flows can load nitrogen and phosphorus to the river. In addition, effluent from WWTFs, associated with developed areas, can provide nutrients to the river as well as other contaminants such as copper (from corrosion of domestic water supply pipes). Land use also affects how water is returned to the river. Agricultural irrigation results in infiltration and some of this water may return to the river as shallow groundwater. Shallow groundwater can carry constituents from both the agricultural use and the aquifer geology.

The land-use map for the Big Thompson watershed shows different patterns in the upper and lower sub-watersheds (Figure 4). The upper sub-watershed is primarily forested, with tundra (indicated as barren land in Figure 4) in the headwaters above tree line. There is an exception in the area of Estes Park, where there is some urbanization and rangeland. The transition between the upper and lower sub-watersheds consists primarily of rangeland with shrub/scrub type vegetation. The lower sub-watershed is primarily agricultural land use, with a major urban center along the river at Loveland, and smaller urbanized areas at Johnstown, Milliken, and Berthoud.

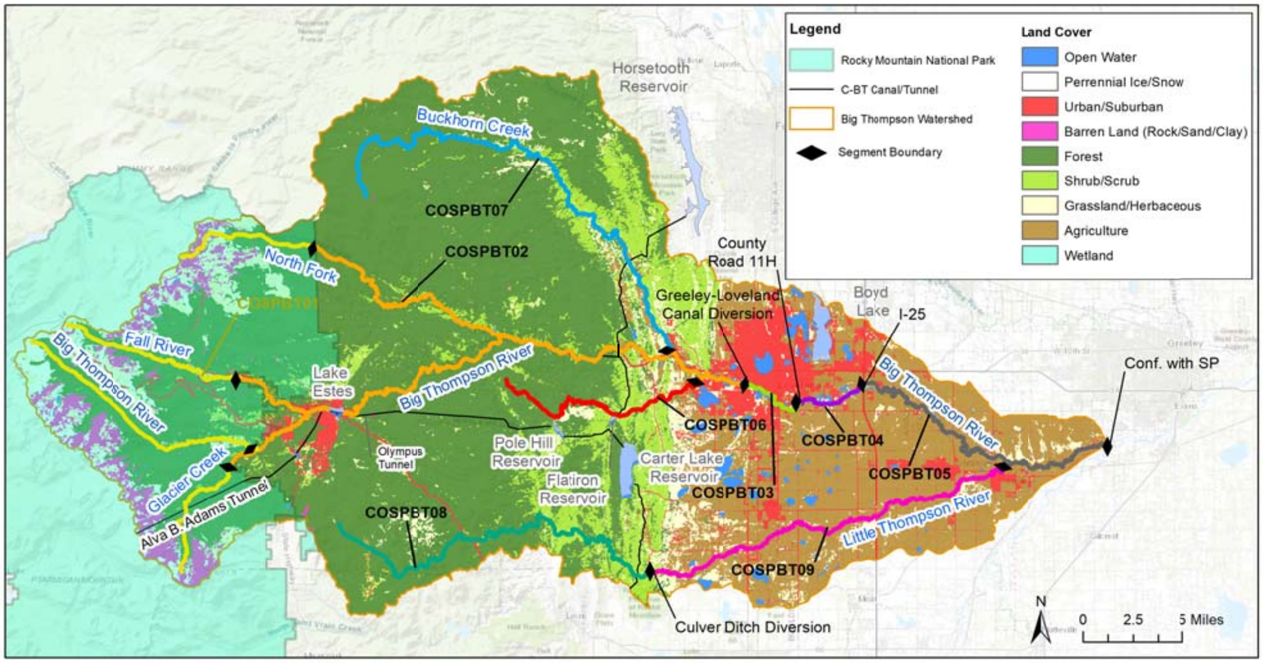


Figure 4. Current Land Use Map for the Big Thompson Watershed (Rodríguez-Jeangros 2017a and b)

1.1.3 Population Density Patterns and Wastewater Treatment Facilities

The population distribution in the watershed can be a useful consideration for understanding factors influencing water quality in a river. More-populated areas are often correlated with greater disturbance of natural channel shape, channel routing, and riparian vegetation, though this is not universally true. More-populated areas can also correlate to increased water-quality stresses on aquatic life due to road salts and other pollutants in runoff, as well as point discharges from industrial and/or municipal WWTFs.

The Big Thompson watershed has a total population of >118,000 based on the 2020 U.S. Census (U.S. Census Bureau, 2020). As depicted in Figure 5, most of the population is located in the lower watershed, thought there is a small center located in Estes Park. The largest and most dense population is in the urban area associated with the City of Loveland. There are also smaller apparent population centers corresponding to the smaller Cities of Johnstown, Milliken, and Berthoud in the Little Thompson watershed.

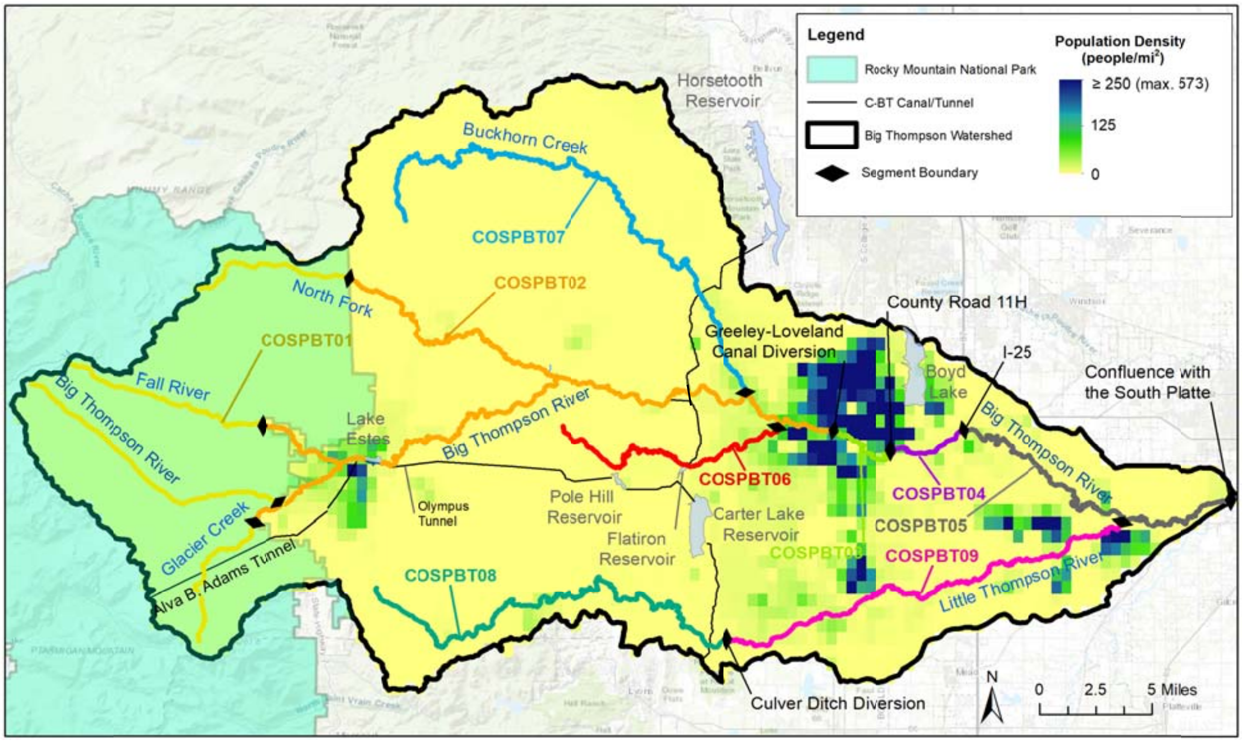


Figure 5. Population Density in the Big Thompson River Basin, (Center for International Earth Science Information Network - CIESIN - Columbia University, 2017)

With population centers comes the need for WWTFs. WWTFs serve an important function in the watershed, treating wastewater (to remove nutrients, organic matter, and other harmful constituents such as metals) and returning water to the river. While concentrations of nutrients, organic matter, and some metals are sharply reduced through treatment, concentrations in effluent are often higher than background concentrations in the river. Therefore, for many rivers, including the Big Thompson, WWTFs represent major point sources for loading of these contaminants of concern. Currently-permitted WWTFs in the Big Thompson Watershed are shown on Figure 6. As shown on the map, there are more WWTFs in the lower watershed than in the upper watershed, corresponding to the relative population differences.

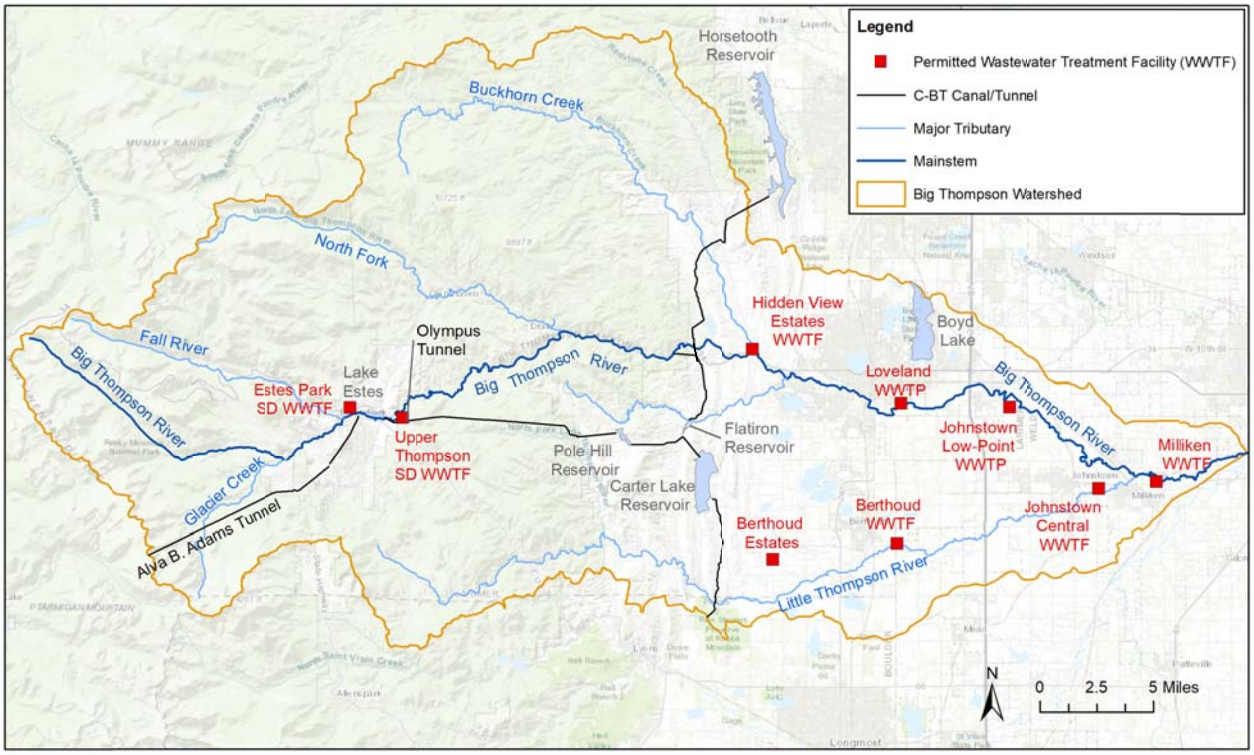
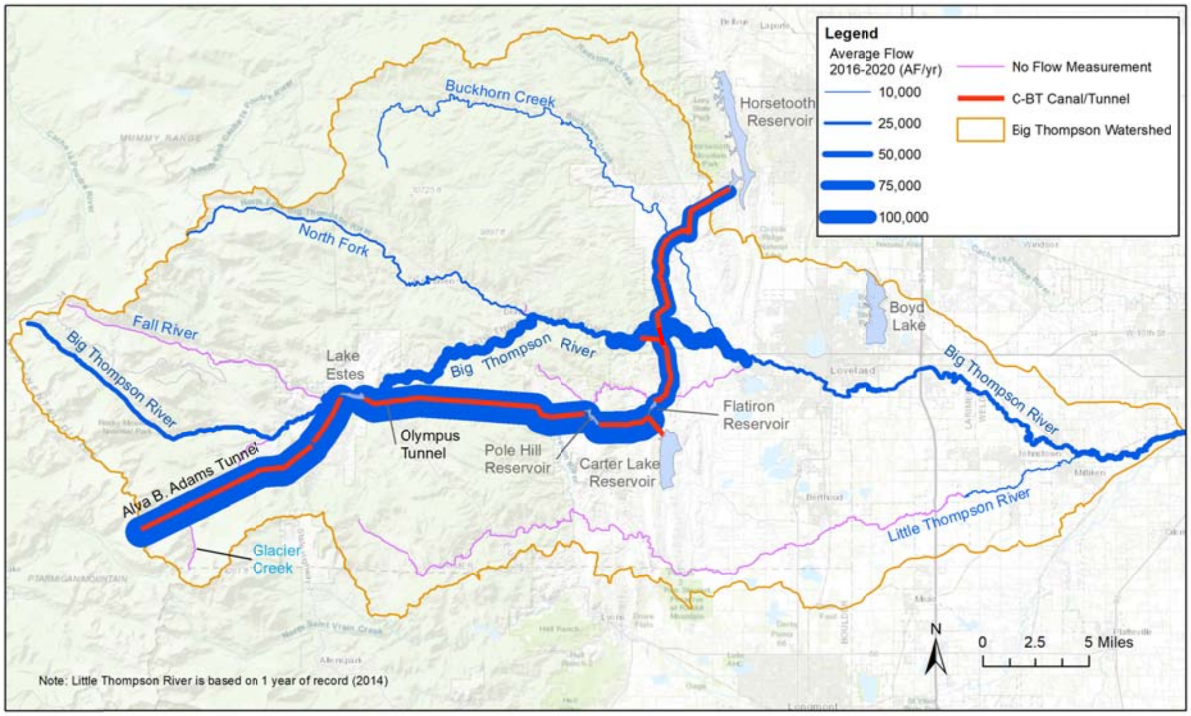


Figure 6. Permitted Domestic Wastewater Treatment Facilities in the Big Thompson Watershed

1.1.4 Water Management

There are numerous diversions and impoundment of water across the Big Thompson River, indicating a heavily managed system. The most significant water management activity in the Big Thompson River is the Colorado-Big Thompson (C-BT) Project. The Big Thompson Watershed serves as a conduit for Colorado's largest trans-basin water diversion, the C-BT Project. The C-BT system brings water from the headwaters of the upper Colorado River on the western slope of the continental divide to the eastern slope via the Adams Tunnel (Figure 1). C-BT water enters the Big Thompson River mainstem at Lake Estes.

Where it enters the Big Thompson River (just above Lake Estes), the C-BT Project contributes much more than twice as much water on an annual average basis as the natural watershed. The largest average annual flow volumes in the Big Thompson watershed are in the canal and tunnel structures of the C-BT Project (Figure 7).



Note: Little Thompson River is based on 1 year of record (2014)

Figure 7. Aortic Diagram of Flows in the Big Thompson Watershed (Annual Average 2016-2020)

From Lake Estes, a portion of the mixed waters from the C-BT and upper Big Thompson River is diverted into a system of tunnels and canals for delivery to downstream, off-channel reservoirs (Figure 7). These include Pole Hill Reservoir, Flatiron Reservoir, Carter Lake

Reservoir, and Horsetooth Reservoir. Construction of a new reservoir, Chimney Hollow Reservoir (to be located just west of Carter Lake Reservoir) began on August 16, 2021, as part of the Windy Gap Firming Project[7]. Near the canyon mouth, water can again be diverted from the Big Thompson River into the C-BT system toward Horsetooth Reservoir (Figure 7). Therefore, flows from the C-BT system mix with water in the Big Thompson River in two locations: (1) at Lake Estes and (2) in the upper watershed at the trifurcation structure located between the North Fork and Buckhorn Creek. Below the canyon mouth, populations increase and river flows are diminished by non-C-BT diversions (Figure 7). Continuing downstream, as the Big Thompson traverses the plains to the confluence with the South Platte River, flows are variable due to numerous irrigation and municipal diversions and returns.

The complexity of water management on the Big Thompson River is exemplified by the "trifurcation" structure (Figure 8), located near the canyon mouth. Water diverted through the Dille Tunnel serves three purposes:

1) Supply the City of Loveland with their decree water from the Big Thompson River, which they then take out of the Loveland Turnout further down on the Charles Hansen Feeder Canal;
2) "Skim" water and pass it through the Big Thompson Power Plant to generate electricity; and,
3) Divert water associated with C-BT water rights in the Big Thompson River during wetter years when the water right comes in priority.

Skim water is returned to the river at the trifurcation structure at the junction of the Charles Hansen Feeder Canal and Big Thompson Canyon. Figure 8 presents a simplified diagram of the trifurcation structure (for clarity, numerous unrelated diversions are not shown).

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[7] The Windy Gap Firming Project is collaboration between 12 northeastern water providers to improve the reliability of water supplies from the Windy Gap Project (which brings water from the western slope the eastern slope of northern Colorado through the C-BT system). Construction of Chimney Hollow Reservoir and associated infrastructure is expected to take roughly five years to complete. More information on the Windy Gap Firming Project is available here: https://watercenter.colostate.edu/wp-content/uploads/sites/33/2019/02/Windy-Gap-Firming-Project-Northern-Water.pdf.

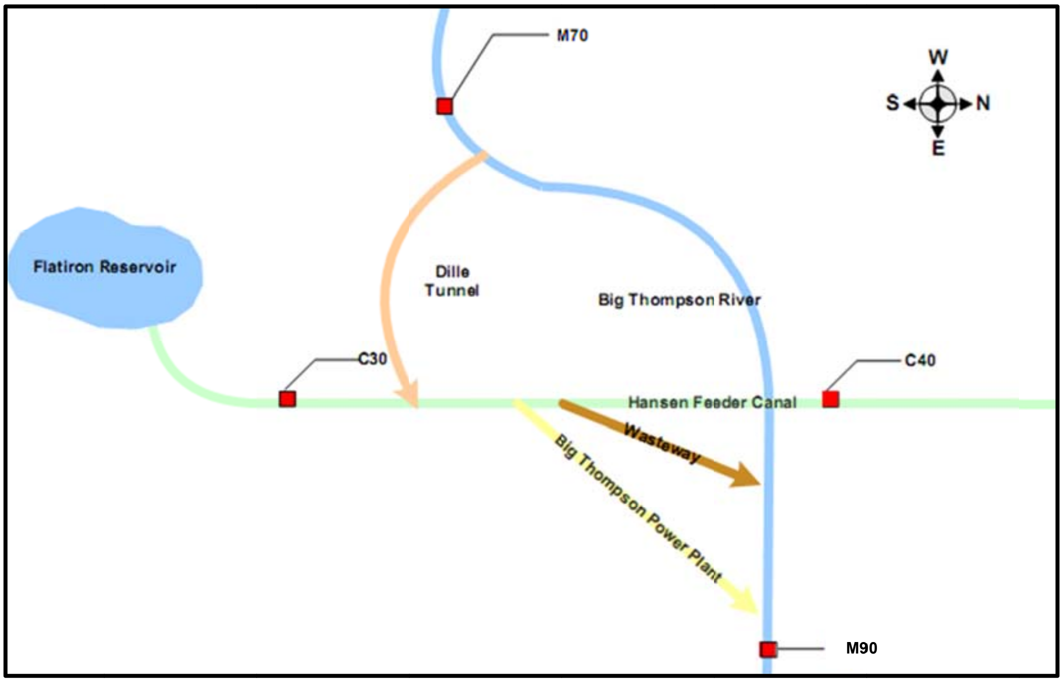

Figure 8. Simplified Depiction of the Trifurcation Structure

1.2 REGULATORY SETTING AND EXISTING WATER-QUALTY CONCERNS

The Big Thompson watershed is categorized for regulatory purposes into segments by the State of Colorado Water Quality Control Commission (WQCC). The segmentation along the Big Thompson River was modified in the June 8, 2020 rulemaking hearing for Regulation 38 (WQCC, 2020d), adjusting, combining, and removing some segments, resulting in the ten segments as shown in Figure 9 and summarized in Table 1.

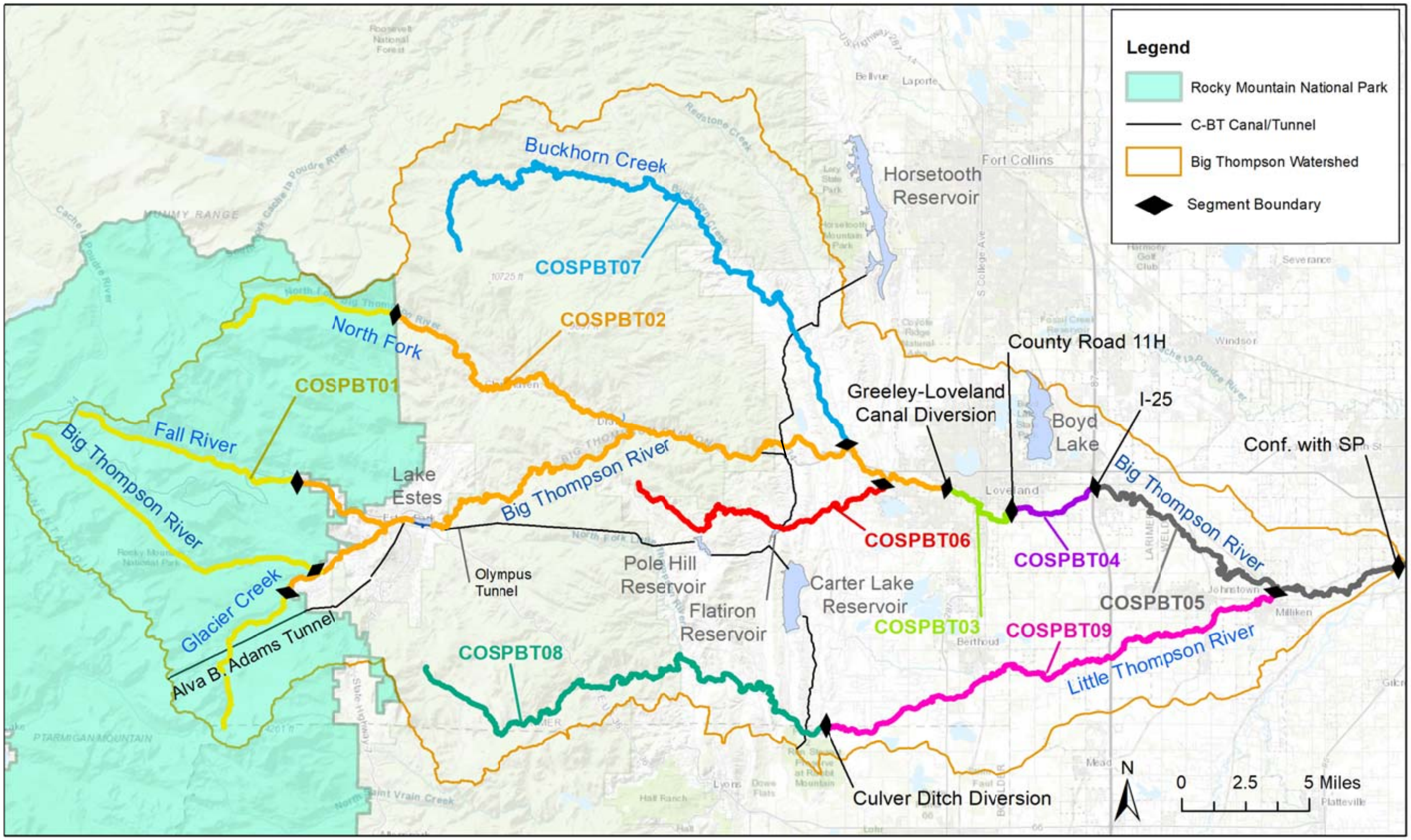

Figure 9. State of Colorado Regulatory Segmentation of the Big Thompson River and Tributaries

Table 1. Description of State of Colorado Regulatory Segments of the Big Thompson River and Tributaries

Segment #	Segment ID	Segment Extent Description
1	**COSPBT01**	Mainstem of the Big Thompson River, including all tributaries and wetlands, within Rocky Mountain National Park.
2	**COSPBT02**	Mainstem of the Big Thompson River from the boundary of Rocky Mountain National Park to the Greeley-Loveland Canal Diversion. All tributaries to the Big Thompson River, including all wetlands, from the boundary of Rocky Mountain National Park to the Home Supply Canal diversion.
3	**COSPBT03**	Mainstem of the Big Thompson River from the Greeley-Loveland Canal diversion to County Road 11H.
4	**COSPBT04**	Mainstem of the Big Thompson River from County Road 11H to I-25.
5	**COSPBT05**	Mainstem of The Big Thompson River from I-25 to the confluence with the South Platte River.
6	**COSPBT06**	All tributaries to the Big Thompson River, including all wetlands, from the Home Supply Canal diversion to the confluence with the South Platte River, except for listings in segments 7, 8, 9, and 10.
7	**COSPBT07**	Buckhorn Creek from the source to the confluence with the Big Thompson River.
8	**COSPBT08**	Mainstem of the Little Thompson River, including all tributaries and wetlands, from the source to the Culver Ditch diversion.
9	**COSPBT09**	Mainstem of the Little Thompson River from the Culver Ditch diversion to the confluence with the Big Thompson River.
10	**COSPBT10**	All tributaries to the Little Thompson River, including all wetlands, from the Culver Ditch diversion to the confluence with the Big Thompson River.

There have been a few consistent, long-term water-quality concerns in the Big Thompson, first noted by founding members of the Forum. Specifically, in 2007, the Forum officially identified phosphorus and nitrogen as constituents of concern for the watershed (Buirgy, 2007). Total organic carbon (TOC) has also been recognized as a concern in the watershed, due to the challenges it presents for drinking water treatment (Beggs et al., 2013).

Additionally, previous State of the Watershed data reviews (Hydros, 2010 and 2015) noted several consistent water-quality concerns relative to regulatory standards. These included copper in the upper watershed, selenium in the lower watershed, and Escherichia coli (*E. coli*) in the lower part of the lower watershed, including the lower Little Thompson River.

The WQCC has also identified water-quality concerns for various segments of the Big Thompson River and its tributaries by including them on Colorado's 2020 (most recent) 303(d) List[8] of impaired waters. For the Big Thompson watershed, the listed constituents are arsenic, copper, iron, macro-invertebrates[9], manganese, mercury, nitrate, selenium, zinc, *E. coli*, pH, and temperature (WQCC, 2020b). A summary of the current 303(d) listings in the Big Thompson River and tributaries is presented in Table 2. Figure 10(a-d) presents the current listings spatially. In addition to these 303(d) listings, *E. coli* is on the Monitoring and Evaluation (M&E[10]) List for Segment 5; and temperature is on the M&E list for Segment 8 (WQCC, 2020b). Current listings covering broad areas include arsenic, copper, and mercury over much of the upper watershed (Figure 10a, b, and c), and selenium over much of the lower watershed (Figure 10b).

The 2020 303(d) List for the Big Thompson watershed includes many changes from the listings reported in the previous State of the Watershed Report (Hydros, 2015). Several new constituents have appeared on the 303(d) List for the Big Thompson since the 2015 report, including arsenic, iron, macroinvertebrates, manganese, mercury, and nitrate. Several other constituents previously listed were de-listed since the 2015 report, including cadmium, dissolved oxygen, and sulfate.

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[8] The 303(d) List identifies water bodies where there are exceedances of water-quality standards or non-attainment of uses. This list of impaired waters is generally updated every two years by the WQCC. The list is submitted to EPA by the states as required by the Clean Water Act. The intent is to identify water-quality concerns triggering development of Total Maximum Daily Loads (TMDLs). At this point, TMDLs have not been developed for any segments of the Big Thompson Watershed, and the timing of TMDL development remains uncertain.

[9] Macroinvertebrates include a wide variety of animals lacking backbones that are large enough to be seen without the aid of a microscope. They include insects in their nymph and larval stages, snails, worms, crayfish, and clams that spend at least part of their lives in water. The type, density, and variety of macroinvertebrates present in an aquatic ecosystem are indicative of the health of the system.

[10] The M&E List identifies waterbodies where WQCC had identified reason to suspect water-quality problems, but believes there is also uncertainty regarding one or more factors, such as the representative nature of the data. Items on the M&E List do not yet require TMDL development and are listed as placeholders to re-evaluate when more data are available.

Table 2. 2020 303(d) Listings for Big Thompson Watershed Stream Segments.
See Colorado WQCC Regulation 93 at: http://www.cdphe.state.co.us/regulations/wqccregs

Segment ID	Segment Portion Description	Clean Water Act Section 303(d) Impairment	303(d) Relative Priority
COSPBT01	Mainstem of the Big Thompson River including all tributaries within Rocky Mountain National Park	Copper (Dissolved); Arsenic (Total); Zinc (Dissolved); Mercury (Total)	High
COSPBT02	Mainstem, including all tributaries and wetlands, from RMNP to Upper Thompson Sanitation District (UTSD) discharge	Arsenic (Total); Copper (Dissolved); Macro-invertebrates; Nitrate; Mercury (Total)	Low; Medium; High; High; High
	Mainstem Big Thompson from UTSD to Cedar Creek; mainstem of Black Canyon Creek and Glacier Creek; downstream of RMNP	Arsenic (Total); Copper (Dissolved); Mercury (Total)	Low; High; High
	Fish Creek below Mary's Lake	pH; Macro-invertebrates; Nitrate; Arsenic (Total)	High; High; High; Low
	Big Thompson Mainstem, including all tributaries and wetlands, from Cedar Creek to Home Supply Canal	Copper (Dissolved); Iron (Total); Temperature; Mercury (Total); Arsenic (Total)	High; High; High; High; Low
	Mainstem of the Big Thompson River from the Home Supply Canal diversion to the Big Barnes Ditch diversion	Arsenic (Total); Copper (Dissolved)	Low; Medium
	Mainstem of the Big Thompson from the Big Barnes Ditch diversion to the Greeley-Loveland Canal diversion	Selenium (Dissolved); Manganese (Dissolved)	High; Low
	North Fork of Big Thompson from RMNP to confluence	Copper (Dissolved); Mercury (Total); Arsenic (Total)	High; High; Low
COSPBT03	Mainstem of the Big Thompson from the Greeley-Loveland Canal diversion to County Road 11H	Selenium (Dissolved); Manganese (Dissolved); Arsenic (Total); Mercury (Total)	Low; Low; Low; High
COSPBT04	Big Thompson River, from County Road 11H to I-25	Mercury (Total)	Medium

Segment ID	Segment Portion Description	Clean Water Act Section 303(d) Impairment	303(d) Relative Priority
COSPBT05	Big Thompson River, I-25 to S. Platte River	Selenium (Dissolved); Mercury (Total)	Low; Medium
COSPBT06	All tributaries to the Big Thompson River, from Home Supply Canal to the confluence with the South Platte River.	Selenium (Dissolved)	Medium
COSPBT07	Mainstem of Buckhorn Creek from the source to the confluence with the Big Thompson River	Arsenic (Total); Mercury (Total)	Low, High
COSPBT08	Mainstem of the Little Thompson River, from source to the Culver Ditch diversion.	Arsenic (Total)	Low
COSPBT09	Mainstem of the Little Thompson River from Culver Ditch diversion to the Big Thompson River	Selenium (Dissolved); *E. coli* (May-October); Manganese (Dissolved)	Low; High; Low

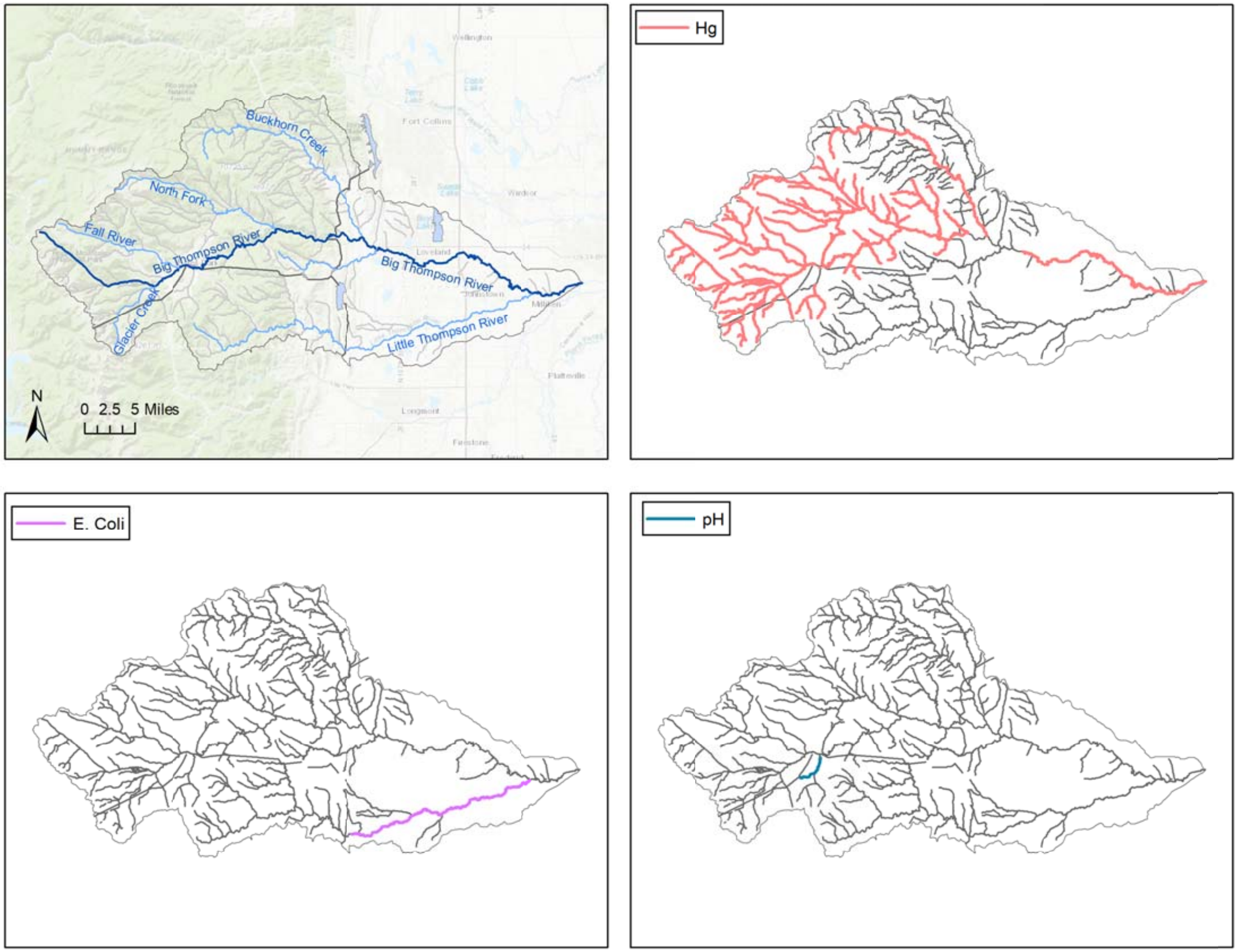

Figure 10a. 303(d)-Listed Stream Segments in the Big Thompson Watershed; Mercury, *E. coli*, and pH

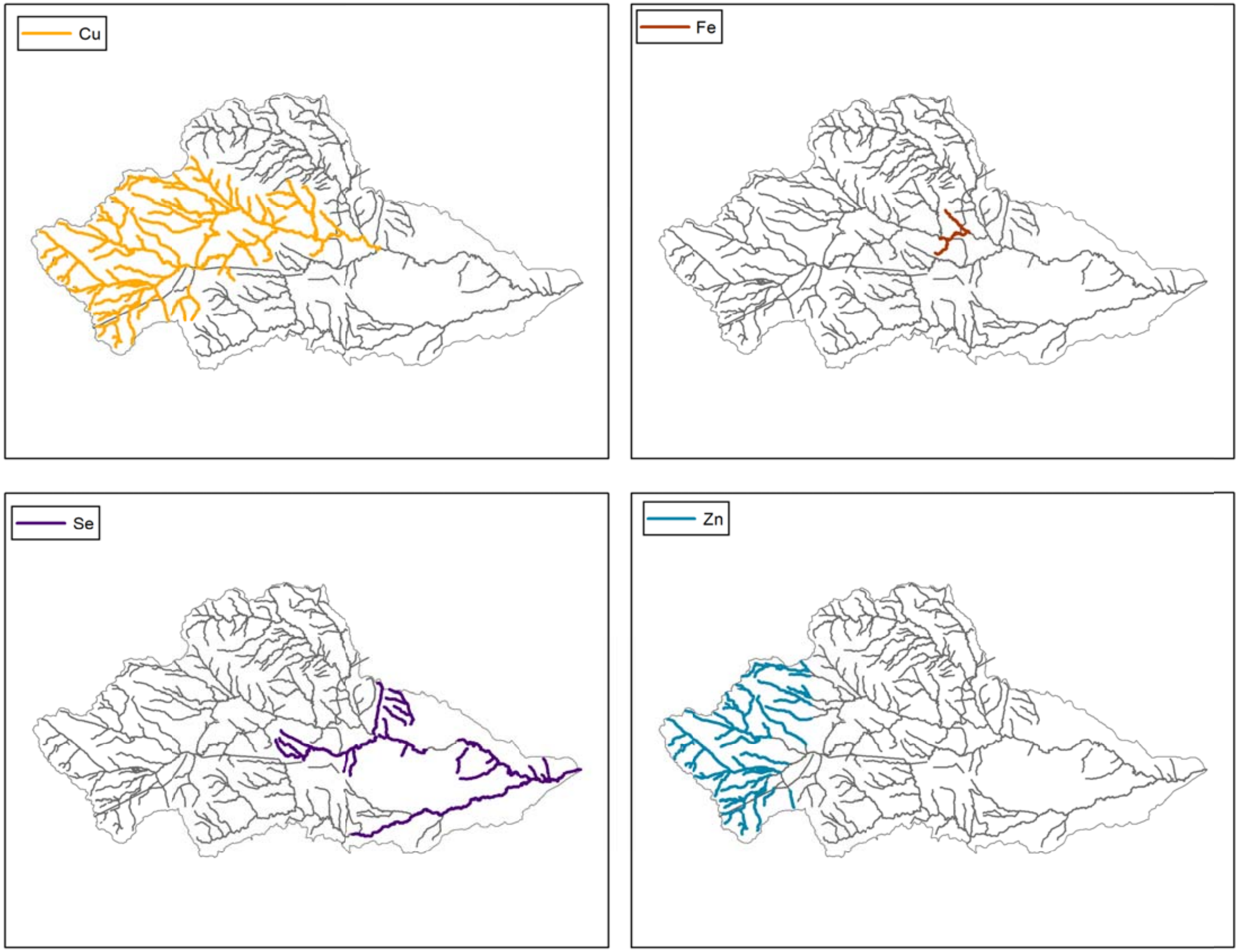

Figure 10b. 303(d)-Listed Stream Segments in the Big Thompson Watershed; Copper, Iron, Selenium, and Zinc

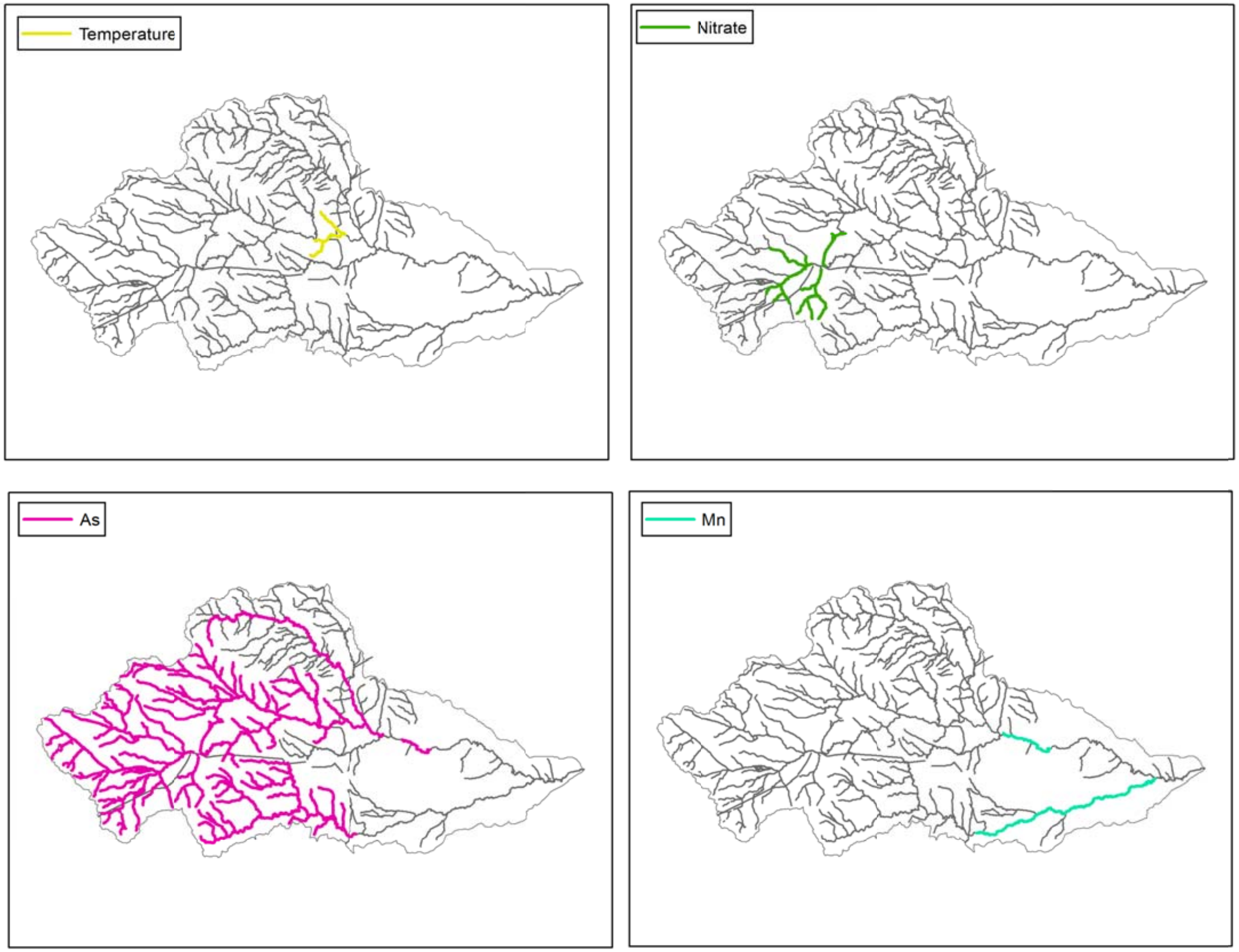

Figure 10c. 303(d)-Listed Stream Segments in the Big Thompson Watershed; Temperature, Nitrate, Arsenic, and Manganese

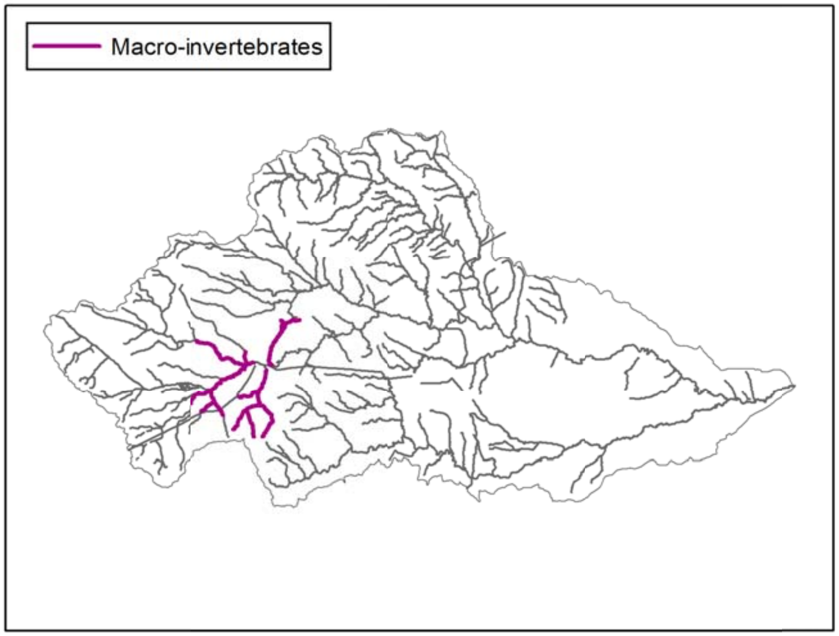

Figure 10d. 303(d)-Listed Stream Segments in the Big Thompson Watershed; Macro-invertebrates

1.3 RECENT MAJOR WATERSHED EVENTS

The recent decade (2010-2020) was eventful in the Big Thompson watershed. Significant population growth, major wildfires, record flooding, and major road reconstruction (including a resulting fish-kill) occurred during this period. These types of changes and disturbances can have significant effects on water quality and were a focus of data analysis for this report.

1.3.1 Population Growth

There has been a rapid increase in population across the Big Thompson watershed over the last ten years (U.S. Census Bureau, 2020). With the exception of Estes Park (with a population increase of 8%), all towns and cities in the watershed grew at a faster rate between the 2010 and 2020 Census than the average growth rate for the State of Colorado (14.5%). The City of Loveland population grew by 18%. The highest rates of growth occurred in the Little Thompson River sub-watershed, with a ten-year population growth rate in Berthoud, Johnstown, and Milliken of 75%, 54%, and 45%, respectively. Increased population can affect water quality in many ways. In addition to the need for more water (increased diversions), more-populated areas often coincide with greater disturbance of natural river channel shape, channel routing, and riparian vegetation, depending on urban planning. More-populated areas can also lead to increased water-quality stresses on aquatic life due to use of road salts, the presence of other pollutants such as fertilizers in runoff, and increased point discharges from municipal WWTFs. Possible water-quality effects related to population growth were considered in review of the Forum dataset and are described in Section 3.

1.3.2 Wildfires

Six major wildfires occurred within the watershed in the recent decade (2010-2020; Figure 11 and Figure 12):

- **Cow Creek Fire**: Started by lightning in June 2010 in the North Fork watershed within a remote area of Rocky Mountain National Park, this fire was eventually extinguished in November 2010 after burning 1,200 acres.

- **Crystal Fire**: Located west of Horsetooth Reservoir near Buckhorn Creek, this fire burned 3,000 acres in April 2011 after being started by an illegal open burn.

- **High Park Fire**: This fire was started on June 9, 2012 by a lightning strike in an area suffering from hot, dry conditions. The fire burned over 87,000 acres, destroying 259 homes before being fully contained on June 30, 2012. The majority of the burn area was located in the Cache la Poudre River watershed; however, the fire also affected the upper Buckhorn Creek of the Big Thompson watershed over a total of 21,606 acres.

- **Fern Lake Fire**: An illegal campfire started this high-elevation fire in October 2012 in Rocky Mountain National Park. The fire burned roughly 3,500 acres within the park before it was eventually extinguished by winter snows that began in December 2012.

- **Cameron Peak Fire**: The Cameron peak fire began on August 13, 2020 and, by October 14, became the largest recorded wildfire in Colorado's history. In total 208,913 acres were burned on the Arapaho and Roosevelt National Forests in Larimer and Jackson Counties and in Rocky Mountain National Park. 65,162 of those acres are located in the Big Thompson watershed. The fire was fully contained as of December 2, 2020. According to the National Wildfire Coordinating Group (NWCG), the cause of the Cameron Peak Fire is still unknown and under investigation (https://inciweb.nwcg.gov/incident/6964/).

- **East Troublesome Fire**: On October 22, 2020, the East Troublesome Fire, which began in Grand County on October 14, crossed the Continental Divide into the Big Thompson watershed. 100% containment was achieved on November 30, 2020. The fire burned a total of 193,812 acres, 4,894 acres of which are in the Big Thompson watershed. According to the National Wildfire Coordinating Group (NWCG), the cause of the East Troublesome Fire is still unknown and under investigation (https://inciweb.nwcg.gov/incident/7267/).

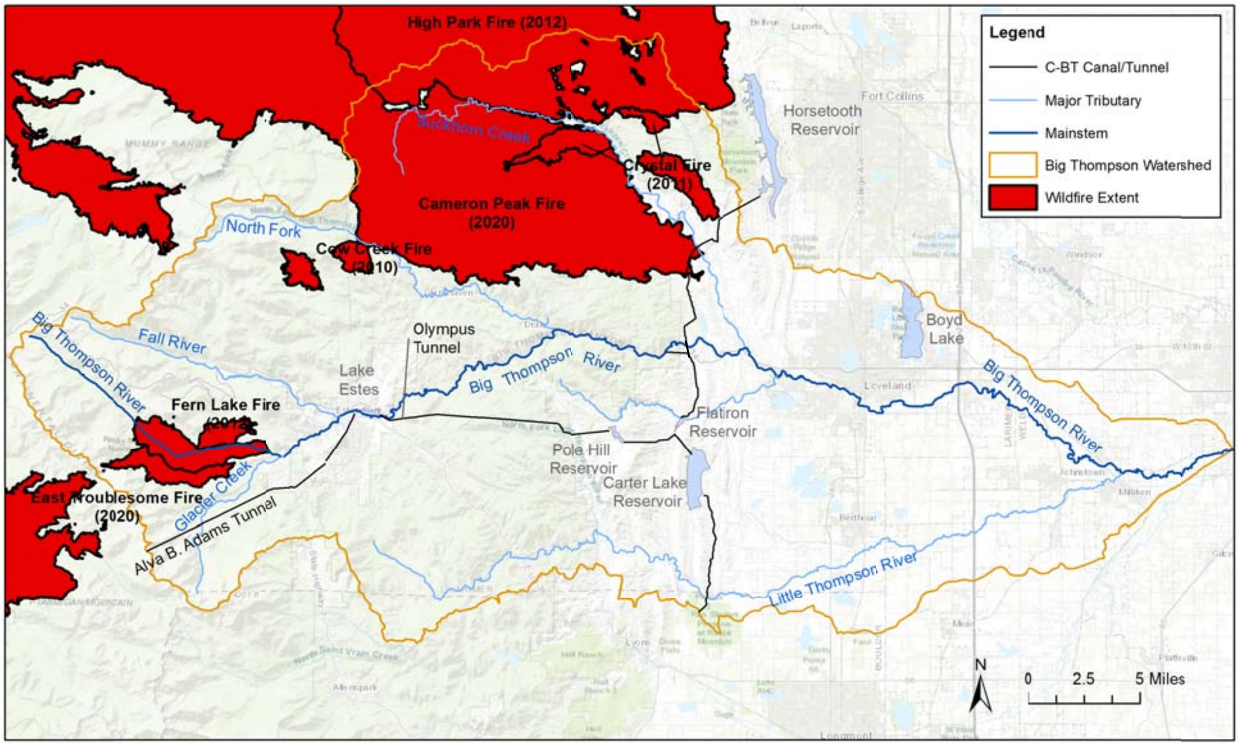

Figure 11. Location and Burn Extent of Recent Fires in the Big Thompson Watershed

Figure 12. Post-Fire Images: (Top Left) Fern Lake Fire Burn Scar in Forest Canyon (Photo: August, 2014 by J. Billica)**; (Top Right) High Park Burned Forest** (CDOT et al., 2012)**; (Bottom Left) Cameron Peak Fire as Seen From Estes Park, October 16, 2020** (Photo by Jim Urquhart, Reuters)**; (Bottom Right) Burned Park Land Following East Troublesome Fire, October 2020** (Photo Provided by Rocky Mountain National Park to Denver Post; article dated Oct 24, 2020).

Fires can have significant effects on surface water quality (e.g., Bitner et al., 2001, Ranalli, 2004, Neary et al., 2005; Rhoades et al., 2011; Rhoades et al., 2019; Rust et al., 2018). Effects may include increased sediment transport and delivery of ash to receiving waters. Increased suspended solids concentrations may bring increased metal concentrations. Due to ash loading, increased concentrations of organic carbon, calcium, magnesium, sodium, potassium, and chloride may be observed. Sulfate concentrations may also increase due to oxidation of sulfur present in soil organic matter. Increased nutrient concentrations (including nitrate, ammonia, organic nitrogen, orthophosphate, and total phosphorus) have also been observed in Colorado surface waters receiving runoff from areas affected by wildfire (e.g., Writer and Murphy, 2012, Oropeza and Heath, 2013, Son et al, 2015, and Rhoades et al., 2019). Note that any notable effects of the fall 2020 wildfires (Cameron Peak and East Troublesome fires) on the Big Thompson water quality will likely be apparent in data collected following the end of the study period for this report (WY2006-WY2020); therefore, subsequent studies should carefully consider any observed water-quality impacts.

1.3.3 September 2013 Flood

As described in the previous State of the Watershed Report (Hydros 2015), a record-breaking rainfall event in September of 2013 resulted in extensive flooding in the Big Thompson watershed. Estimates developed for the Colorado Water Conservation Board (CWCB) indicate that this was a 100- to more than 500-year flood for the Big Thompson and Little Thompson Rivers (CH2MHill, 2014, Jacobs, 2014, and Jacobs, 2015). Damage from flash flooding and debris flows was extensive, including homes, businesses and roadways (CWCB, 2014; Figure 13 through Figure 15 show examples of the flooding from upstream to downstream).

Flooding can impact water quality during and after flood events. Flooding can produce large sediment loads, bringing increased metals concentrations and other associated contaminants. Major flooding can modify and reroute drainages and introduce new contaminants to rivers by mobilizing material previously isolated from the river. Increased suspended solids concentrations (across the watershed) and increased baseflow (in the lower watershed) were noted over the first year following the flood (Hydros, 2015). Data were reviewed for any longer-term effects, as discussed in Section 3.

Figure 13. September 2013 Flooding, Fun City in Estes Park (Photo from Twitter by @TWCBreaking)

Figure 14. September 2013 Flooding, Highway 34 Big Thompson Canyon, Highway Damage (Photo by Andy Cross, The Denver Post)

Figure 15. September, 2013 Flooding on the Big Thompson River at 1st Street and Taft Avenue in Loveland, CO (Photo Courtesy of the City of Loveland)

1.3.4 Road Reconstruction Following 2013 Flood

Extensive reconstruction of roads and infrastructure was needed following the September 2013 flood. Following emergency repairs to reopen access to Estes Park and Rocky Mountain National Park, a multi-year project, led by the Colorado Department of Transportation (CDOT)

Flood Recovery Office was initiated in 2016. The project included rebuilding of bridges and repair of nearly 23 miles of U.S. 34, mostly between the City of Loveland and Estes Park. The project was largely completed in early 2019 at an estimated total cost of ~$280 million, with some minor repairs continuing into 2020. Reconstruction was designed to not only return road function, but also to make the road more resilient to floods in the future. The project also included critical river restoration work, which will benefit aquatic life in the Big Thompson watershed in the long-term.

While the CDOT-led construction project took all required precautions to protect river water quality during construction, increased erosion often occurs with such large-scale projects. Turbidity values, elevated well above typical levels, were observed over the 2017-2018 winter at real-time gages operated by the City of Loveland and the USGS upstream of intakes for water treatment (Fayram, 2018). Increases in turbidity, generally indicative of increased suspended solids concentrations, can also be associated with increases in metals and organic carbon concentrations. Increased turbidity and metals concentrations can have adverse effects on aquatic life in the river. High turbidity, metals, and organic carbon can all cause challenges for water treatment. Possible construction-related water-quality effects were considered in review of the Forum dataset described in Section 3, though it is recognized that shorter-term effects may not be apparent in the periodic/pre-scheduled sampling data included in the Forum database.

1.3.5 Fish Kill 2016

An accident occurred during reconstruction of the Storm Mountain Bridge on Larimer County Rd 43 near Drake. The bridge reconstruction was being conducted to repair damage from the 2013 flood, but was unaffiliated with the larger CDOT project on U.S. 34. On March 7, 2016, lime-based concrete was poured behind an earthen berm at the bridge reconstruction location on County Rd 43. That berm failed, allowing the unset concrete to enter the North Fork River and subsequently the Big Thompson River. As a result, the pH in the river increased sharply, along with turbidity and aluminum concentrations[11], resulting in a major fish kill. It is estimated that on the lower half mile of the North Fork, all of the fish in the river died during the incident, and roughly half of the fish died in the 8.3 mile stretch of the Big Thompson River between the North Fork confluence and the City of Loveland (CPW, 2016). In total, it is estimated that more than 5,600 fish died. Fish species killed in the incident include rainbow trout, brown trout, longnose suckers, and longnose dace.

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[11] Elevated aluminum concentrations, well above both previous observations and acute fish toxicity thresholds, were observed near the site of concern at Forum sampling station T10, which was sampled two days after the incident (on March 9, 2016; Fayram, 2017).

In response to the incident, the contractor was fined and agreed to monitor pH daily and better inspect materials used for earthen dams. No other fish kills were reported in the Big Thompson watershed during the multi-year construction efforts to rebuild roads and bridges following the 2013 flood.

1.4 REPORT OBJECTIVES

This report directly supports the Forum's mission and program goals through the review, analysis, assessment, and documentation of flow and water-quality data in the streams, rivers, and C-BT canals of the Big Thompson watershed. The assessment builds on four previous State of the Watershed reports that included analysis of data from the flowing water sites: Jassby and Goldman (2003), Haby and Loftis (2007), Hydros (2011), and Hydros (2015). Insights developed in those reports are reevaluated in this assessment with the context provided by the recent additional six years of data. This report attempts to answer the following questions based on review of monitoring data for the 15-year period of record (WY2006 – WY2020):

1. What is the current state of Big Thompson River water quality as revealed by the data collected for the Forum's monitoring programs?
2. What seasonal and spatial patterns are apparent in the water-quality parameter concentrations?
3. What are the statistically-significant long-term temporal trends in water-quality concentrations across the watershed?
4. What are the estimated annual and seasonal loads of nutrients and total organic carbon, and the spatial patterns of these loads?
5. How do water-quality data compare to applicable State of Colorado water-quality standards and interim nutrient criteria?

Additionally, monitoring program recommendations generated through this analysis are provided.

1.5 REPORT ORGANIZATION

This report is organized in five main text sections, with six appendices presenting the extensive supporting figures and tables. The main report is organized as follows:

- **Section 1 - Introduction and Background**
- **Section 2 – Dataset and Graphics** — This section presents the dataset, including description of the data treatment and handling. Section 2 also describes the calculations, statistical testing, and tabular and graphical products referenced throughout the remainder of the document.

- **Section 3 - Data Analysis** — This section presents findings of the analysis of the data, organized by parameter group.
- **Section 4 – Summary of Findings and Recommendations**
- **Section 5 - References**

The supporting appendices are organized as follows:

- **Appendix A** — Summary Statistics;
- **Appendix B** — Flow Rate Figures;
- **Appendix C** — Concentration Figures;
- **Appendix D** — Loading Calculation Results;
- **Appendix E** — Statistical Analysis of Long-Term Concentration Trends; and
- **Appendix F** — Comparison of Data to Compliance Values.

2 DATASET AND GRAPHICS

This section presents the dataset analyzed in this report, as well as a description of the graphical and statistical methods applied to evaluate the data.

2.1 DATASET

This report reviews and evaluates the water-quality and flow-rate data from rivers, streams, and C-BT canals in the Big Thompson watershed from WY2006 through WY2020. In total, the final dataset contains over 145,000 records for the focus parameters. These data were collected as part of the U.S. Geological Survey (USGS) Cooperative (COOP) Program[12] , by Northern Water, or as part of the Forum's Volunteer Monitoring Program, which was discontinued in November of 2015[13].

The water-quality database for this report was compiled by Leonard Rice Engineers on behalf of the Forum. That database excluded the historical Volunteer Monitoring Program data, so those data were added to the database from the dataset developed for the 2015 State of the Watershed Report (Hydros, 2015).

Water-quality and flow-rate summary statistics are presented in Appendix A, organized by parameter group. The summary statistics present the following information for each parameter at each station:

- Location,
- Units,
- Number of samples/ measurements,
- Number detected[14],

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[12] The Forum's Cooperative Monitoring (COOP) Program is a Joint Funding Agreement (JFA) with its major funders (City of Fort Collins, City of Greeley, City of Loveland, Northern Colorado Water Conservancy District, and Tri-Districts-Soldier Canyon Filter Plant) and the U.S. Geological Survey (USGS). For this program, USGS personnel collected all samples at flowing water sites. Analyses were split between three labs. The USGS NWQL analyzed for metals, nutrients and physical parameters;the Fort Collins water quality lab analyzed for total organic carbon and chlorophyll *a*; and the Loveland water quality lab analyzed for *E. coli* and total coliforms.

[13] The Forum's Volunteer Monitoring Program was a joint effort between the Forum and the U.S. Environmental Protection Agency Region VIII (USEPA8) which collected data from 2001 through 2015. In this program, Forum staff and watershed science volunteers collected water quality samples. Samples were analyzed by USEPA8 laboratories.

[14] Analytical equipment and procedures generally report a concentration limit below which the method is not sensitive enough to return a result. This value is called the detection limit. A detected result has a concentration above this limit, and a non-detect result has a concentration below this limit.

- Percent detected,
- Sampling date range,
- Range of observed detection limits,
- Range of observed concentrations,
- Mean concentration,
- Median concentration, and
- Standard deviation.

The following sections describe the sampling locations and parameters included in the dataset, as well as data treatment.

2.1.1 Sampling Locations

In total, 20 sampling stations[15] are included in this analysis, including 13 USGS COOP stations, two stations sampled by Northern Water that were formerly part of the Volunteer Monitoring Program (VT05 and VM05), and the five canal stations currently sampled by Northern Water and the USGS[16]. Figure 16 presents the location of each station on the watershed map. Table 3 lists the stations in approximate order from upstream to downstream, including identification of the sampling program and a brief description of the primary sampling objective(s) for each location.

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[15] Note that 11 stations from the Volunteer Monitoring Program were discontinued in 2015 and are not included in this report. These locations were included in the 2015 State of the Watershed Report (Hydros, 2015) but are excluded from this report because little to no additional data have been collected at these sites since the 2015 report.

[16] C10 and C20 are sampled by the USGS. C30, C40, and C50 are currently sampled by Northern Water.

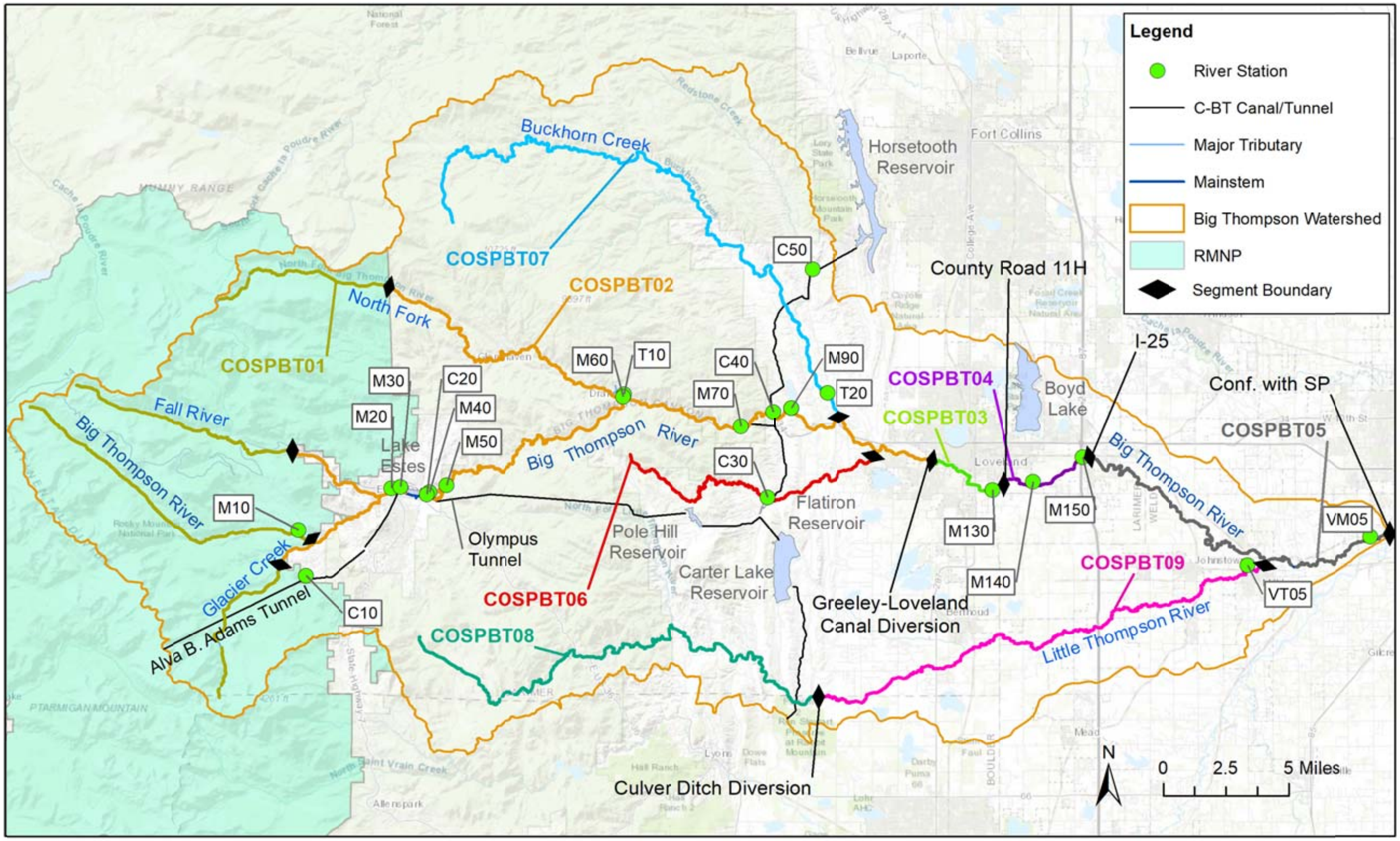

Figure 16. Locations of Sampling Stations

Table 3. Water-Quality Monitoring Stations

Station ID	Location Type	General Description	Station type	Stream Segment ID	Assessment Purpose
M10	Mainstem Big Thompson	Upstream	COOP	COSPBT01	Upstream-most sampling location; Located in Rocky Mountain National Park
M20	Mainstem Big Thompson	Upstream of Estes Park Sanitation District	COOP	COSPBT02	Impacts of runoff in Estes Park
M30	Mainstem Big Thompson	Downstream of Estes Park Sanitation District	COOP	COSPBT02	Indicates effects of Estes Park Sanitation District effluent
C10	Canal	Adams Tunnel – East Portal	Canal	n/a	Indicates C-BT water quality from west slope Three Lakes
C20	Canal	Olympus Tunnel	Canal	n/a	Lake Estes outflows; mixing of water from C-BT and Big Thompson watershed
M40	Mainstem Big Thompson	Downstream of Olympus Dam	COOP	COSPBT02	Assess baseline for Big Thompson River below Lake Estes and upstream of Upper Thompson Sanitation District
M50	Mainstem Big Thompson	Downstream of Upper Thompson Sanitation District	COOP	COSPBT02	Assess effects of Upper Thompson Sanitation District effluent

Station ID	Location Type	General Description	Station type	Stream Segment ID	Assessment Purpose
M60	Mainstem Big Thompson	Upstream of Confluence with North Fork	COOP	COSPBT02	Assess effects of upper canyon watershed inputs
T10	Tributary	North Fork Big Thompson	COOP	COSPBT02	Tributary input
M70	Mainstem Big Thompson	Upstream of Dille diversion	COOP	COSPBT02	North Fork and lower-canyon watershed inputs
C30	Canal	Hansen Feeder Canal – canal outlet of Flatiron Reservoir	Canal	n/a	Water quality for Hansen Feeder Canal out of Flatiron Reservoir and upstream of Dille Tunnel diversions
C40	Canal	Hanson Feeder Canal – downstream of trifurcation	Canal	n/a	Assess changes in Hansen Feeder Canal downstream of Dille Tunnel
C50	Canal	Hansen Feeder Canal – upstream of Horsetooth Reservoir	Canal	n/a	Input water to Horsetooth Reservoir
M90	Mainstem Big Thompson	Upstream of Loveland drinking water intake	COOP	COSPBT03	Big Thompson water quality upstream of Loveland Drinking Water intake
T20	Tributary	Buckhorn Creek	COOP	COSPBT07	Indicates water quality from Buckhorn Creek

Station ID	Location Type	General Description	Station type	Stream Segment ID	Assessment Purpose
M130	Mainstem Big Thompson	Upstream of Loveland WWTP	COOP	COSPBT04	Water quality upstream of Loveland WWTP effluent
M140	Mainstem Big Thompson	Downstream of Loveland WWTP	COOP	COSPBT04	Monitor effects of Loveland WWTP effluent
M150	Mainstem Big Thompson	At I-25	COOP	COSPBT05	Monitor downstream changes in Big Thompson (end of the COOP program)
VT05	Tributary	Little Thompson River – near confluence	Former-Volunteer	COSPBT09	Little Thompson tributary input, effects of Johnstown and Berthoud WWTP;
VM05	Mainstem Big Thompson	Near confluence with South Platte	Former-Volunteer	COSPBT05	Assess conditions at the end of the system and Town of Milliken WWTP

2.1.2 Parameters

The parameter list evaluated in this report was specified by the Forum. The parameters fall into five general categories (flow rate, metals, general parameters, nutrients, and microbiological parameters). The parameters included in this report are listed below, along with a brief basis for inclusion.

Flow Rate –- The Forum's database includes flow records for all 20 of the monitoring stations considered in this report (Figure 16). Measurement frequency varies from daily to approximately monthly. Thirteen of these stations are the COOP monitoring stations, five are C-BT canal stations, and two are former Volunteer Monitoring Program stations. The flow rate data are including in this report to support evaluation of the site hydrology (natural and operational) and to estimate loading rates.

Metals – The parameter list includes six metals:

- Arsenic,
- Copper,
- Cadmium,
- Lead,
- Selenium, and
- Zinc.

This report evaluates dissolved concentrations of all six metals on the list[17]. Of these six metals, four (arsenic, copper, selenium, and zinc) are on the 2020 303(d) List for flowing sites in the Big Thompson watershed (WQCC, 2020b; Table 2 and Figure 10a, b). Lead is included because it is currently on the 303(d) List for two water bodies that receive water from the Big Thompson River and the C-BT system, Lake Estes and Carter Lake (WQCC, 2020b). Finally, cadmium is not on the current 303(d) List for the Big Thompson flowing sites or receiving waters; however, it was previously listed in the watershed (WQCC, 2012).

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[17] For arsenic, use of total arsenic data (not dissolved arsenic) would have been preferred since that is the measure that is applicable to the widespread 303(d) listings in the Big Thompson watershed; however, there were major gaps in the total arsenic dataset making it largely unusable. First, total arsenic data were only available at seven sites (the canal sites [C10, C20, C30, C40, and C50] and at M70 and M90). No total arsenic data were available from the other 13 sites in this study. Further, the detection limits increased and sampling frequency decreased for total arsenic at the seven sampled sites in 2013/2014. As a result, 87 to 95% of the analytical results for total arsenic at these locations are non-detects in the recent five years. It is recommended, given the extensive 303(d) listings, to add total arsenic to the regular analyte list for laboratory analysis at all flowing locations in the watershed. Further, a method providing a detection limit of 0.05 µg/L or less is recommended (based on the historical range of detected results). The current detection limit for total arsenic in samples from recent years is 0.4 µg/L, which explains the high fraction of non-detect results.

Note that the list of metals considered does not include mercury, iron, or manganese, all of which are on the current 303(d) List for flowing sites in the watershed (WQCC, 2020b; Table 2 and Figure 10a, b, and c). Future data analysis efforts may benefit from inclusion of these parameters.

General Parameters – There are nine[18] general parameters included in this assessment:

- Alkalinity (a measure of a water's buffering capacity against changes in pH),
- Dissolved oxygen (a measure of gaseous oxygen dissolved into water),
- Hardness (a measure of the mineral content of water, usually dominated by calcium [Ca^{2+}], and magnesium [Mg^{2+}]),
- pH (a measure of hydrogen ion activity in water; water with pH< 7 is acidic, water with pH>7 is basic),
- Specific conductivity (a measure of the concentration of ions in solution),
- Sulfate[19] (an oxidized anionic form of sulfur),
- Water temperature,
- Total organic carbon (TOC; a measure of naturally occurring organic matter [terrestrial sources and in situ algal sources] plus organic matter from anthropogenic sources [including wastewater effluent and agriculture runoff]), and
- Total suspended solids (TSS; a measure of mass of solids in a water sample).

These parameters are included in this report because they provide a wide-spectrum review of the overall physical, chemical, and biological conditions present in the watershed. Hardness is included because it is used for the evaluation of the toxicity of metals. Additionally, pH and temperature are directly relevant to evaluation of the toxicity of ammonia, and both are on current the 303(d) List for flowing sites in the watershed (WQCC, 2020b; Table 2 and Figure 10a, c). Finally, TOC is included because it is a critical parameter of interest for drinking water treatment plants.

Nutrients – The parameter list includes seven measures of nutrients (four nitrogen and three phosphorus parameters):

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[18] Note that turbidity data were excluded from this analysis over concerns from the Forum about comparability of turbidity data with NTU and NTRU units. Excluding data with either unit would leave an extremely limited dataset from which few, if any, patterns could be assessed (Thorpe and Hartenstine, 2021 email communication).

[19] Sulfates are an essential plant nutrient and are naturally occurring, often resulting from decay of organic matter. Sulfates can be introduced to rivers at higher than natural concentrations by WWTF effluent, fertilized agricultural lands, or atmospheric deposition. Sulfates can also be present in surface water at high concentrations due to water from rock or soil containing high sulfur minerals such as gypsum. Pierre Shale, a source of selenium, can also be a source of sulfate.

- Total nitrogen,
- Ammonia nitrogen,
- Total Kjeldahl nitrogen (TKN; sum of organic nitrogen plus ammonia),
- Nitrate + nitrite,
- Total phosphorus,
- Dissolved phosphorus, and
- Orthophosphate.

The nitrogen and phosphorus parameters listed above are included in this report because the Forum long ago identified nutrients as constituents of concern for the watershed (Buirgy, 2007). Further, the 2015 State of the Watershed Report (Hydros, 2015) identified widespread potential future concerns for total nitrogen and total phosphorus concentrations at flowing sites in the Big Thompson watershed relative to the State of Colorado interim nutrient criteria (Regulation 31; WQCC, 2020c). While total nitrogen and total phosphorus interim nutrient criteria are not yet applicable standards over most of the watershed's flowing sites, total phosphorus standards are in place for segment 1 and parts of segment 2. Further, nitrate is currently on the 303(d) List for a small area in the upper watershed (WQCC, 2020b; Table 2 and Figure 10c)

Microbiological Parameters – The parameter list includes two measures of bacteria:

- Total Coliforms, and
- Escherichia Coliforms (*E. coli*).

These parameters are included in this report because *E. coli* is on the current 303(d) List for the Little Thompson River (WQCC, 2020b; Table 2 and Figure 10a).

2.1.3 Data Treatment

Data processing was conducted to prepare the dataset for graphical review and statistical analysis. The goals of the data processing for this report were to reconcile duplicate/replicate data, make full use of subcomponent data, and manage results below detection limits. This section describes the data processing rules applied to the Forum dataset.

Duplicates

For some parameters and stations evaluated, there were duplicate or replicate entries in the database—meaning multiple results for a given station, sampling date, parameter, and sampling fraction. These multiple entries were often due to field duplicates and field replicates. A single result for each discrete station/date/parameter/fraction combination was selected by applying the following rules:

1. If all of the duplicate results for a given station, date, parameter, and fraction are below detection limits, the lowest detection limit was taken, and the result were designated as a non-detect.

2. If at least one detected result was found, the maximum detected result was taken.

The intention behind these rules to was to garner as much information from results below detection limits and to avoid obscuring detected results with duplicate non-detect results at high detection limits.

Missing Totals

In some cases, the analytical result for a parameter of interest was not available for a given date/location, but the analytical results for the various fractions comprising that parameter were available. For example, in some cases TKN was not reported; however, ammonia and organic nitrogen were available. To fully utilize the available data, summing of analytical results was performed as necessary. The calculation of sums was done using the following approach:

1. If sub-analyte A and sub-analyte B were both detected, the direct sum was used and reported as detected.

2. If sub-analyte A and sub-analyte B were both below detection limits, the highest detection limit was reported, and the value was reported as non-detect.

3. If sub-analyte A was detected but sub-analyte B was below detection limits, the value for sub-analyte A plus half the detection limit for sub-analyte B was reported for the sum.

Non-Detect Results

In analytical chemistry, the detection limit is defined as the lowest quantity of a substance that can be distinguished from the absence of that substance by the test method. In cases where the chemical concentration is below the detection limit, the laboratory will report the result as non-detect. For many of the parameters in this report, existing concentrations are often below detection limits. Detection limits at or above concentrations of interest (e.g., regulatory thresholds) or a high frequency of non-detect results can bias the findings of an analysis. Detection limits can also change over time if different analytical methods are applied, which can bias data analysis, including trend testing, if it is not addressed directly. Therefore, it is important to understand, at a minimum, the range of detection limits and the frequency of non-detect results in a dataset to appropriately design analyses and interpret results.

The summary statistics presented in Appendix A present the range of detection limits and the percent of samples above detection limits for each station and parameter. High percentages (>50%) of non-detect results were observed at some locations in part or all of the study period for the following parameters:

- Metals: Cadmium, copper, and lead;
- General Parameters: TSS; and
- Nutrients: Ammonia and orthophosphate.

In general, non-detect results are set to half the detection limit for analyses in this report, with two exceptions:

1. Loading - For ammonia and orthophosphate, loading estimates were generated in two ways: (1) setting non-detect results to half detection limits (consistent with other analytes), and (2) setting non-detect results to zero. This approach allowed for an assessment of the effect of detection limits on the results for these parameters with higher non-detect frequencies.
2. Trend Testing: High-biasing non-detect (HBND) results were identified as non-detect values with a detection limit greater than the median of the detected values for that constituent at that location. These HBND values were excluded from trend testing to avoid artificial identification of trends due to trends in laboratory detection limits.

This approach is generally consistent with treatment of non-detect results in the previous watershed reports (Jassby and Goldman, 2003; Haby and Loftis, 2007, Hydros, 2011 and 2015).

2.2 STATISTICAL AND GRAPHICAL METHODS

This section provides a detailed description of the graphical presentations and statistical analyses of the data in this report.

2.2.1 Concentration Figures

A primary objective of this assessment is to review the temporal (including seasonality[20]) and spatial patterns in the water-quality dataset. Consistent with the two most-recent State of the Watershed reports (Hydros, 2011 and 2015), two general plot types were developed to support visualization of the data for all focus parameters: (1) concentration time-series plots and (2) concentration box plots.

The concentration time-series plots allow for visual review of temporal patterns in the dataset. These plots are presented in Appendix C1. The time-series plots present several types of information:

- **Data**: The individual concentration results over the full 15 year period of record for a given station and parameter are provided on the scatterplot. Additionally, these plots show seasonality through data point color and shape. The plots also show the patterns

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[13] Seasonality was defined by the Forum Science and Monitoring Committee for the 2011 and 2015 State of the Watershed studies, based on a detailed understanding of the patterns in the datasets. Three seasons were defined as follows: Fall (August through October); Winter (November through March); and Summer (April through July).

in analytical detections, with non-detect results included at the full detection limit but designated by a hollow symbol.

- **Compliance Values**: Where applicable and present within the selected y-axis scale, a compliance standard level (or interim criteria value for nutrients) is also indicated on these plots. Note that the most-stringent applicable compliance value for the location/parameter is shown; however, it is only shown for reference. In many cases the standard is not applicable for review against each data point (but is instead assessed against a summary metric of the data). Compliance values are discussed in greater detail in Section 2.2.3.
- **Trends**: For cases where trend testing indicated a statistically-significant temporal trend over the 15-year period of record, a dashed trend line is shown, reflecting the slope of that trend (trend testing is discussed in greater detail in Section 2.2.2)

An example time-series concentration plot is shown below in Figure 17.

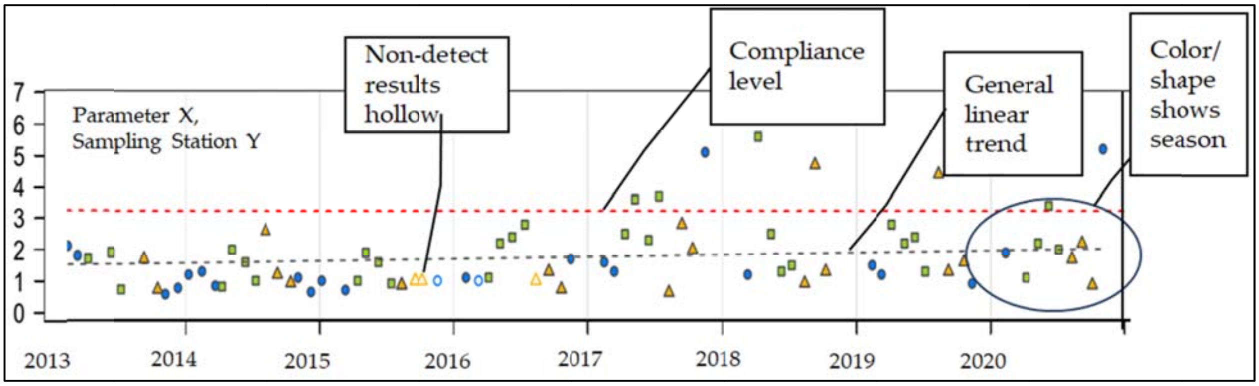

Figure 17. Example Concentration Time-Series Plot (Truncated to Exclude 2006-2012)

In addition, at the bottom of each panel on the time-series concentrations plots, there is a small station location map (e.g., Figure 18). This was added to support informed review of the plots.

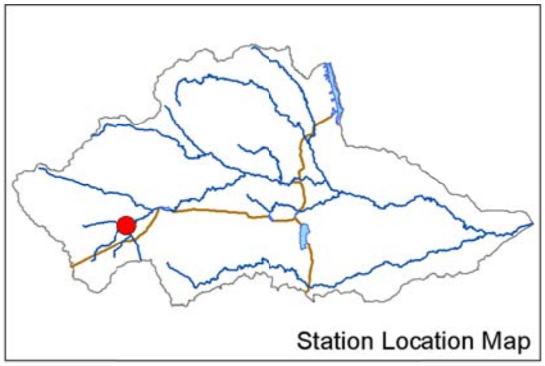

Figure 18. Example Station Location Map, Showing M20

The concentration box plots allow for visual review of the spatial trends in the dataset. These plots are presented in Appendix C2. The concentration box plots present visual statistical summaries of the full 15-year dataset for a given parameter across the watershed. For each station, the concentration results are shown using a box and whisker plot. These plots provide an indication of both the range and central tendency of the measured data. Figure 19 provides an explanation of the boxplot construction.

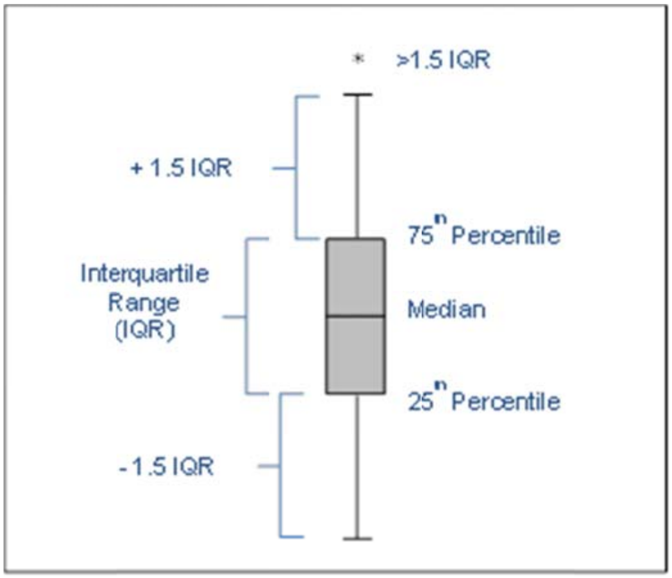

Figure 19. Example Box and Whisker Plot

The boxplots are presented in combined plots for each parameter, ordered generally from upstream to downstream to facilitate review for spatial patterns. Station types are differentiated with shading to indicate stations on the mainstem of the Big Thompson River, stations on natural tributaries to the Big Thompson River, and off-channel canal locations.

2.2.2 Concentration Trend Testing

Testing for statistically-significant trends in concentration over the 15-year period of record at each station was another Forum objective for this assessment. To accomplish this, the Seasonal Mann-Kendall trend test was applied. This is a robust, non-parametric test that accounts for seasonal variation without sensitivity to outliers or non-normality in the data (Helsel and Hirsch, 1992). The test was run using R, an open source programming language and software environment for statistical computing and graphics. The wql package, Version 0..4.9 (Jassby et al., 2017), provided the functional code to run the test in R.

Trend testing was run for all parameters and stations, and returned values estimating the statistical significance (p-values[21]) and magnitude (Sen slope[22]) of the trends in the dataset. The "seasons" in this test were set to 12 per year (monthly). This temporal interval was the shortest duration supported by the data and the method (note: the method ignores missing data). This minimized potential error associated with assignment of larger "seasons" that may not accurately describe the annual patterns in the dataset. The test results were not considered if all data for the parameter/station were below detection limits. Further, non-detect results were set to half the detection limit, with HBND results removed (as descried in Section 2.1.3). A confidence interval of 90% (critical p-value = 0.10) was set by the Forum's Science and Monitoring committee as a threshold for identifying potential trends for the previous State of the Watershed reports (Hydros, 2011 and 2015), so the same confidence interval was used here. Lastly, interpretation of trending in the results should always consider a visual review of the time-series dataset. That approach was followed in the data analysis section (Section 3) of this report.

A table summarizing the results of the Seasonal Mann-Kendall testing is presented in Appendix E. For each station and parameter, this table presents: the number of samples, the percent detection, the p-values (with p-values < 0.1 shaded if the Sen slope was also non-zero), and the Sen slopes (expressed as a percent of the mean for relative comparison of magnitude). For cases with p-values <0.1 and non-zero Sen slopes, the Sen slopes are represented on the concentration time-series plots (Appendix C1). Slopes, however, were not plotted on the concentration time-series plots if a station/parameter had three or fewer years of data.

2.2.3 Compliance Analysis and Standards

The water-quality data were assessed relative to Colorado's applicable numeric water-quality standards, in accordance with State Regulation 38 (WQCC, 2020d) and State Regulation 31 (WQCC, 2020c). It should be noted that all 15 years of record were evaluated against the most recently published Colorado water-quality regulations. Standards have changed over time, and this analysis is not intended to assess actual compliance during each year of record. The information provided does not constitute a legal interpretation of current or historical compliance. Instead, this analysis assesses patterns in the dataset relative to the most recent water-quality standard values for informational purposes only.

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[14] P-values are a measure of the statistical significance of the apparent trend. A lower p-value indicates greater confidence that the observed trend is statistically significant. For example, a p-value of 0.05 corresponds to a finding that the observed trend is statistically significant at a 95% confidence value.

[22] The Sen slope (also called Theil or Theil-Sen slope) is the median slope joining all observation pairs and represents an estimate of the magnitude of the trend in the dataset. An observation pair is a set of two values that represent the same month during two different years.

Of the parameters discussed in this report, numeric water-quality standards are presented in Regulation 38 for the following in river segments of the Big Thompson watershed:

- Ammonia,
- Arsenic,
- Cadmium,
- Copper,
- Dissolved Oxygen,
- *E. coli*,
- Lead,
- Nitrate,
- pH
- Phosphorus (Total),
- Selenium,
- Sulfate,
- Temperature, and
- Zinc.

Total phosphorus standards are only applicable at this time in Segment 1 and part of Segment 2. For informational purposes, recognizing potential future applicability, the interim nutrient criteria values for total phosphorus were compared to observed data at all other non-canal locations. Similarly, total nitrogen concentrations were compared to the interim numeric values in Regulation 31 (WQCC, 2020d) at all non-canal locations.

Standards are assigned by stream segment with some cases of variation in applicability within a given segment. Therefore, standards are specific to each sampling station. Further, standards can vary over time and by other water-quality conditions:

- Constant numeric threshold(s):
  - pH, *E. coli*, arsenic, sulfate, nitrate, and selenium.
- Seasonally varying thresholds:
  - Temperature and dissolved oxygen.
- Hardness dependent thresholds:
  - Cadmium, copper, lead, and zinc.
- Season-, temperature-, and pH-based thresholds:
  - Ammonia.

For hardness-based aquatic life standards (cadmium, copper, lead, and zinc), the hardness value for the corresponding sample data/location was used to calculate the standard value. A summary of the applicable metals standards is presented in Table 4, and a summary of the non-metals standards is presented in Table 5. For some parameters, different standards apply to the different classifications (i.e., aquatic life, domestic water supply, agriculture, recreation); the standards presented in Tables 3 and 4 represent the most stringent classification for that parameter at that sampling station.

Table 4. Site Specific Water-Quality Criteria, Aquatic Life Acute and Chronic Standards for Metals (all units μg/L)

Seg.	Station	Arsenic (Dissolved–Acute; Total-Chronic)		Cadmium (Dissolved)		Copper (Dissolved)		Lead (Dissolved)		Selenium (Dissolved)		Zinc (Dissolved)	
		Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute	Chronic
1	M10	340	0.02	HD-t[1]	HD-t[1]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
2	M20	340	0.02*	HD-t[1]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M30	340	0.02*	HD-t[1]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M40	340	0.02*	HD-t[1]	HD[2]	11.0	7.50	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M50	340	0.02*	HD-t[1]	HD[2]	11.0	7.50	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M60	340	0.02*	HD-t[1]	HD[2]	11.0	7.50	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M70	340	0.02*	HD-t[1]	HD[2]	11.0	7.50	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	T10	340	0.02*	HD-t[1]	HD[2]	11.0	7.50	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
3	M90	340	0.02*	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
4	M130	340	7.6	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	M140	340	7.6	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
5	M150	340	0.02*	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
	VM05	340	0.02*	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
7	T20	340	0.02*	HD-t[1]	HD-t[1]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]
9	VT05	340	HD[2]	HD[2]	HD[2]	HD[3]	HD[3]	HD[4]	HD[4]	18.4	4.6	HD[5]	HD[5]

* Temporary Modification until 12/31/24 – Arsenic (chronic) = hybrid for dischargers, i.e., current conditions for existing dischargers or up to 3 μg/L for new or increased dischargers. Note: Flowing sites data compared to 0.02 μg/L in this report.

[1] HD-t indicates Hardness Dependent-trout; Acute (Trout) = (1.136672-[ln(hardness) x (0.041838)])*e^(0.9789[ln(hardness)]-3.866)

[2] HD indicates Hardness Dependent; Acute = (1.136672-[ln(hardness) x (0.041838)])*e^(0.9789[ln(hardness)]-3.443);
Chronic = (1.101672-[ln(hardness) x (0.041838)])*e^(0.7977[ln(hardness)]-3.909)

[3] Acute = e^(0.9422[ln(hardness)]-1.7408); Chronic = e^(0.8545[ln(hardness)]-1.7428)

[4] Acute = (1.46203-[ln(hardness) x (0.145712)])*e^(1.273[ln(hardness)]-1.46);
Chronic = (1.46203-[ln(hardness) x (0.145712)])*e(1.273[ln(hardness)]-4.705)

[5] Acute = 0.978 e^(0.9094[ln(hardness)]+0.9095); Chronic = 0.986 e^(0.9094[ln(hardness)]+0.6235)

Table 5. Site Specific Water-Quality Criteria, Non-Metals

		Nutrients (All mg/L)				**Micro-biological (cfu/100 mL)**	**General**			
							mg/L	**stu**	**mg/L**	**Classification[2]**
Seg.	**Station**	**TN* (acute)**	**TP (acute)**	**Ammonia (acute, chronic)**	**Nitrate (acute)**	***E. coli* (chronic)**	**DO (chronic)**	**pH (min, max)**	**Sulfate (chronic)**	**Temperature (acute, chronic)**
1	M10	1.25*	0.11	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-1
2	M20	1.25*	0.11	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M30	1.25*	0.11	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M40	1.25*	0.11	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M50	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M60	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M70	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	M90	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
	T10	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
3	M90	2.01*	0.17*	Var.	10	126	5	6.5 to 9.0	250	WS-I
4	M130	2.01*	0.17*	Var.	100	126	5	6.5 to 9.0	--	WS-I
	M140	2.01*	0.17*	Var.	100	126	5	6.5 to 9.0	--	WS-I
5	M150	2.01*	0.17*	Var.	10	126	5	6.5 to 9.0	250	WS-I
	VM05	2.01*	0.17*	Var.	10	125	5	6.5 to 9.0	250	WS-I
7	T20	1.25*	0.11*	Var.	10	126	6.0, 7.0[1]	6.5 to 9.0	250	CS-II
9	VT05	2.01*	0.17	Var.	10	126	5	6.5 to 9.0	250	WS-I

* Noted interim nutrient criteria values are not currently applicable for the noted stations, but may be considered for adoption as water-quality standards prior to or after May 31, 2022, depending on determination by the WQCC.

-- Indicates no applicable standard at this location.

Var. Indicates ammonia standard value varies depending on pH, temperature, season, and segment (See Regulation 31, WQCC, 2020c)

[1] First value is for non-spawning time period (assumed to be August 1-April 30), second value is for spawning period (assumed to be May 1 –July 31).

[2] Designates seasonal table value temperature standards: Acute standards: CS-I: June-Sept 21.7 °C, Oct-May 13°C; CS-II: April-Oct 24.3°C, Nov-Mar 13°C; WS-I: Mar-Nov 29°C, Dec-Feb 24.6°C.

Non-detect results were not compared to compliance values, though they are included in the denominator of calculations of percent compliance. In other words, regardless of the detection limit value, non-detect results were considered to be in compliance for this analysis. This handling of non-detects is consistent with the listing methodology used by WQCD for the 303(d) listing process (WQCC, 2020a).

The compliance assessment results for each station are presented in Appendix F as compliance percent results (percent of observations above standard values) for each parameter for the complete data set. Compliance percent results are also summarized for each year of record in separate tables in Appendix F. Note that compliance percent results are simple comparisons of observed values to standard values and do not take into account assessment timeframes or allowable exceedance frequencies. As a reminder, these results are not intended to comprise an assessment of compliance with standards; instead, they are included to provide information on spatial and temporal patterns in the data relative to standard thresholds.

2.2.4 Loading Calculations

Loading in flowing waters refers to the mass of a parameter passing a given location over a given time interval. Loading calculations were generated for nutrient parameters and TOC for stations with adequate flow records. Loads were calculated on a monthly basis and summed to generate seasonal and annual loads. For each month, average flow rates and concentrations were generated from the full dataset to support the calculations. Non-detect results were set to half the detection limit prior to development of average concentrations. For ammonia and orthophosphate, loading calculations were also run with non-detect results set to zero. This allowed an assessment of the effects of frequent non-detect results and variable detection limits on the loading calculations for those two parameters.

To calculate monthly loads, values for both flow rate and concentration were needed for each month. Representative monthly flows and concentrations were calculated as the arithmetic mean of all data in a given month. Flow rates and concentrations for months with no sampling data were estimated by interpolation between the previous and subsequent observed results.

The loading estimates for 2013 do not account for loads associated with the September 2013 flood event. It is recognized that the extremely high flows would be associated with large loadings. However, as described in the previous State of the Watershed Report (Hydros, 2015), samples were not collected during the rising limb, peak or falling limb of the flood (for safety reasons). Sampling occurred just before and approximately 4-6 weeks following the start of the event. Therefore, as in the previous report (Hydros, 2015), loading estimates for 2013 exclude the September flood.

Loading estimates are presented in two ways to allow for both spatial and temporal (including seasonal) review. First, the annual loading results are presented as box plots, with all stations presented on a single figure for a given parameter. These plots, presented in Appendix D1, follow the general format described above (Section 2.2.1) for concentration box plots. Second, the loading estimates are presented annually by station with the seasonal breakdown for each year of data. These figures are called loading bar graphs and are presented in Appendix D2. In contrast to other data presentations that provide a full 15-year data record, loading bar graphs are limited to the most recent 10 years. An example segment of a bar graph is shown below in Figure 20.

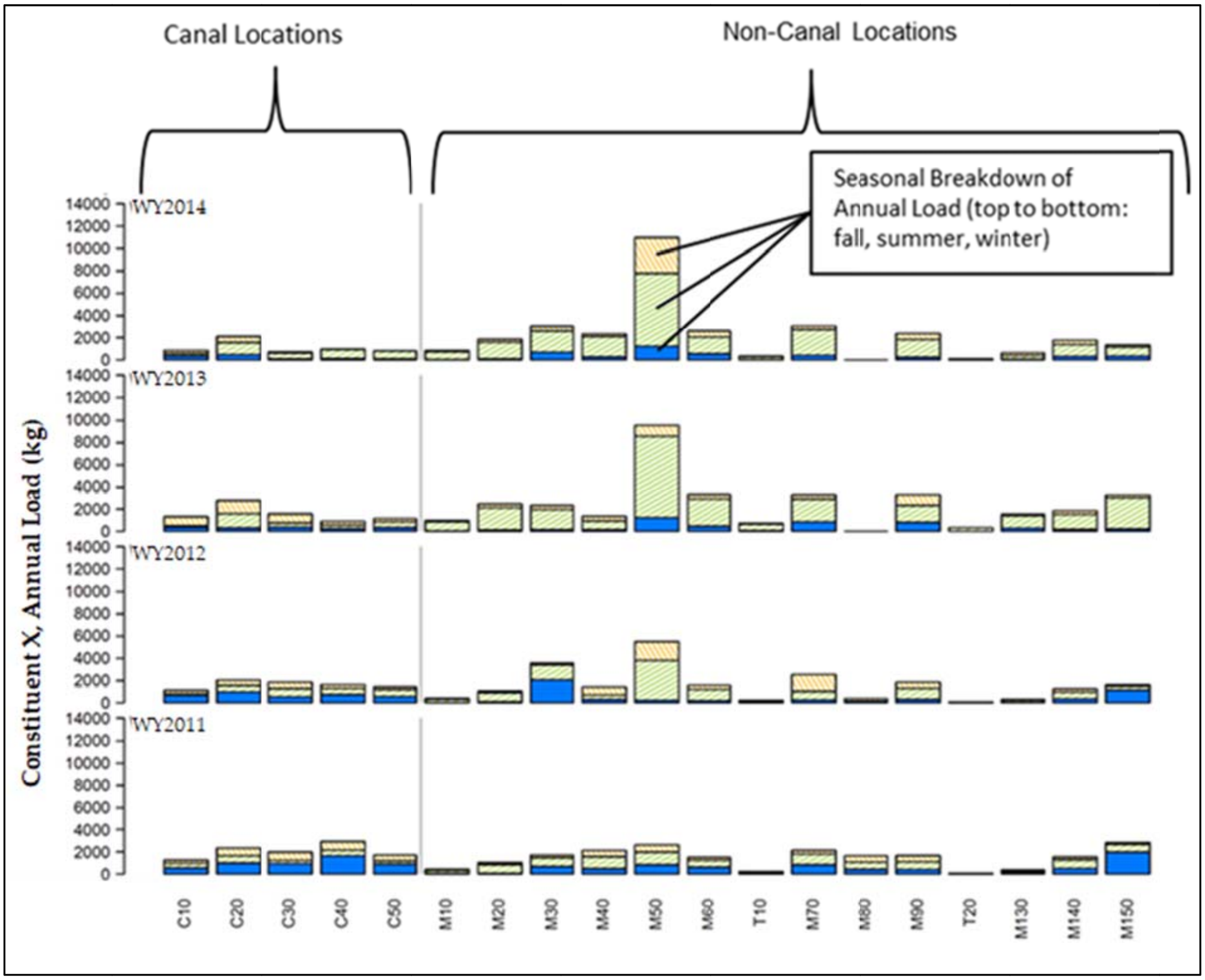

Figure 20. Hypothetical Example Loading Bar Graph

Annual loading estimates are also presented in tabular form in Appendix D3. The table groups estimates by station and parameter. The table also presents annual flow-weighted mean concentrations, which were estimated by dividing the total annual load by the annual flow volume.

3 DATA ANALYSIS

This section presents discussions of water quality across the watershed based on review of the time-series plots, concentration box plots, loading analysis, trend testing, and compliance analysis. The discussions are organized by parameter group (flow rate, nutrients, metals, microbiological parameters, and general parameters). The analysis presented here is based on supporting figures and tables presented in Appendices A through F:

Appendix A. Summary Statistics
Appendix B. Flow Rate Figures
    B1. Time-series Flow Rate Records
    B2. Flow Volume Plots
Appendix C. Concentration Figures
    C1. Time-series Concentration Plots
    C2. Concentration Box Plots
Appendix D. Loading Calculation Results
    D1. Loading Box Plots
    D2. Loading Bar Graphs
    D3. Annual Loading Tables
Appendix E. Statistical Analysis of Long-Term Concentration Trends
Appendix F. Compliance Assessment Results

3.1 FLOW RATES

Flow records were compiled and reviewed for the 13 COOP, five canal, and two volunteer stations shown in Figure 16. The frequency of flow rate measurements varies from daily to ≤10 per year. Flow rate records were plotted in two ways to show temporal and spatial patterns. First, all observed flow rates were plotted for each station for the period of record (WY2006-WY2020). These plots are presented in Appendix B1. Second, box plots and seasonal bar graphs were generated using flow volume totals for each station. These graphics are presented in Appendix B2.

3.1.1 Mainstem Upstream to Downstream

Annual flow rates from upstream to downstream exhibit a consistent pattern in most years along the mainstem of the Big Thompson River, and the recent five year pattern matches that of the longer-term record (Figure 21):

- Annual flows increase in the upper sub-watershed between M10 and M20, reflecting inflows from Glacier Creek and Fall River.

- There tends to be a decrease in annual flow volume downstream of the Olympus Tunnel at M40, reflecting diversions to the C-BT system

- Flow rates tend to increase moving downstream to near the canyon mouth at M90, reflecting inflows from the North Fork and local watershed. North Fork flows comprise an average of ~20% of the flow in the Big Thompson River where they meet.

- There is a sharp drop in annual flow volumes between M90 and M130. This drop in flow volumes reflects the effects of major irrigation and municipal water diversions, including the City of Loveland drinking water treatment plant intake (below M90). Buckhorn Creek enters the Big Thompson River in this reach; however, it comprises less than 10% of the annual mainstem flow at this location.

- From M130 to the confluence with the South Platte, annual flow volumes are variable, reflecting diversions, return flows, and gains. There is an increase in flow near the downstream end of the river (Figure 21), due to inflows from the Little Thompson River, which comprise roughly 25% of the flow in the river at confluence with the South Platte.

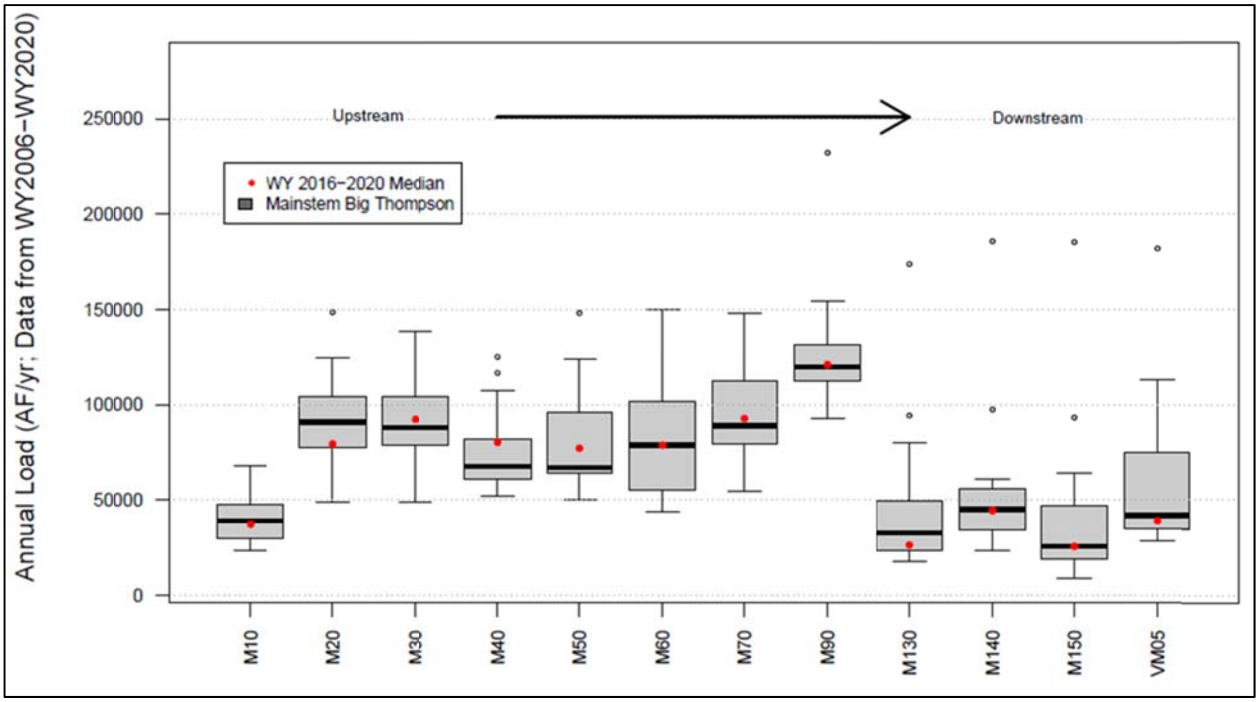

Figure 21. Box Plot Summary of Mainstem Annual Flow Volumes (AF/yr; WY2006-WY2020)

3.1.2 Seasonal Patterns

Seasonal flow patterns vary widely across the watershed (Figure 22). The differences are due to variations in natural runoff, diversions, and land use.

- **Canals** - The canal stations (e.g., C10 on Figure 22) show flow operational patterns of the C-BT system that are dramatically different than natural flow patterns across most of the Big Thompson River. While canal flow rates can be high any time of the year, the C-BT system typically brings high flow rates from the west slope in winter months (much higher than natural flow rates in the mainstem of the Big Thompson River), to help fill Horsetooth Reservoir and Carter Lake. As seen in the averaged conditions of Figure 7, annual flow volumes through the canals are typically much higher than flows in the river at gaged locations.

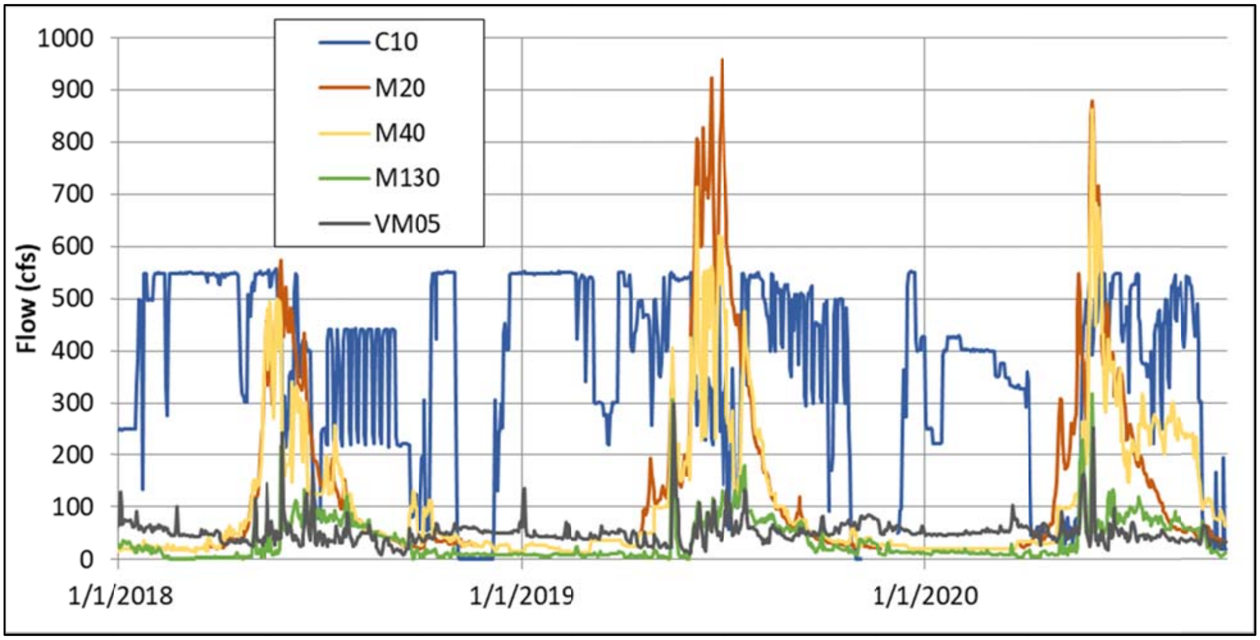

Figure 22. Flow Records from C10, M20, M40, M130, VM05; 2018 - 2020

- **Annual Snowmelt Peak in the Upper Watershed** - At the top of the watershed in Rocky Mountain National Park, annual Big Thompson River hydrographs are dominated by the snowmelt peaks in spring, with the lowest flows in winter months. The recent 15-year record includes years with relatively high snowmelt runoff, such as 2011, and relatively low runoff, such as 2012 (Figure 23). Snowmelt-driven flow rates above Lake Estes (e.g., M20 on Figure 22) typically peak on the hydrograph between May and June with a falling limb extending into September. Below Lake Estes (e.g., M40 on Figure 22), the snowmelt hydrograph peaks are still apparent, but are diminished in some years by operation of the reservoir and C-BT diversions to the Olympus Tunnel (e.g., 2019 in Figure 22).

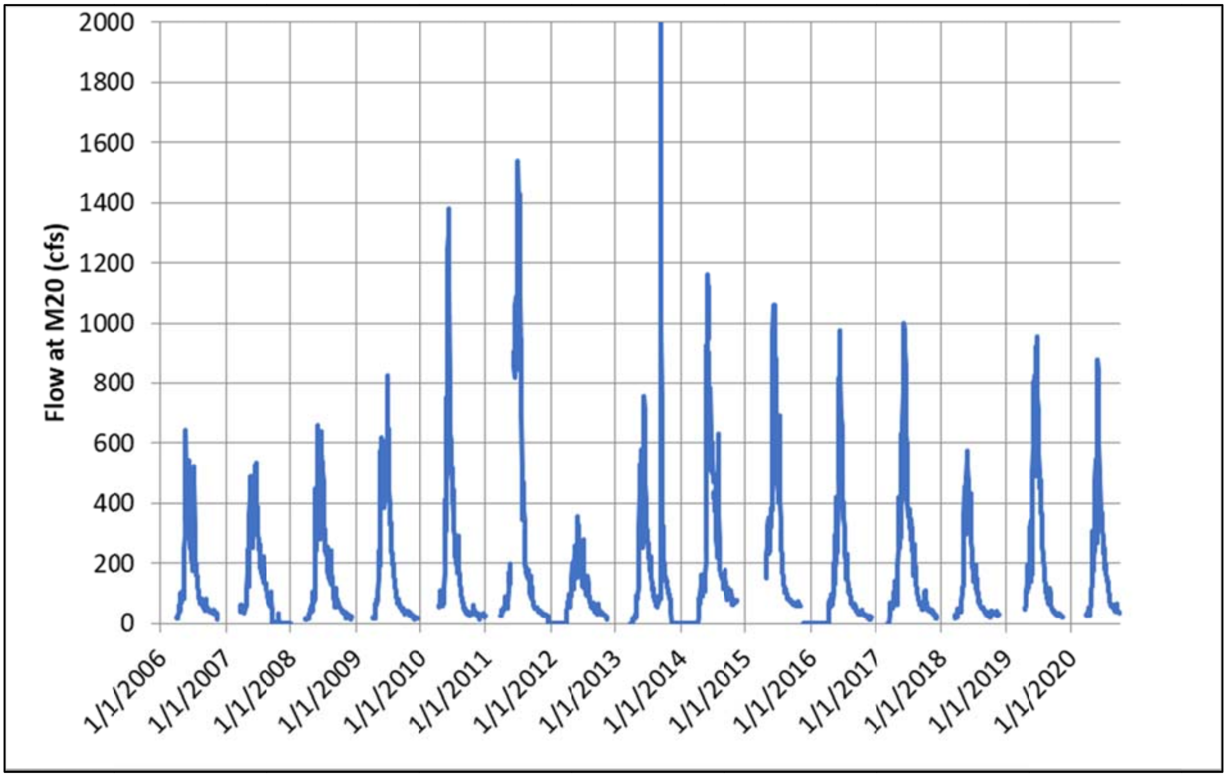

Figure 23. Flow Records from M20, 2006 - 2020

- **Annual Snowmelt Peak in the Lower Watershed and Major Diversions** - Downstream of the mouth of the canyon, in the more populated areas of the lower watershed from Loveland to the South Platte (e.g., M130 and VM05 on Figure 22), the snowmelt hydrograph peaks are often greatly reduced relative to the upper watershed. This drop in flow rates from the upper watershed to the lower watershed during the runoff hydrograph reflects the effects of major irrigation and municipal water diversions. These include the City of Loveland drinking water treatment plant intake (below M90) and other diversion such as Home Supply, Handy, South Side, Louden, Big Barnes, Chubbuck, and Farmers.

- **Winter Flow Rates** - While flow rates are sharply lower in spring and summer in the lower watershed as compared to the upper watershed, winter flows tend to be higher at the downstream end of the watershed (VM05 in Figure 22). This reflects lower watershed inflows to the river from groundwater and wastewater effluent.

- **Storm Response** - The greater percent of impervious surfaces present in the urban areas results in a "flashier" flow rate response in the river, reacting to precipitation events with sharp hydrograph peaks (e.g., see M130 and VM05 on Figure 22).

3.1.3 September 2013 Flooding

As described in Section 1.3.3, a week of record-breaking rainfall totals in September of 2013 resulted in extensive flooding across the Front Range. Estimates developed for CDOT and the CWCB indicate that this was a 100- to more than 500-year flood in the Big Thompson and the Little Thompson Rivers with peak flow rates ranging from 5,000 to over 20,000 cfs across the mainstem (CH2MHill 2014, Jacobs, 2014, and Jacobs, 2015).

The September 2013 flooding also increased the baseflow into the Big Thompson and Little Thompson Rivers, particularly in the downstream areas (e.g., M130 and downstream) where notable amounts of alluvium are present allowing for greater amounts of shallow groundwater (Figure 3). These alluvial deposits were recharged by the flood event, increasing groundwater levels and resulting in greater inflow of groundwater as baseflow to the river, which is most apparent in winter months. As shown in Figure 24, flow rates in the winter between 2013 and 2014 were notably elevated in the lower watershed (e.g., M130, VM05) relative to previous years. The pattern continued but diminished in subsequent years. The effect was apparent for two years at M130, but continued for three years at VM05 (Figure 24). The longer effect at VM05 is expected to be due to the more extensive and deeper alluvial valleys upstream of this station, as compared to M130. In contrast, winter flow rates in the upper watershed (e.g., M20 and M40) did not show a clear post-flood increase (Figure 24), likely due to lack of notable alluvium for shallow groundwater storage in that part of the river (Figure 3).

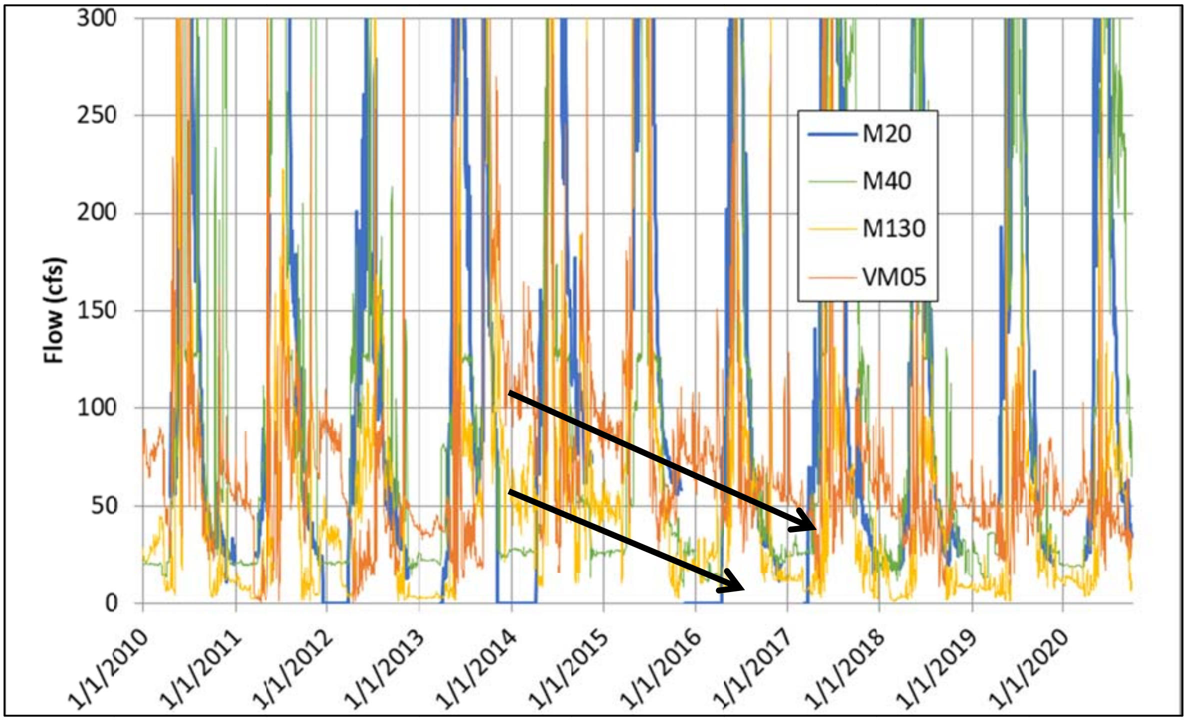

Figure 24. Hydrographs M20, M40, M130, VM05; 2010-2020; Focus on Lower Flow Rates, Black Arrows Show Diminishing Effect of Increased Winter Baseflow at M130 and VM05 Following the 2013 Flood

3.2 NUTRIENTS

The Forum has long recognized nutrients as constituents of concern for the watershed (Buirgy, 2007). This was further supported by findings in the previous State of the Watershed Reports (Hydros, 2011 and 2015). Seven measures of nutrients are included in this data review:

- Nitrogen parameters:
    - Ammonia nitrogen,
    - Total Kjeldahl nitrogen (TKN; = organic nitrogen + ammonia nitrogen),
    - Nitrate + nitrite, and
    - Total nitrogen (= TKN + nitrate + nitrite).

- Phosphorus parameters:
    - Total phosphorus,
    - Dissolved phosphorus, and
    - Orthophosphate.

Nitrogen and phosphorus are macronutrients that serve as chemical building blocks for plant and animal life; however, in excess, they can lead to degradation of water quality through the effects of over fertilization (eutrophication) and toxicity.

- Nitrogen exists in various forms in natural waters as it moves through the nitrogen cycle, including: dissolved nitrogen gas (N_2), organic nitrogen, ammonia, ammonium ion, nitrite, and nitrate. Certain forms of nitrogen can be toxic to fish or animals at elevated concentrations. For example, ammonia can be toxic to fish when present in the un-ionized form [NH_3], which is dominant at higher pH; and nitrate in drinking water can be toxic to infants. Ammonia can also lead to oxygen depletion and increased nitrate concentrations through nitrification.

- Phosphorus is naturally a fairly scarce resource in most environments; however, many human activities increase phosphorus loading to surface waters. Sources include human and animal wastes, fertilizer, phosphate detergents, and anthropogenic soil erosion. Between nitrogen and phosphorus, phosphorus is generally the more-limited nutrient in natural waters, making it the primary controlling nutrient for eutrophication; however, this can vary depending on local aquatic systems and sources (Walker, 1992). Orthophosphate is the form that is most readily available to plants. Dissolved phosphorus includes both orthophosphate and non-particulate organic and inorganic phosphorus.

This section describes the findings of review of time-series concentration plots, the trending tests, loading calculations, and the compliance analysis for nutrients.

3.2.1 Nutrient Concentrations

Nutrient concentrations are presented on time-series concentration plots in Appendix C1 (Figures C1-21 through C1-60) and in concentration box plots in Appendix C2 (Figure C2-9 through C2-15). The following subsections describe and discuss patterns observed in the concentration dataset for nitrogen and phosphorus nutrients, referencing the appendix figures and select example graphics.

The concentrations and seasonality of nutrients vary widely across the watershed. Observed concentrations of nitrogen and phosphorus parameters vary spatially by up to three orders of magnitude, depending on the parameter (e.g., Figure 25). Lower nutrient concentrations are typically observed in the upper watershed, and higher concentrations are typically observed in the lower part of the watershed (Figure 25 and Figure 26), with a clear change apparent at M140 (located downstream of the City of Loveland WWTP effluent).

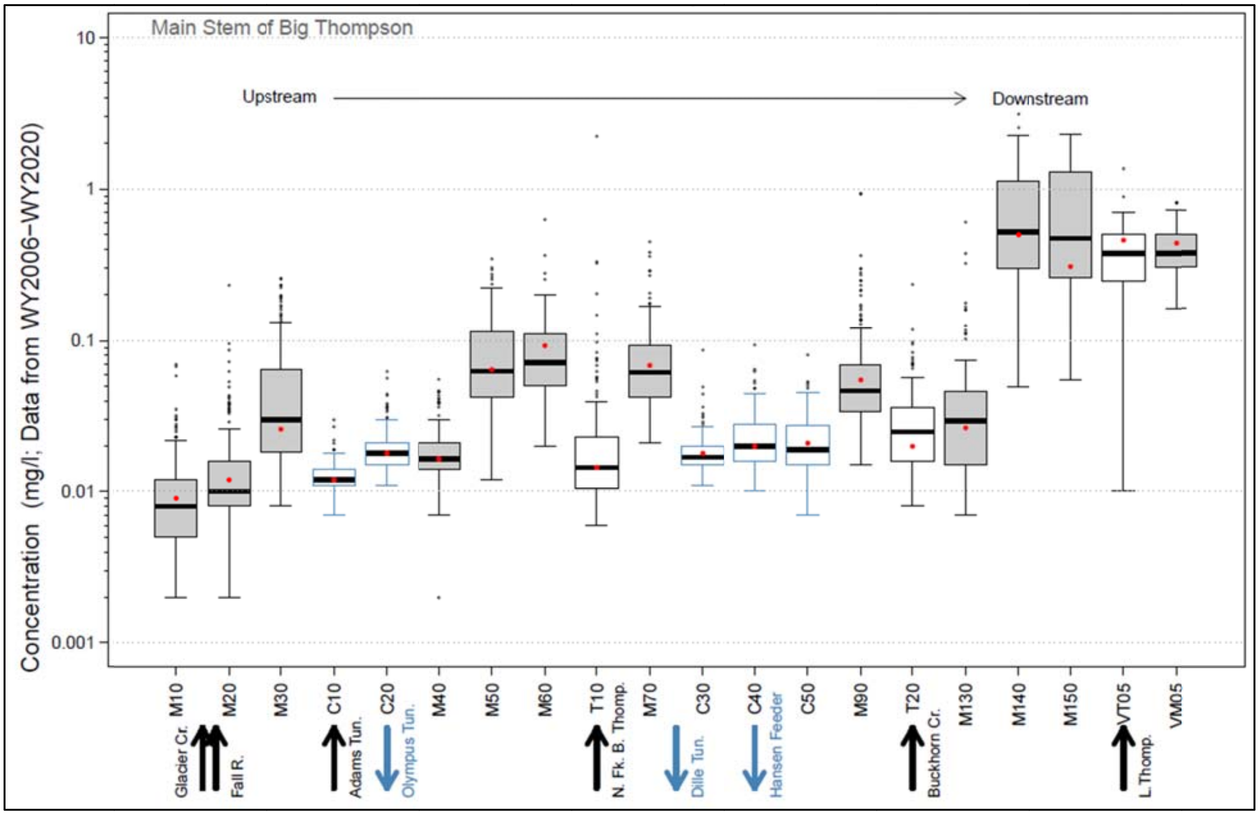

Figure 25. Box Plot of Total Phosphorus Concentrations (mg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

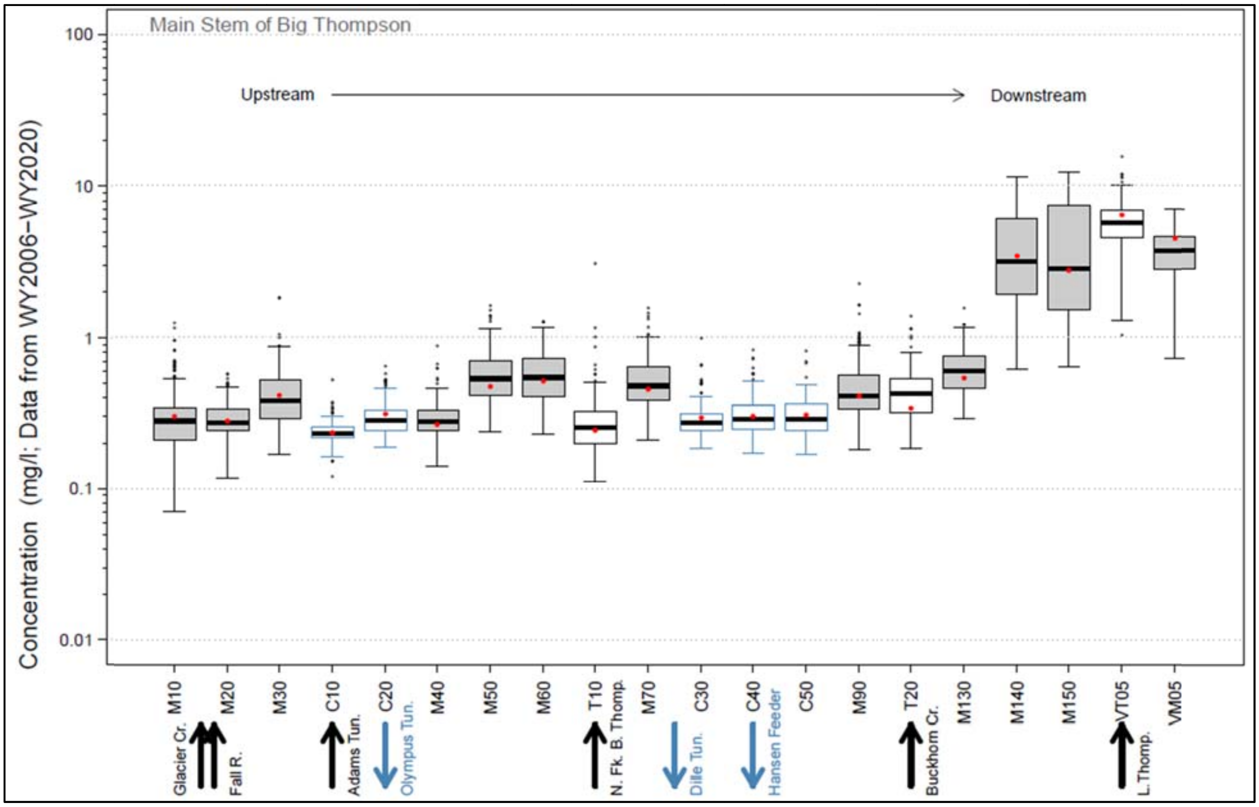

Figure 26. Box Plot of Total Nitrogen Concentrations (mg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

There are a few consistent and noteworthy patterns in nutrient concentration variations across the Big Thompson River watershed. These patterns give insights into to the role of WWTF effluent, C-BT inflows, and tributaries inflows on in-river nutrient concentrations:

- **Increased Nutrients below WWTFs:** Below each major WWTF releasing effluent to the Big Thompson River, there is a notable increase in nitrogen and phosphorus concentrations. This includes total phosphorus, orthophosphate, total nitrogen, ammonia, nitrate + nitrite, and TKN (e.g., Figure 25 and Figure 26, as well as Appendix Figures C2-9 through C2-15). The effluent locations are between the following sampling stations:
    - <u>M20 to M30</u> – Nitrogen and phosphorus concentrations exhibit a relatively small increase between M20 and M30 (e.g., Figure 25 and Figure 26), reflecting loading from the Estes Park Sanitation District WWTF effluent (Figure 6).

  - M40 to M50 – Nitrogen and phosphorus concentrations increase between these two stations (e.g., Figure 25 and Figure 26) due primarily to effluent from the Upper Thompson Sanitation District WWTF (Figure 6).

  - M130 to M140 – The nutrient increase between these two stations (e.g., Figure 25 and Figure 26) is primarily attributable to effluent from the Loveland WWTP (Figure 6). The increase in concentrations at M140 is larger than those noted at M30 and M50 for two main reasons: (1) the Loveland WWTP is a larger facility that serves a much larger population, and (2) major water diversions upstream of the Loveland WWTP outfall reduce dilution from the river. Note that treatment upgrades in 2019 at the Loveland WWTP have sharply decreased effluent phosphorus concentrations, notably benefitting the river downstream, as discussed in Section 3.2.2.

- **Low Nutrient Concentrations from the C-BT Project:** Total phosphorus and total nitrogen concentrations entering the watershed from the west slope at C10 are comparable to those in the upper Big Thompson watershed above where they enter the river (M30; Figure 25 and Figure 26). Concenrations of the most readily-available nutrients for plant uptake (orthophosphate, ammonia, and nitrate) at C10 exhibit an even bigger difference (much lower concentrations) when compared to those in the upper Big Thompson watershed (Appendix Figures C2-10, C2-12, and C2-13). Therefore, the C-BT Project does not have an adverse effect on the Big Thompson River in terms of nutrient concentrations. Canal locations (C10, C20, C30, C40, and C50) show small increases in nutrient concentrations from upstream to downstream, reflecting some mixing with and diversion of Big Thompson River water along the way.

- **Varying Effects of Tributaries:**

  - North Fork – The North Fork (T10), exhibits low nutrient concentrations more consistent with the upper-most watershed (M10 and M20) than with the Big Thompson River at its confluence (M60). This reflects the largely pristine, high mountain watershed of the North Fork. Inflows from the North Fork cause a small reduction in nutrient concentrations in the Big Thompson River as compared to concentrations upstream of the North Fork (M60 vs M70; e.g., Figure 25 and Figure 26).

  - Buckhorn Creek – Nutrient concentrations from Buckhorn Creek (T20) are comparable to concentrations in the Big Thompson River just upstream of Buckhorn Creek (M90; e.g., Figure 25 and Figure 26). Given this minimal concentration difference and the relatively low volume contribution from Buckhorn Creek (~10% of the flow in the Big Thompson River below the confluence), there is limited impact to nutrient concentrations in the Big Thompson River from this tributary.

  - Little Thompson River – The Little Thompson River (VT05) brings in higher concentrations of total nitrogen (Figure 26), ammonia, nitrate, and TKN (relative to Big Thompson River water quality just upstream of the confluence). The same is not the case for phosphorus from the Little Thompson, where total phosphorus and orthophosphate concentrations are typically comparable to or slightly lower than those of the Big Thompson where they join (e.g., Figure 25).

Seasonal patterns in nitrogen and phosphorus concentrations vary across the system showing some consistent patterns and some patterns indicating response to major watershed events. The following consistent seasonal patterns were noted in the extended dataset:

- **Seasonal nutrient concentration patterns near the top of the watershed:** At the upstream end of the system (M10 and M20) and in the major upper-watershed tributaries of North Fork (T10) and Buckhorn Creek (T20), total phosphorus and TKN concentrations are typically highest during the spring snowmelt runoff period (May – June) due to the mobilization of natural organic and inorganic materials within the watershed. Nitrate plus nitrite is highest in the winter, possibly reflecting shallow groundwater baseflow sources and lack of/limited periphyton uptake in the winter.

- **Seasonal nutrient concentration patterns from the C-BT system:** Similar patterns to those noted near the top of the Big Thompson watershed (previous bullet) are observed in C-BT water coming from the west slope (C10; Adams Tunnel). One difference however, is that TKN at C10 is often highest in the fall (August – September), possibly reflecting late summer algal growth in west slope C-BT system lakes and reservoirs.

- **Seasonal nutrient patterns in the rest of the watershed (anthropogenic influence):** Beginning at M30 (downstream of Estes Park Sanitation District) seasonal nutrient concentrations patterns reflect the influence of more anthropogenic sources, including WWTF effluent. Loading from the WWTF effluent is most apparent in in-river concentrations at times of lower flows in the river. Therefore, beginning at M30 and continuing downstream, concentrations of total nitrogen, nitrate, ammonia, total phosphorus, and orthophosphate tend to be higher in the fall and winter and lower at times of higher flow in spring and summer.

The following event-related responses were noted in the seasonal nutrient data:

- **Fern Lake Fire Effects at M10:** As noted in the previous State of the Watershed report (Hydros, 2015), there were some apparent increases in organic forms of nutrients (TKN [and correspondingly total nitrogen]) at M10 (the nearest gage to the October 2012 Fern Lake fire; Appendix Figure C1-41). 2013 data at the next downstream Big Thompson River station (M20) are not as definitive, suggesting the duration and spatial extent of the effects of the Fern Lake fire on nutrient concentrations were limited. The magnitude of those observed effects in 2013 was not significant enough to impact aquatic life and drinking water supplies (Billica, 2014). Note that recent fires in the fall of 2020 (described in Section 1.3.2), however, may have greater adverse impacts, given their location, extent, and severity.

- **2013 Flood Effects at M10:** The time-series plots for M10 show an increase in nitrate concentrations (and a corresponding increase in total nitrogen) during snowmelt runoff in the three years following the 2013 flood (Figure 27). The same pattern was not seen in TOC (Appendix Figure C1-21), metals (Appendix Figure C1-1), TKN (Appendix Figure C1-41), or phosphorus (Appendix Figure C1-21), suggesting no increase in suspended solids. The pattern was, however, seen at M10 in other measures of dissolved constituents (specific conductivity, hardness, and alkalinity; Appendix Figure C1-61; as discussed in Section 3.5). This pattern is not seen elsewhere in the basin, including relatively pristine basins like the North Fork which also experienced the 2013 flood. Based on this, it is expected that the response is the combination of the Fern Lake Fire (October 2012) in the M10 watershed and the 2013 flood. The combination resulted in extensive vegetation and soil disruption and transport. Moraine Park, just upstream of M10, is a natural solids trap, and may have served to limit the extent of solids transport from this disruption. The disruption, however, could have led to increased contact time for snowmelt water with rock and soil, leading to increased dissolved constituent concentrations. Further, the combined event destruction of vegetative cover could lead to additional nitrate loss from the system, explaining the increased nitrate concentrations.

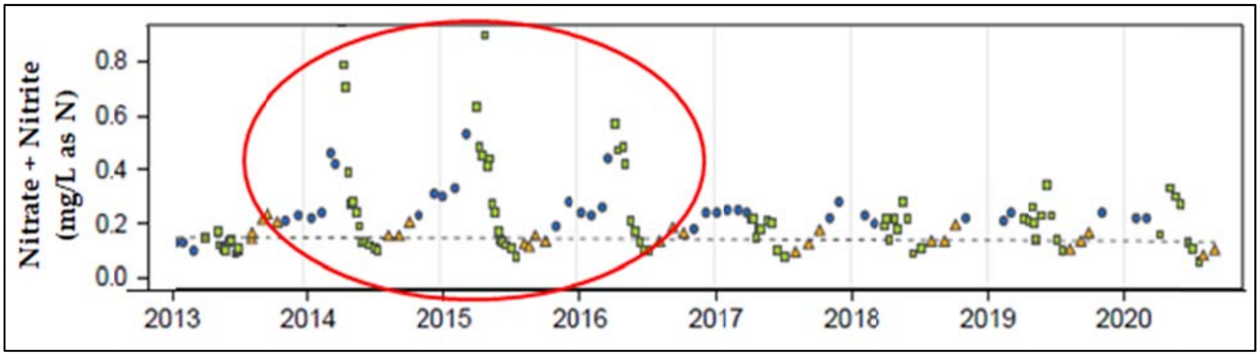

Figure 27. Nitrate + Nitrite Concentrations (mg/L) at M10, 2013-2020, Post-Flood Concentrations Circled

(Symbol colors indicate season; black dashed line indicates long-term linear trend [discussed in Section 3.2.2])

- **2013 Flood Effects in the lower sub-watershed:** Following the 2013 flood, the increase in baseflow rates in the lower sub-watershed, apparent in winter months as discussed in Section 3.1.3, served to dilute phosphorus and nitrogen from WWTF effluent. This winter-time dilution is most apparent in reduced nutrient concentrations in the mainstem of the Big Thompson river from M140 (located below the Loveland WWTP outfall) to the confluence with the South Platte. As an example, total phosphorus concentrations at M140 are presented in Figure 28. The effect lasted for two years in the upper portion of the lower sub-watershed and may have extended into the third year after the flood at the lower end of the watershed near the South Platte (though this is difficult to state definitively, given nutrient data gaps at VM05 in 2015 and 2016).

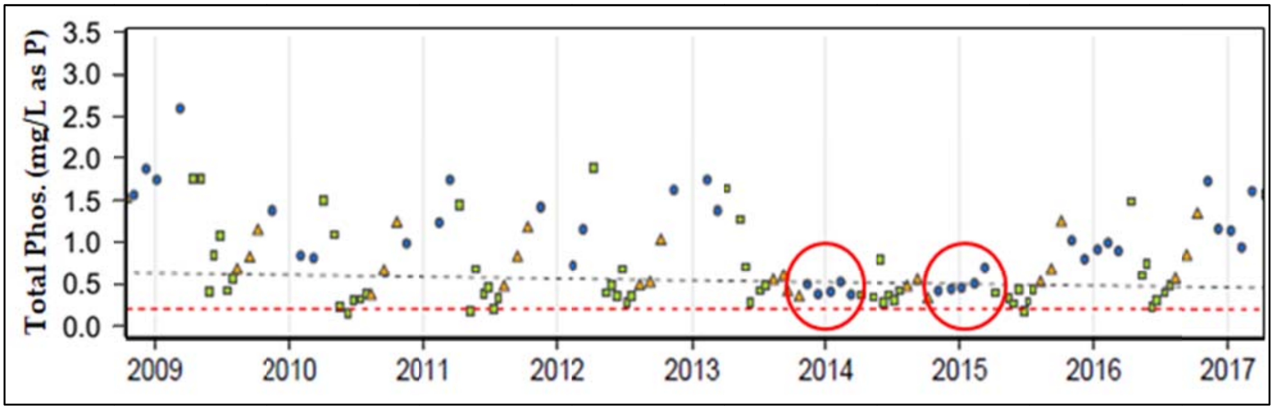

Figure 28. Total Phosphorus Concentrations (mg/L) at M140, 2009-2017, Post-Flood Winter Concentrations Circled

(Symbol colors indicate season; red dashed line indicates the interim nutrient stream standard [not currently applicable]; black dashed line indicates long-term linear trend [[discussed in Section 3.2.2].)

3.2.2 Nutrient Concentration Trends

Concentration time-series data for nutrients were evaluated for statistically-significant trends applying Seasonal Mann-Kendall testing, as described in Section 2.2.2. The trend testing assesses whether or not there is a statistically-significant trend of increasing or decreasing concentration from WY2006 through WY2020. The testing also indicates the magnitude (rate) of any identified trends. Using a 90% confidence level, trends were evaluated for all nutrients across the system. Complete trend testing results are provided in Appendix E. The trends were further assessed with a review of the time-series plots considering potential influences of major events that could cause step changes in concentrations and affect the trend testing results, such as the 2013 flood or WWTF upgrades. The following presents highlights of the findings generated from this analysis.

The previous State of the Watershed report (Hydros, 2015) noted a statistically-significant trend of decreasing nitrate concentrations in the upper watershed. The overall trend agreed well with recently published findings of a long-term study in the Colorado Front Range (Mast et al., 2014). Mast et al. (2014) found that stream nitrate concentrations below Loch Vale (a high elevation location in Rocky Mountain Nation Park) increased in the early 1990's but have been decreasing since the early 2000s. Nitrate concentrations were found to have decreased by over 40% since the peak in the early 2000s. This is reported by Mast et al. (2014) to be coincident with an observed decline in nitrogen oxides in the atmosphere in response to USEPA-mandated regulatory limits on vehicle and stack emissions. The recent trend analysis, including six years of more recent data, also show statistically-significant trends of decreasing nitrate concentrations (Figure 29); however, the magnitude of the trend has decreased, and it is only apparent in the upper-most portion of the watershed (M10, C10). The drop in nitrate over the recent 15 years is on the order of 1 to 3 µg/L per year. Over the 15-year period, this corresponds to a decrease of 24 to 67% of the mean nitrate concentration in the upper-most watershed, though the pattern is somewhat complicated by the noted effect of the Fern Lake fire and 2013 flood on winter nitrate levels at M10 (discussed in Section 3.1.2). The decreasing rate of decline and decreasing spatial extent of apparent effect (relative to the WY2000-WY2014 analysis) may indicate a diminishing effect over time.

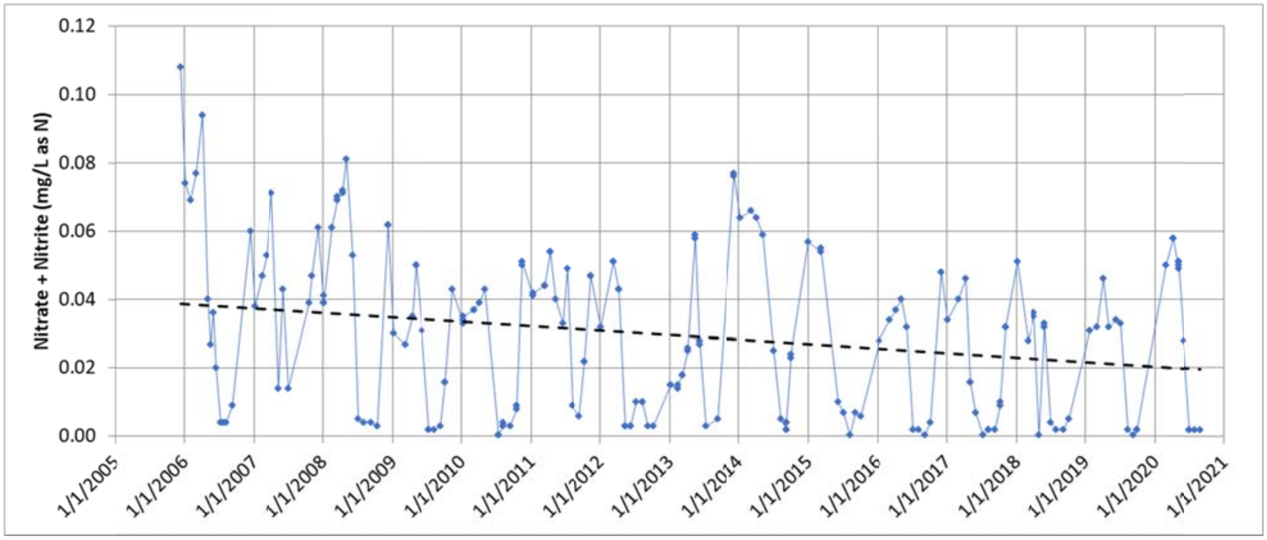

Figure 29. Nitrate + Nitrite Concentrations (mg/L) at C10 (Trend slope shown as black dotted line)

At M30, located upstream of Lake Estes and downstream of the Estes Park Sanitation District WWTF, there is a decreasing trend of orthophosphate (as well as total phosphorus). Review of the time-series graph indicates a reduction in winter phosphorus concentrations at M30, suggesting improvements in effluent water quality at the Estes Park Sanitation District WWTF. The Estes Park Sanitation District WWTF has been making operational and structural improvements since 2006, including additional improvements in 2016, 2020, and 2021 (Duell, 2021). It appears that these improvements are benefiting the Big Thompson River below the outfall in terms of phosphorus concentrations. The trend rate amounts to 1.8 µg/L per year orthophosphate (as P), though most of benefit looks, from the graph, to have come in recent eight years.

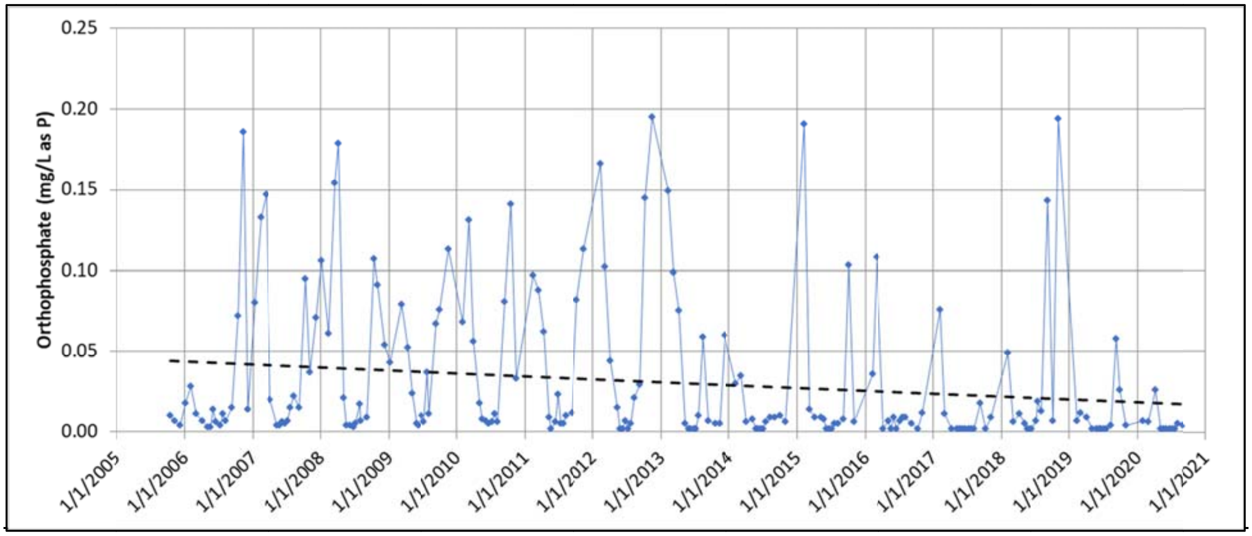

Figure 30. Orthophosphate (mg/L) at M30 (Trend slope shown as black dotted line)

The statistical testing indicated a decreasing trend in phosphorus concentrations (dissolved, total, and orthophosphate) at M140, corresponding to a rate of decrease of 17 to 28 µg/L per year. Review of the time-series graphics show that, instead of a consistent downward trend, there is a sharp drop in concentrations starting in 2019 (e.g., Figure 31). This step change is directly attributable to upgrades made at the Loveland WWTP (just upstream of M140) that went online in 2019 to improve phosphorus removal. The benefit is also clearly apparent in phosphorus concentrations downstream at M150.

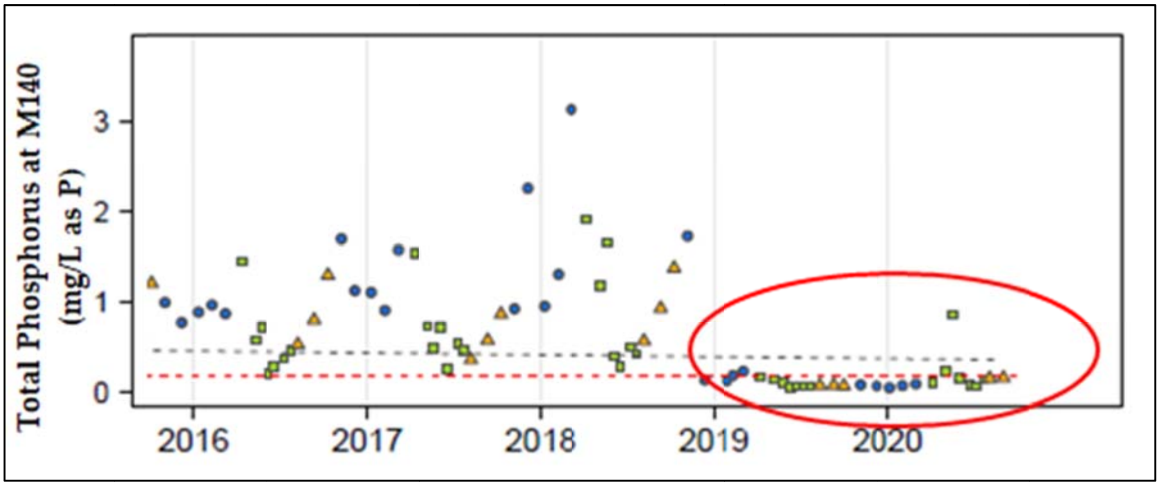

Figure 31. Total Phosphorus Concentration Data at M140, 2016-2020 *(Red Circle Indicates Period of Record Following Loveland WWTF Upgrade)*

Statistically-significant trends of increasing nutrients were found at the end of the Little Thompson River (VT05). Increases were seen across seasons for total phosphorus, orthophosphate, nitrate + nitrite, and total nitrogen. This trend was one the largest across constituents and sampling locations in terms of rate of increase, ranging from 8% per year for nitrate + nitrite to 15% per year for total phosphorus (Figure 32). It is expected that this increasing trend corresponds to the rapid population growth rate in the area (Section 1.3.1) from 2010 through 2020. The effects extend to the Big Thompson River, resulting in increasing concentrations of total phosphorus, nitrate + nitrite, and total nitrogen (statistically significant trends) at VM05 (just upstream of confluence with the South Platte).

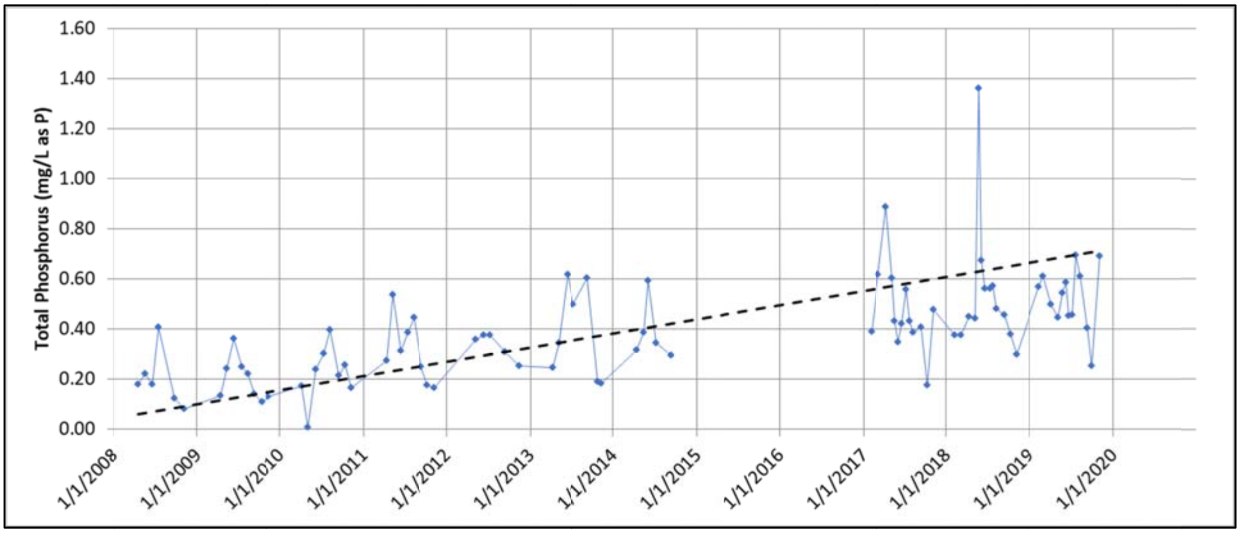

Figure 32. Total Phosphorus (mg/L) at VT05 (Trend slope shown as black dotted line)

3.2.3 Nutrient Loading

Nutrient loading analysis results are summarized in Appendix D (Figures D1-1 through D1-10 [box plot figures] and D2-1 through D2-10 [bar graph figures]). Nitrogen and phosphorus load calculation results reflect expected patterns based on flow and concentration data (e.g., Figure 33). Specifically, nutrient loads increase below major WWTPs. Due to a jump in nutrient concentrations, annual nutrient loads in the lower part of the watershed below M140 are comparable to or higher than upstream loads despite lower flow rates. Loads from tributaries with multiple years of flow records (North Fork and Buckhorn Creek) are low relative to mainstem locations. Canal locations have relatively high nutrient loads in spite of relatively low concentrations, due to high volumes.

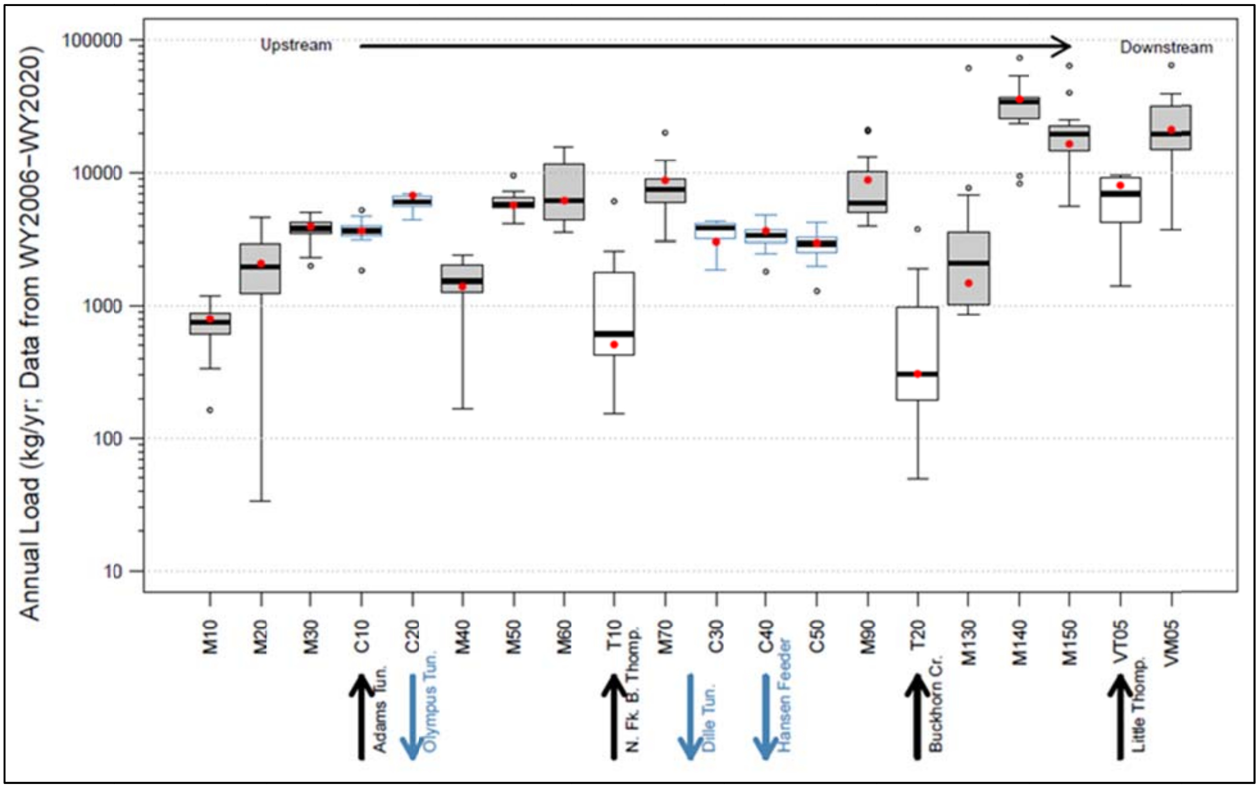

Figure 33. Box Plot of Total Phosphorus Load (kg/yr) in the Big Thompson Watershed, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

Loading results were reviewed to help assess the relative composition of total nitrogen and total phosphorus across the watershed. As shown in Figure 34 through Figure 36, TKN (organic nitrogen plus ammonia) comprises the majority of the total nitrogen load in the Big Thompson River from the headwaters to M130, and in the canals. Because ammonia is a small fraction of total nitrogen, this indicates that the total nitrogen is dominated by organic nitrogen in these areas. From M140 to the confluence with the South Platte and in the Little Thompson River (VT05), the pattern changes. In these reaches, nitrate comprises the greater fraction of the total nitrogen load, reflecting WWTF loading and possibly the influences of livestock. These findings agree with those from the previous State of the Watershed report (Hydros, 2015).

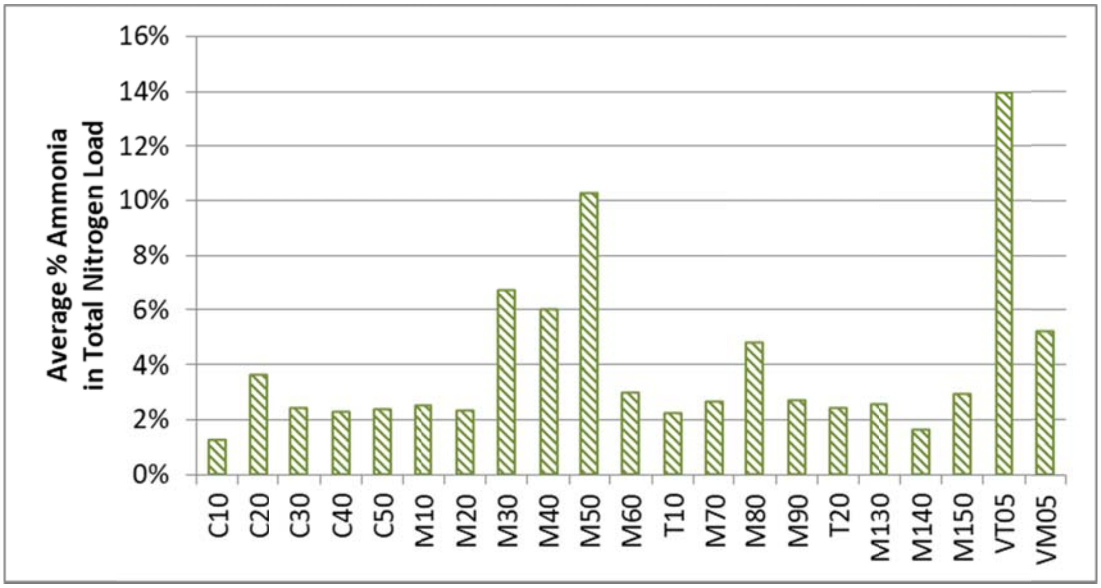

Figure 34. Average Ammonia Fraction in Total Nitrogen Load, WY2006-WY2020

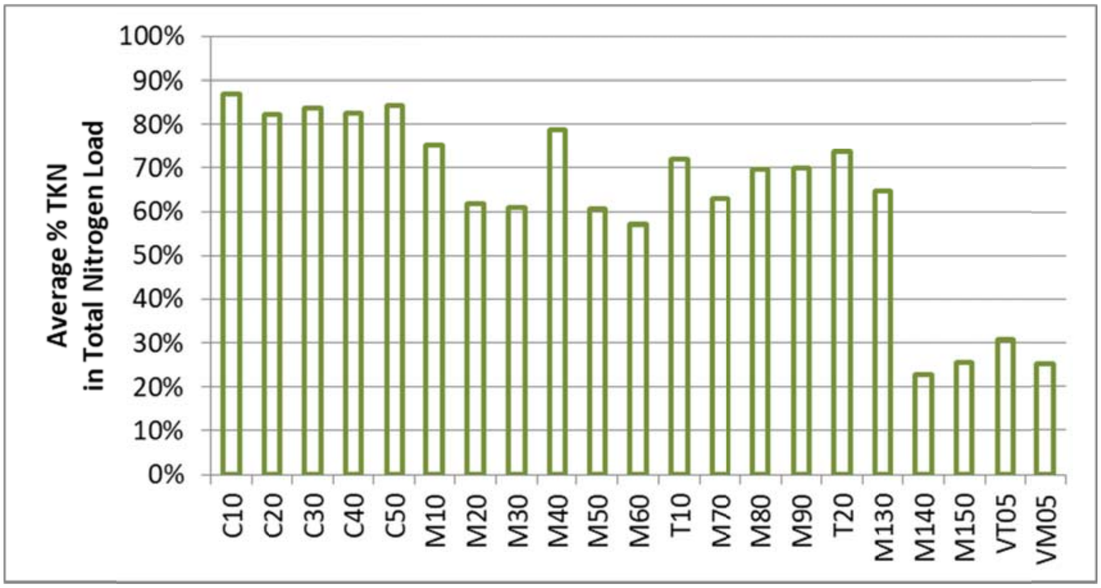

Figure 35. Average TKN Fraction in Total Nitrogen Load, WY2006-WY2020

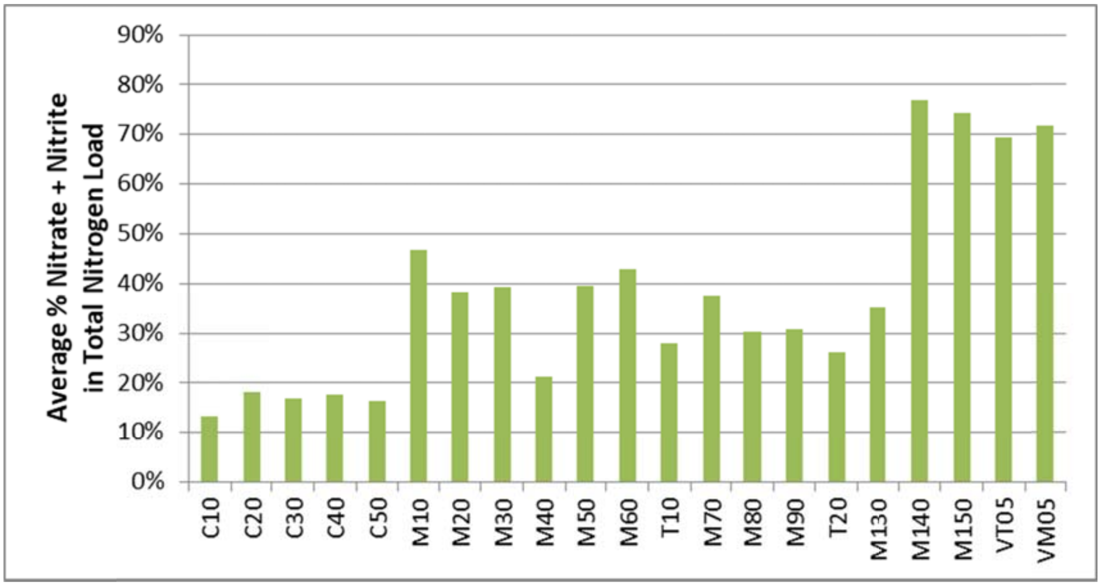

Figure 36. Average Nitrate plus Nitrite Fraction in Total Nitrogen Load, WY2006-WY2020

Phosphorus loading data were reviewed to assess the relative fraction of orthophosphate in total phosphorus across the watershed (Figure 37). Orthophosphate is the form most readily available to aquatic plants/algae, and it is an important parameter in assessment of eutrophication. The C-BT canal system carries a low fraction of orthophosphate, indicating primarily organic phosphorus coming from the west slope. The fraction of orthophosphate in the total phosphorus increases below each major WWTP outfall (M30, M50, and M140; Figure 37).

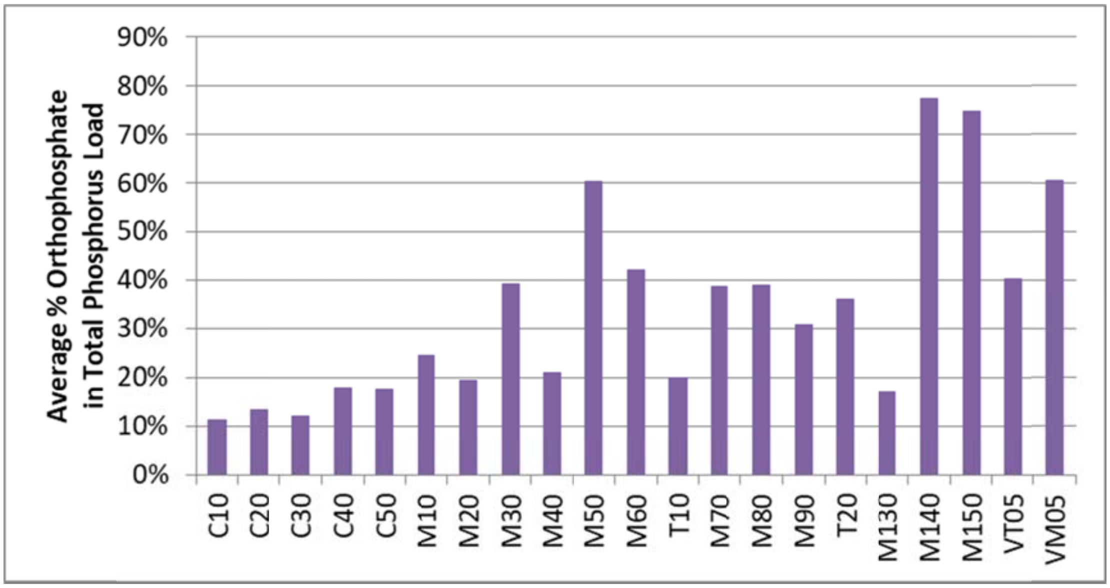

Figure 37. Average Fraction of Orthophosphate in Total Phosphorus Load, WY2006-WY2020

3.2.4 Nutrient Compliance

As described in Section 2.2.3, ammonia data were compared to applicable acute and chronic aquatic life Colorado WQCC water-quality standards (Regulation 38; WQCC, 2020d), while nitrate data were compared to applicable domestic water supply or agriculture standards. Additionally, total nitrogen and total phosphorus concentrations were compared to the interim Colorado numeric nutrient criteria (Regulation 31; WQCC, 2020c)[23]. Comparison of observations to ammonia standards, nitrate standards, and interim total nitrogen and total phosphorus criteria are summarized in tables in Appendix F.

Nitrate standards are very high relative to typical natural concentrations (10 mg/L standard for protection of domestic water supplies [applicable across the watershed flowing sites, except for Segment 4], and a 100 mg/L standard for protection of agriculture [livestock] water supplies [applicable in Segment 4]; Table 5). Comparison of observed data to these standards indicated very infrequent occurrence of observations above the nitrate standard. Only two locations (M150 and VT05) exhibit concentrations in the 15 year record above the nitrate standard, and the frequency at these locations was ≤ 3% of samples.

For ammonia, the standard varies as a function of pH (and in some cases temperature). There are two samples, one from M140 and one from M150 in the spring of 2019, that exceeded the calculated acute standard value, corresponding to ≤ 1% of samples at each of those locations. There are no cases across all sites of observations greater than the calculated chronic standard values for ammonia.

Comparison of the 15 years of record to the interim numeric criteria for total nitrogen and total phosphorus indicate potential future areas of concern at the downstream end of the watershed, beginning at M140, below the Loveland WWTP outfall, extending to the South Platte at VM05 and including the Little Thompson River (VT05). Median annual concentrations for total nitrogen and total phosphorus from M140, M150, VT05, and VM05 would have exceeded the interim total nitrogen and total phosphorus values in 87 to 100% of the recent 15 years with historical data (Figure 38). It should be noted, however, that the recent two years of record (2019 and 2020) would have met the total phosphorus interim criteria value at M140 and M150 due to the recent upgrades at the Loveland WWTP (discussed in Section 3.2.2; see Figure 31). Therefore, in the future, the key area of concern for total nitrogen and total phosphorus

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[23] Total phosphorus standards have been adopted for Segment 1 and part of Segment 2 of the Big Thompson River (applicable only to M10, M20, M30, and M40). A total nitrogen standard has not yet been adopted for any segment in the Big Thompson watershed. While the interim nutrient criteria are largely not applicable across the Big Thompson watershed, they may be considered for adoption as water-quality standards prior to or after May 31, 2022, depending on determination by the WQCC. Therefore, comparisons of WY2006-WY2020 data to interim nutrient criteria from were made for all sampling stations to provide perspective on conditions relative to the interim criteria.

concentrations is the Little Thompson River (which is also causing the issues downstream at VM05).

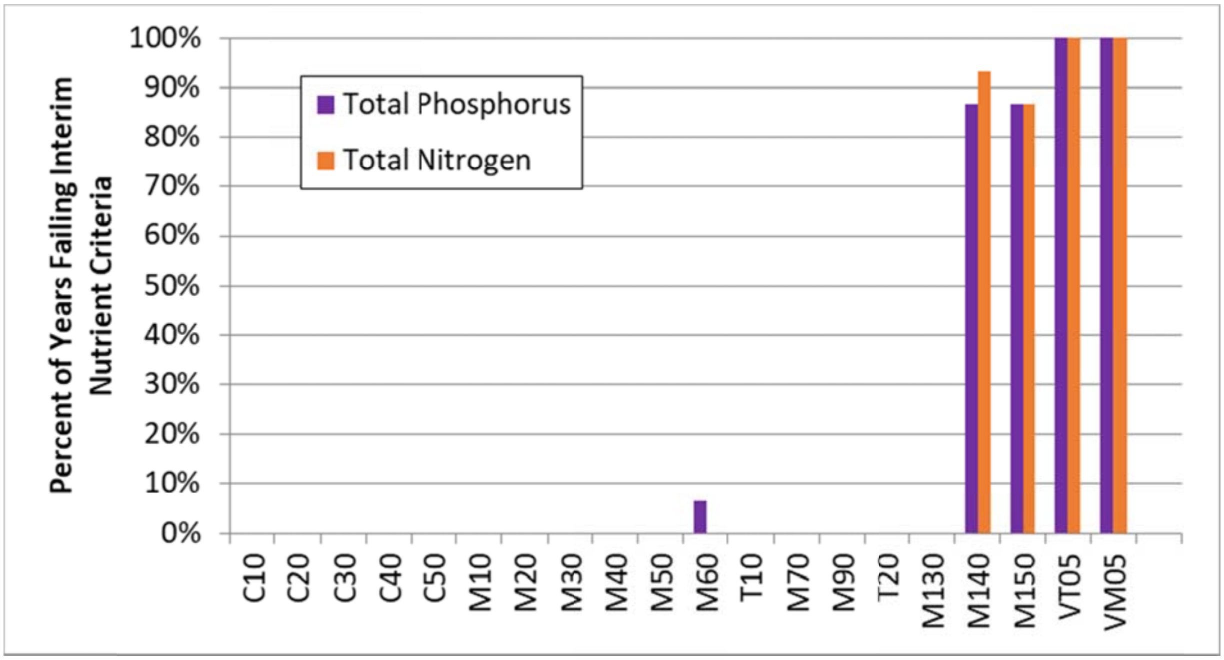

Figure 38. Summary of Data Comparison to Interim Nutrient Criteria (Annual Medians Compared to Cold and Warm Water Interim Criteria for Rivers), 2006-2020 *(Note that the Interim Criteria will Not be Applicable to Canal Locations and are Only Currently Applicable for Total Phosphorus at M10, M20, M30, and M40.)*

3.3 METALS

The metals considered in this assessment are:

- Arsenic,
- Copper,
- Cadmium,
- Lead,
- Selenium, and
- Zinc.

There are current or recent regulatory concerns for each of these metals in the Big Thompson watershed. First, there are current 303(d) listings in Big Thompson River segments for arsenic, copper, selenium, and zinc (Figure 10a-c). Lead is not listed for river segments, but it is currently on the 303(d) List for two water bodies that receive water from the Big Thompson River and the C-BT system, Lake Estes and Carter Lake (WQCC, 2020b). Finally, cadmium is not on the current 303(d) List for the Big Thompson flowing sites or receiving waters; however, it was previously listed in the watershed (WQCC, 2012).

The metals considered in this report are ubiquitous, naturally occurring elements in the crust of the earth. Concentrations of these metals in rock and soils are typically low. Elevated concentrations of these metals can occur due to mineral deposits or as the result of human activities. Copper, selenium, and zinc are essential elements for plants and animals (including humans); however, elevated concentrations can be toxic. Arsenic, cadmium, and lead however, are not essential and have forms identified as being carcinogenic or potentially carcinogenic (ATSDR, 2003, 2004, 2005, 2007, and 2008). Of these metals, selenium and arsenic are known to bioaccumulate in animals (ATSDR, 2003 and 2007).

While all of these metals are present naturally, anthropogenic activities can greatly affected their distribution and cycling in the environment. Cadmium is primarily released as a by-product of mining and manufacturing processes and can be present at concentrations above background in WWTF effluent. Zinc releases are also driven by mining and metal production activities. Anthropogenic lead emissions were historically driven by the combustion of lead-containing gasoline and lead-based paint. Certain geologic formations, such as the Pierre shale occurring on the Plains portion of the watershed, are known to be enriched in selenium. Anthropogenic releases of selenium are dominated by fossil fuel combustion and irrigation return flows in areas underlain by Pierre shale. Arsenic is used in some cases to create pressure-treated wood and in some pesticides and can also be derived from Pierre Shale (USGS, 1980).

Copper sulfate was historically used in the C-BT canals in the Big Thompson watershed to control periphyton (attached algae) and aquatic plants, with Northern Water's use dating back to around 1964. However, both Northern Water and the U.S. Bureau of Reclamation (USBR) have discontinued the use of copper sulfate in the C-BT canals. Northern Water discontinued its use in April 2008 (Hydros, 2011), while the USBR discontinued its use sometime before June 2012 when the Pole Hill canal was covered over (personal communication between J. Billica, Northern Water, and Tony Curtis, USBR, 5/8/15). Because of the 303(d) listings for copper in downstream stream segments, the use of copper-containing aquatic herbicides in C-BT canals is not allowed under the USBR's EPA NPDES Pesticide General Permit or Northern Water's Colorado Pesticide General Permit. Prior to 2015, the City of Loveland occasionally used copper sulfate for algal biomass control in Green Ridge Glade Reservoir (a reservoir near site M90, which can discharge augmentation water back to the Big Thomson River); however, the City of Loveland discontinued use of copper sulfate in 2015 (Bohling, 2021).

This section describes the findings of concentration plotting, trend analysis, and the compliance analysis for metals.

3.3.1 Metals Concentrations

Metal concentrations are presented on time-series concentration plots (Appendix C1, Figures C1-1 through C1-20) and concentration box plots (Appendix C2, Figure C2-1 through C2-6).

The following subsections describe and discuss patterns observed in the concentrations dataset for the six metals of interest.

Metals concentrations vary across the watershed. Lower concentrations are typically observed in the upper sub-watersheds, and higher concentrations are typically observed at in the lower sub-watersheds. The upstream-to-downstream concentration changes are relatively small in magnitude (generally less than one order of magnitude), with the exception of selenium. There are a few noteworthy patterns in these concentration variations across the watershed:

- **Geology Driven Selenium and Arsenic Concentrations:** The most readily apparent trend in metals concentrations is the large increase in selenium concentrations observed downstream of station M90 (Figure 39). There is also a similar pattern of increasing arsenic concentrations (Figure 40). These increases appear to be driven by a change in geology. Pierre shale is known to be enriched in selenium and can also be a source of arsenic (USGS, 1980). In the lower sub-watershed (beginning between M90 and M130), Pierre shale becomes a major component of the subsurface geology (Figure 3), matching the pattern of observed selenium and arsenic concentration increases (Figure 39 and Figure 40). The highest concentrations of both selenium and arsenic are observed in the Little Thompson, which has a greater proportion of watershed underlain by Pierre shale. There is also a higher fraction of agricultural land-use in the Little Thompson sub-watershed (Figure 4), which can increase selenium transport to rivers through irrigation returns.

  The highest selenium concentrations in the lower sub-watershed are observed in winter when the ratio of influent groundwater to in-stream flows is the highest. Interestingly, peak arsenic concentrations in the lower sub-watershed are observed outside of winter months (typically mid-summer). The reasons for the pattern difference for arsenic and selenium are currently unclear but may relate to differing removal effectiveness in domestic wastewater treatment. Another notable difference in arsenic and selenium patterns is that CB-T inflows (at C10) have higher arsenic concentrations than the upper-most watershed (e.g., M10 through M30; Figure 40), which is not the case for selenium (Figure 39).

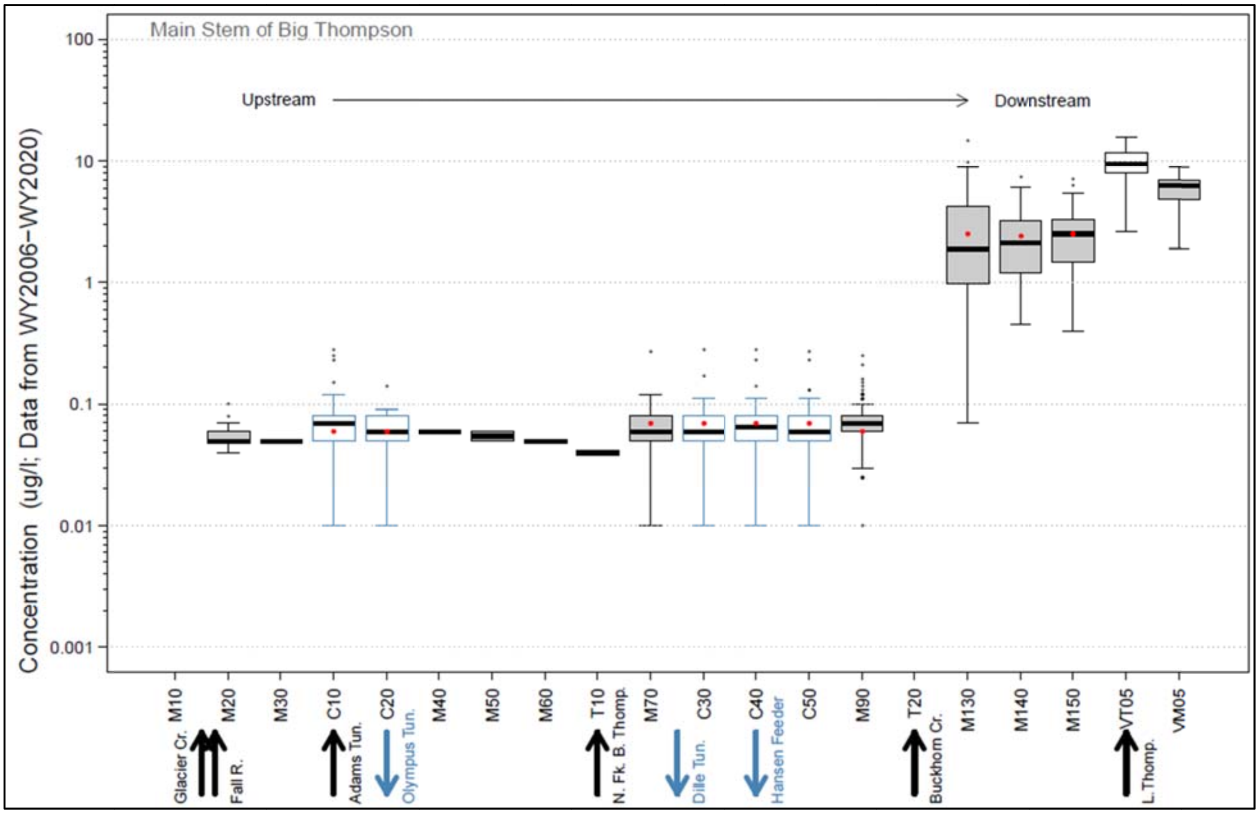

Figure 39. Box Plot of Selenium Concentrations (μg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

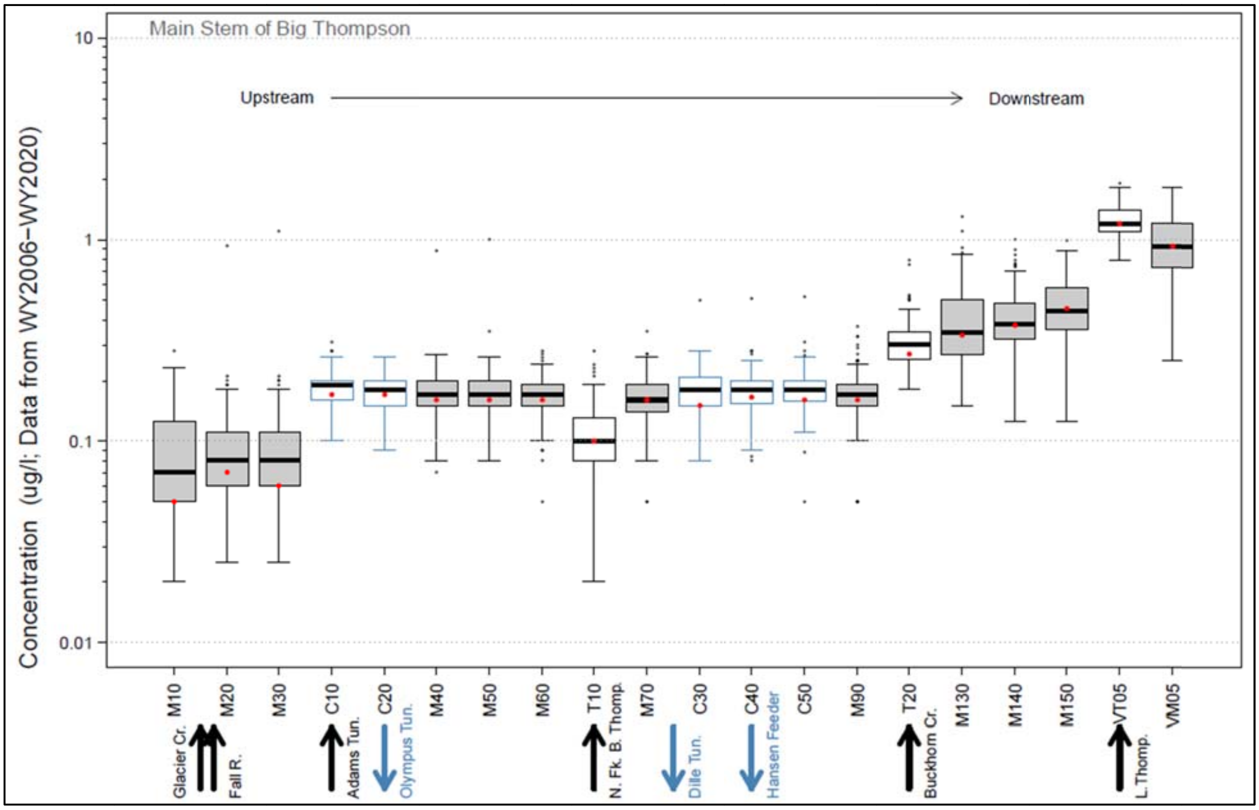

Figure 40. Box Plot of Arsenic Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **Highly-Censored Data:** "Censored" is a term used to describe analytical results below the detection limit. Much of the cadmium concentration dataset is highly censored. (Figure 41). The limited spread of cadmium data in Figure 41 is due to a high percentage of the results being reported as below the detection limit. As noted in the following subsections, there are no concerns for cadmium relative to applicable standards across the watershed. Further, there are no increasing cadmium concentration trends. Therefore, at this time, it is justifiable to discontinue sampling for dissolved cadmium or lower the detection limit for analysis if additional understanding is desired.

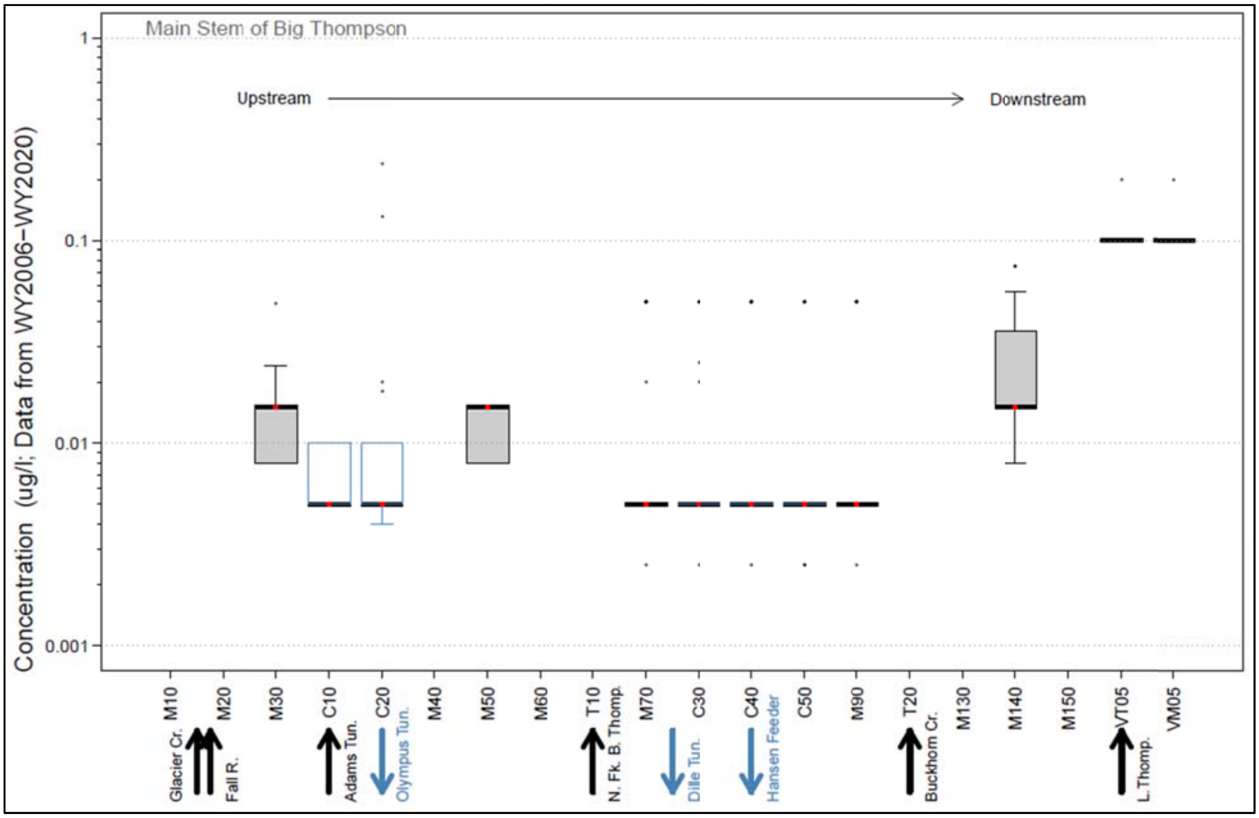

Figure 41. Box Plot of Dissolved Cadmium Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **Population Density/WWTP Influences on Lead, Zinc, and Copper:** The Big Thompson watershed does not have major industrial or mining point sources for metals. However, there is an increase in lead and zinc (and to a lesser extent copper) concentrations in the lower sub-watershed beginning at M140 (Figure 42, Figure 43, and Figure 44). These metals can be elevated in treated domestic wastewater, and the spatial pattern fits that explanation based on population density (Figure 5) and WWTP locations (Figure 6). Note that C-BT inflows (C10) tend to have lower lead, zinc, and copper concentrations than the upper watershed (M10, M20, and M30) into which they flow (Figure 42, Figure 43, and Figure 44).

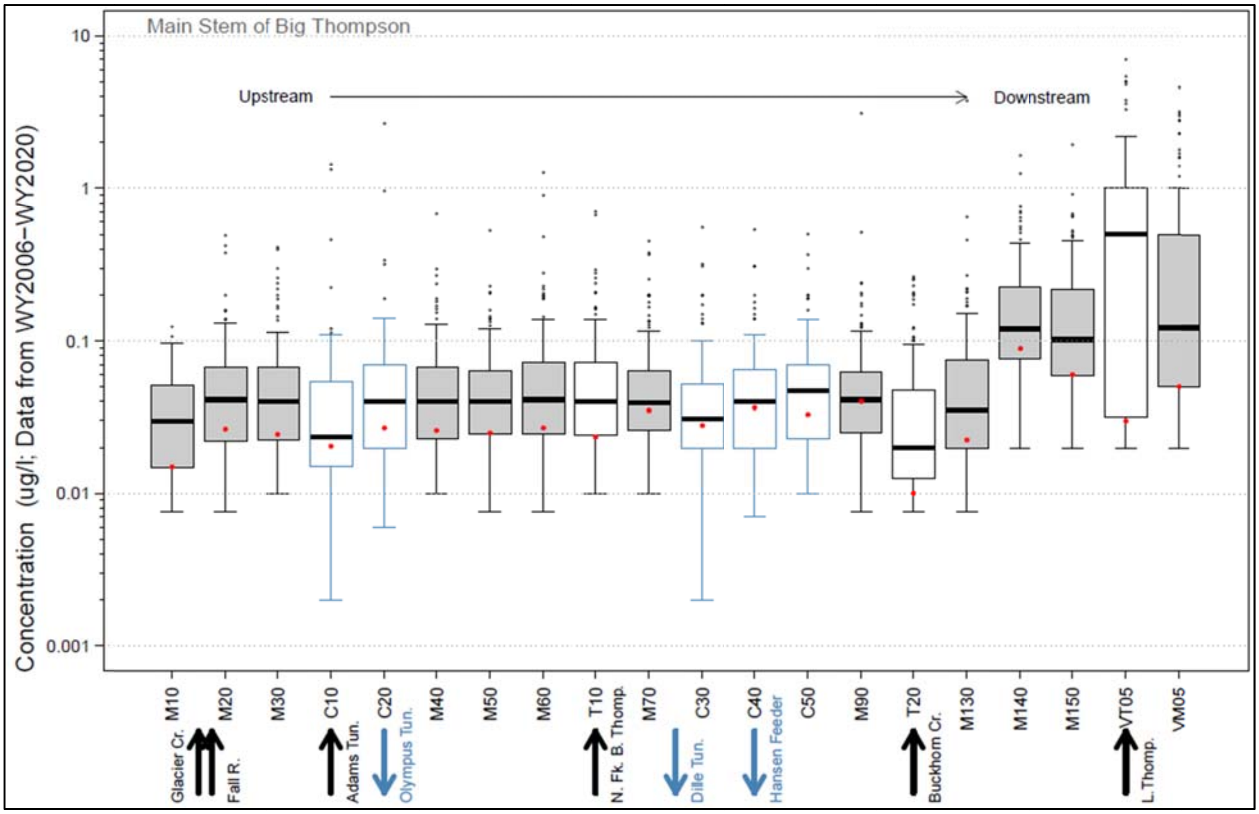

Figure 42. Box Plot of Dissolved Lead Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

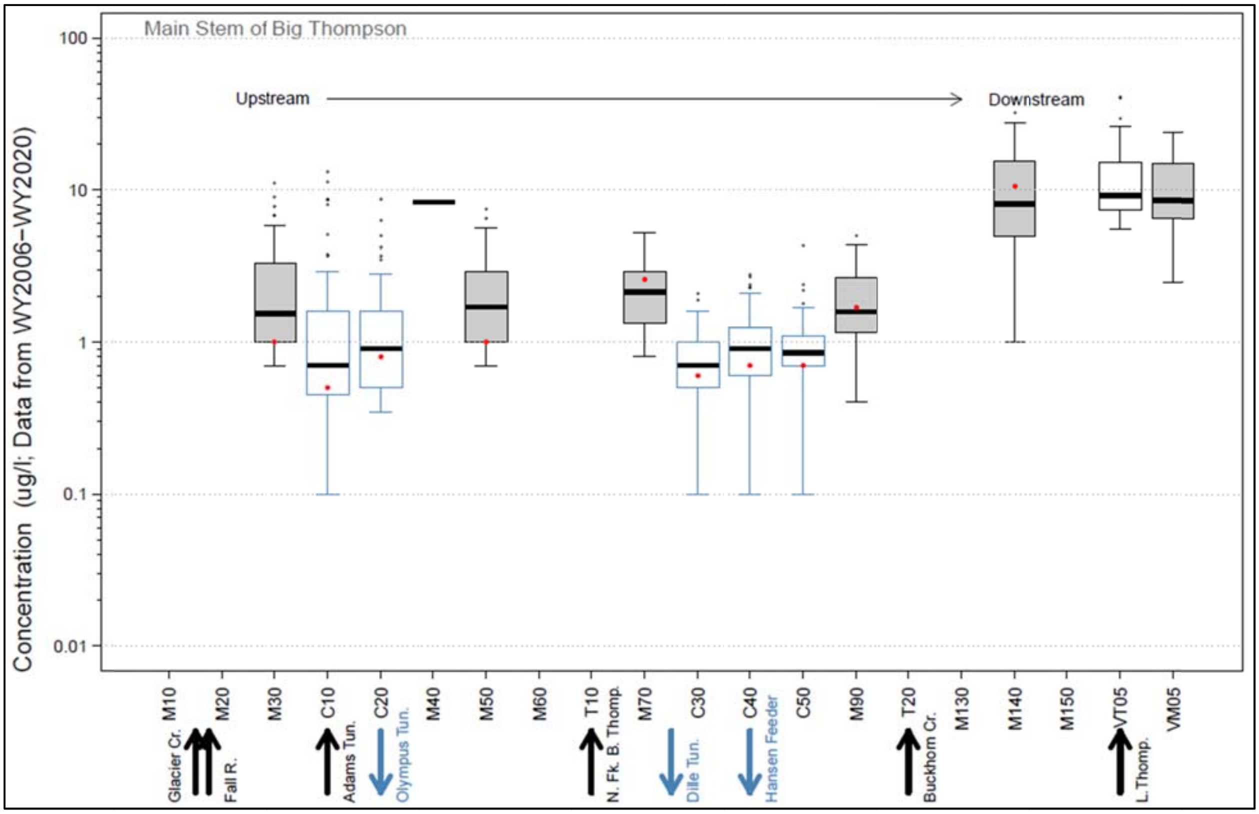

Figure 43. Box Plot of Dissolved Zinc Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

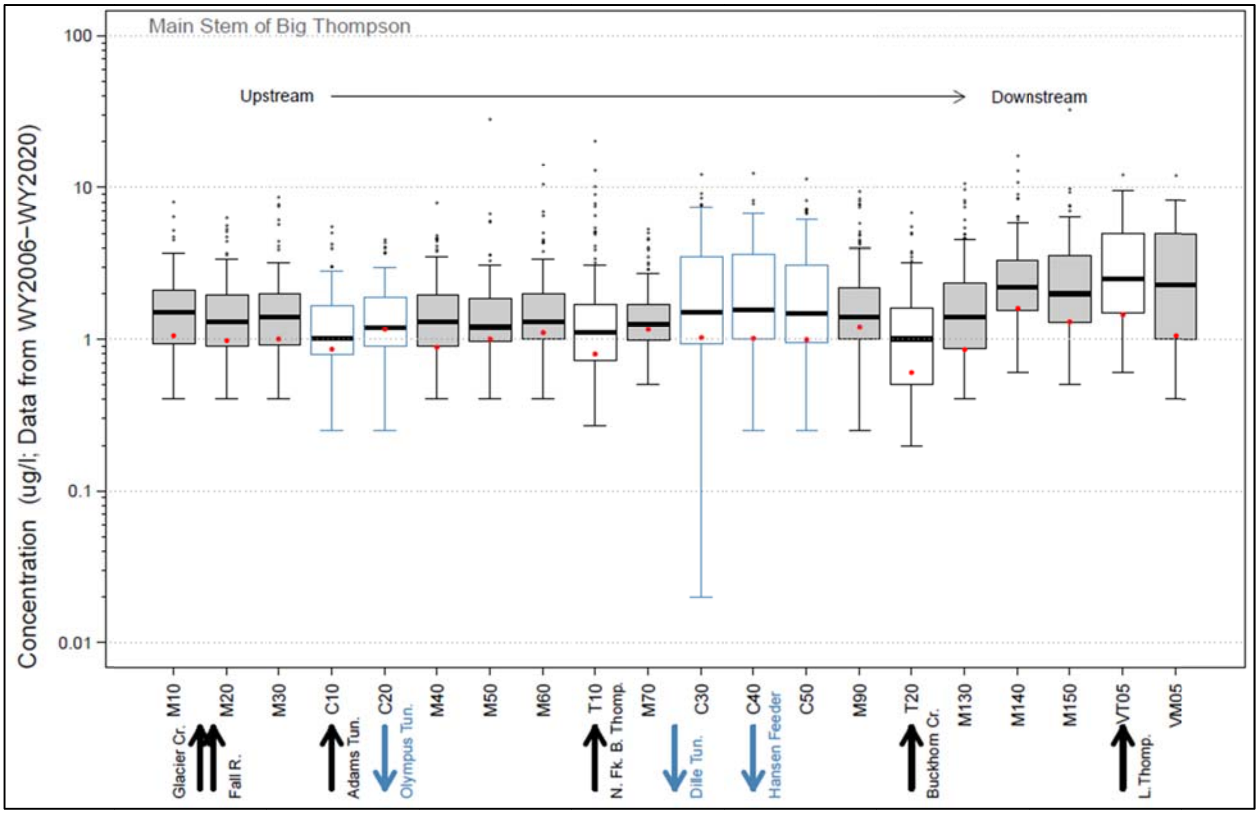

Figure 44. Box Plot of Dissolved Copper Concentrations (µg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **Fire Effects:** Within the Forum database, there are no definitive patterns in metals data associated with the 2012 fire upstream of M10 or 2011 and 2012 fires upstream of T20. This agrees with the analysis presented in the previous State of the Watershed Report (Hydros, 2015). It is, however, possible that there will be increased metals concentrations in the Big Thompson River due to the much larger fires in the fall of 2020 (described in Section 1.3.2). Any such effects should be evaluated in the next analysis reviewing flowing-sites data.

- **September 2013 Flood Effects:** As noted in the previous State of the Watershed Report (Hydros, 2015), metals concentrations are expected to have increased during the 2013 flooding due to increased suspended solids; however, sampling was not conducted on the river during the flooding event due to access and safety issues. There are some indications of short-term increases in some metals concentrations (e.g., lead) in the upper watershed and C-BT canals based on sampling following the peak of the September 2013 flood. Further, there may be a decrease in winter selenium concentrations in the lower watershed in the two years following the flood, suggesting dilution of Pierre shale-contacting groundwater by groundwater from other saturated areas. Overall, the recent six years of data do not show any long-lasting effect on metals concentrations from the 2013 flood event.

3.3.2 Metals Concentration Trends

Concentration time-series data were evaluated for statistically-significant trends applying the Seasonal Mann-Kendall approach, as described in Section 2.2.2. The trend testing assesses whether or not there is a statistically-significant trend of increasing or decreasing concentration from WY2006-2020. The testing also indicates the magnitude of trends. Using the generally inclusive significance threshold of p-values less than or equal to 0.10 (90% confidence level), trends were evaluated, and results are presented in Appendix E. Three of the metals evaluated, copper, lead, and zinc show notable, statistically-significant trends in the watershed.

Across the watershed (M10, M30, M40, M50, M60, T10, T20, M130, M140, M150, VT05, and VM05) data show statistically-significant decreases in copper concentrations. The magnitude of the decrease is on the order of 3% per year in the upper watershed and 6 to 10% per year in the lower watershed. There is also a pattern of decreasing copper concentrations at canal stations C30, C40, and C50. These patterns reflect discontinued use of copper sulfate within the C-BT canals and discontinued use of copper sulfate by the City of Loveland (as of 2015; Bohling, 2021); however, the cause of decreasing concentrations in the upper-most watershed is uncertain.

Lead concentrations exhibit a statistically-significant decrease at nearly all stations across the watershed with a magnitude of ~6% per year. This may reflect long-term reductions in atmospheric loading of lead from leaded petroleum products.

Zinc concentrations exhibit statistically-significant decreases over the 15-year period at most canal locations (C10, C20, C40, and C50), but not at any non-canal locations. The reason for this apparent decrease (on the order of 4 to 8% per year) is uncertain.

3.3.3 Metals Compliance

Metals concentration data in the Forum database were evaluated against both acute and chronic aquatic life metals standards (Table 4). Results are summarized in tables in Appendix F. As described in Section 2.2.3, this does not comprise a regulatory assessment against standards; instead, it is a simple comparison of observed values to acute and chronic standard values. No notable concerns relative to acute or chronic standard values were noted in the evaluation for cadmium, lead, or zinc[24]. Issues noted for copper, selenium, and arsenic are described below:

- **Copper:** There is a high frequency of observations above the aquatic life copper standard (70% for chronic and 56% for acute) in the most upstream station in the watershed (M10). The low hardness values at this station result in very low copper water-quality standards. Moving downstream, increasing hardness concentrations result in rapidly increasing copper standards and correspondingly few cases of observations above standard values (M30: 38% above chronic standard values and 27% above acute standard values). By M40, observed results above standard values for copper are ≤1%. There are no notable issues relative to copper standards across the rest of the watershed, with the exception of M90 (31% of observations are above the chronic standard value and 21% are above the acute standard values). Historically, the City of Loveland occasionally used copper sulfate for algal biomass control in Green Ridge Glade Reservoir (adjacent to their drinking water treatment facility near site M90), which can discharge augmentation water back to the Big Thomson River. This practice was discontinued in 2015 (Bohling, 2021), and the time-series plots show that there have been very few cases of values above the copper standards at M90 from 2016 through 2020 (Appendix C1, Figure C1-14). Based on this change, it may be appropriate to modify the copper 303(d) listings to exclude Segment 2 altogether in the future.

- **Selenium:** For selenium, there no cases of observed values above the acute standard value across the watershed; however, there are relatively high frequencies of observations above the chronic standard value in the lower sub-watershed. At M130, M140, and M150, cases above the chronic standard value range from 6% to 23% of observations. This increases sharply on the Little Thompson River and on the mainstem below the Little Thompson River to 94% of observations (VT05) and 77% of observations (VM05). These patterns match the conceptual understanding of the areas of influence for Pierre shale, indicating a natural source for the selenium, though concentrations may be exacerbated by agricultural land use.

- **Arsenic:** With the exception of Segment 4, which has a chronic arsenic standard of 7.6 µg/L, the chronic arsenic standard across the watershed is 0.02 µg/L. At all sampling

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[24] Note that zinc is currently on the 303(d) list as a high-priority in Segment 1. Unfortunately, there are no data in the Forum database for zinc at the only station in this segment (M10). It is recommended that dissolved zinc be added to the analyte list for routine sampling at M10 and M20 to support future analyses.

stations except those in Segment 4, every detected observation[25] is above the 0.02 µg/L chronic standard value. This chronic standard value is below any detection limit in the existing dataset; however, that is not a limitation in this analysis since most observations are above detection limits. Given this pattern across the watershed from pristine waters in Rocky Mountain National Park (M10) to anthropogenically-influenced waters in the lower watershed, the 0.02 µg/L standard does not appear to be attainable in the Big Thompson watershed. The current 303(d) listings do not include the Little Thompson River or Segment 5; however, based on the observed data, it is likely that the entire watershed would fail to meet the 0.02 µg/L chronic arsenic standard. As such, only Segment 4 (with a chronic standard of 7.6 µg/L) should be excluded from the 303(d) list as long as the 0.02 µg/L remains. Note that there are widespread issues across the state relative to the 0.02 µg/L chronic arsenic standard.

3.4 MICROBIOLOGICAL PARAMETERS

Two microbiological parameters are included in this analysis:

- Total coliforms, and
- *E. coli*.

Total coliforms and *E. coli* are indicators of the potential presence of pathogens. Total coliforms is a measure of the concentration of coliform bacteria present in the water; and is often sampled as an inexpensive potential indictor of fecal contamination and related pathogens. These bacteria can come from the feces of warm-blooded animals and humans or from bacteria naturally present in soils. *E. coli* is a sub-group of the total coliform group, and its presence indicates fecal contamination from warm blooded animals (Birge, 1992). As such, it is a better indicator of the potential presence of harmful pathogens. Most *E. coli* bacteria themselves are harmless and are naturally found in the intestines of people and warm-blooded animals; however, some strains can cause severe illness. Water-quality standards exist for *E. coli* to protect recreational and domestic water supply uses of surface waters.

3.4.1 Microbiological Parameter Concentrations

Total coliforms and *E. coli* exhibit consistent spatial patterns in the Big Thompson watershed. Concentrations tend to be lower in the upper sub-watershed, but they increase by more than an

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[25] As discussed in Section 2.1.2, due to data limitations, only dissolved arsenic is evaluated here even though the standard is based on total arsenic. Note that the findings here are considered to be conservative estimates of concerns relative to the standard, recognizing that dissolved arsenic concentrations will be less than or equal to the corresponding total arsenic concentrations.

order of magnitude in the lower sub-watershed below Buckhorn Creek (e.g., Figure 45). The increase in the lower sub-watershed likely reflects increased population and the effects of livestock in some areas. The concentrations in the Adams Tunnel (C10) are generally low relative to even the upper sub-watershed concentrations (e.g., Figure 45).

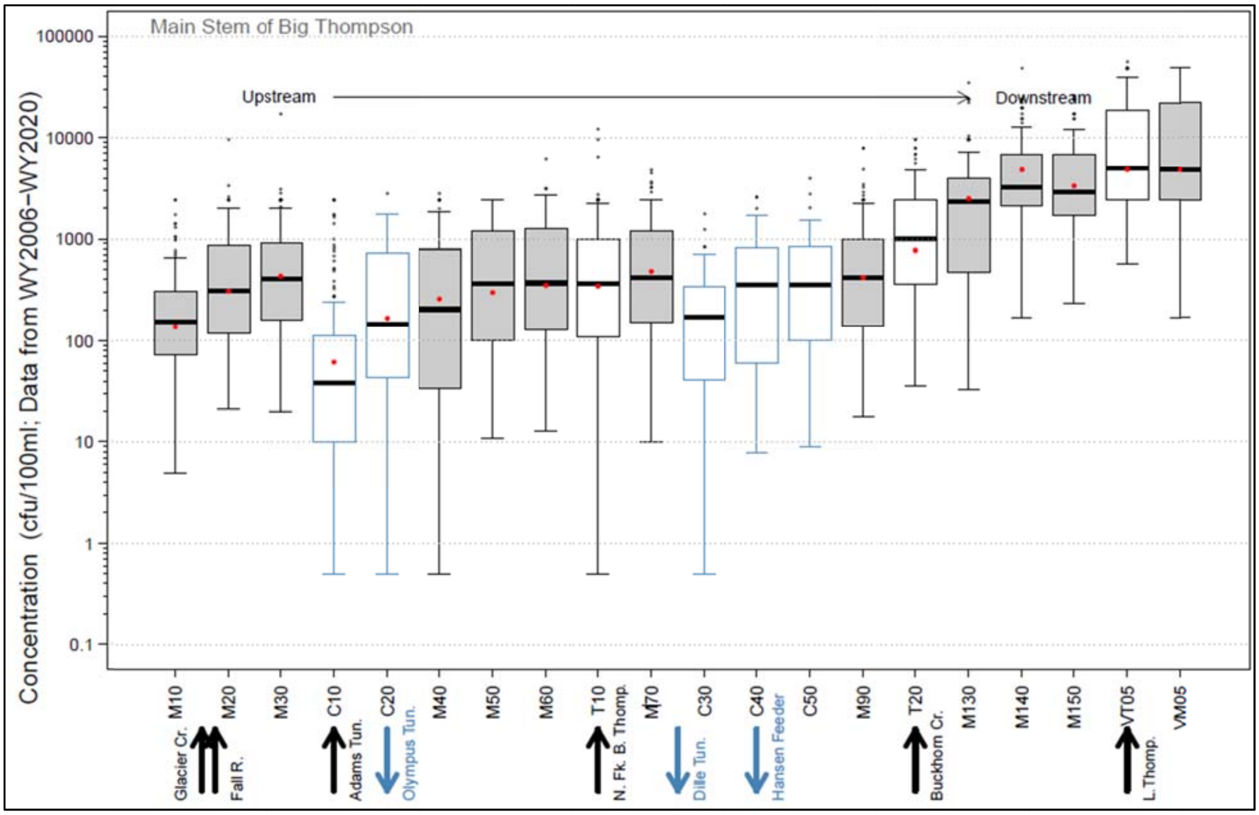

Figure 45. Box Plot of Total Coliforms Concentrations (cfu/100mL) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

Across the watershed, including C-BT canal locations, both total coliforms and *E. coli* show similar seasonal patterns of lower concentrations in winter and elevated concentrations in summer and fall (Appendix Figures C1-81 through C1-100). The highest concentrations of total coliforms were observed on the Little Thompson River at VT05. In addition to being an area of rapid population growth, there are also livestock sources of bacteria in this reach. Concentrations in T20 (Buckhorn Creek) are also noteworthy in that they are consistently high relative to the upstream mainstem concentrations at M90.

Coliform time-series data do not show any clear patterns of effects from the flood, fires, or road reconstruction activities.

3.4.2 Microbiological Parameter Concentration Trends

Concentration time series data for microbiological parameters were evaluated for statistically-significant trends applying the Seasonal Mann-Kendall approach, as described in Section 2.2.2. Statistically-significant trends at a 90% confidence level were identified for both total coliforms and *E. coli*, as listed in Appendix E. The trends were further assessed with a review of the time-series plots.

Statistically-significant trends of increasing total coliforms or *E. Coli* were observed at several stations (M10, M60, T10, M130, M140, M150, and VM05), with some increasing and some decreasing trends. There were no consistent spatial patterns, and, in many cases, trend findings disagreed with findings noted in the previous Big Thompson State of the Watershed Report (Hydros, 2015), suggesting uncertainty and variability in the patterns. The trend with the largest rate of change in terms of percent of the mean was a 34% increase at M60; however, this actually amounts to a relatively small change in terms of the observed range of data (35% of the mean corresponds to <10 CFU/100mL per year at a station with observations ranging from 0 to 1,300). Similar trends are not seen at nearby stations, adding to uncertainty in the pattern. It should also be noted that coliforms tend to be transported through runoff during storm events. Therefore, the existing watershed sampling program may catch occasional storm events, but it is not designed to target such events. As such, these spatially-varying patterns in coliform trends with no apparent explanation should be considered cautiously.

3.4.3 Microbiological Parameter Compliance

Of the microbiological parameters evaluated, water-quality standards only exist for *E. coli*. The data were compared to the Class E (Existing Primary Contact) and Class U (Undetermined Use) recreational use standard of 126 cfu/100 mL. The percent of observations above the standard value are presented in Appendix F. Note that the chronic standard is not assessed as a comparison of the standard value to each individual observation; however, this comparison is made for information and pattern investigation purposes in this report.

Observations above the chronic *E. coli* standard value have occurred at most locations across the watershed, though cases are infrequent in the upper reaches and central mainstem (Figure 46). In the lower watershed, beginning with T20 (Buckhorn Creek), the frequency of observations above the chronic standard generally increases and continues to increase moving downstream (Figure 46). Cases of observations above the chronic standard on the mainstem are most frequent at the downstream end of the Big Thompson River (VM05), downstream of the confluence with the Little Thompson River. The lower Little Thompson River is on the 303(d) List for *E. coli* (Figure 10a). The Little Thompson River exhibits a high frequency of *E. coli* observations above the standard value (>60%). This may reflect livestock sources of bacteria in this reach.

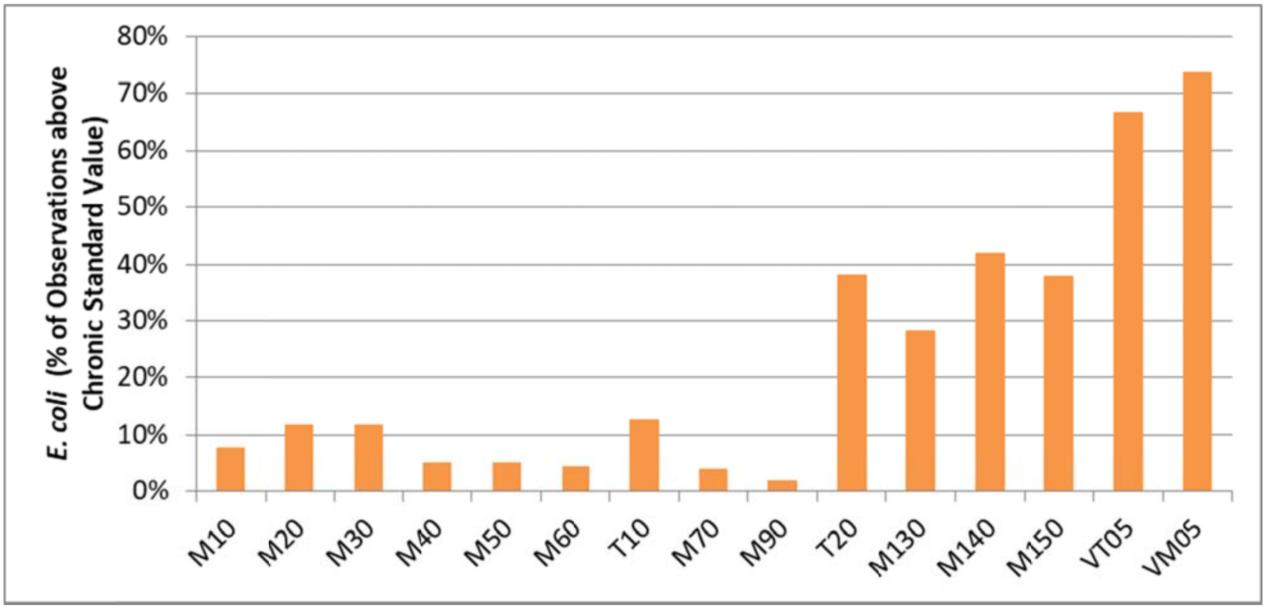

Figure 46. Summary of Data Comparison to *E. coli* Standards, WY2006-WY2020

3.5 GENERAL PARAMETERS

There are nine general parameters included in this assessment:

- Alkalinity,
- Dissolved oxygen,
- Hardness,
- pH,
- Specific conductivity,
- Sulfate,
- Water temperature,
- TOC, and
- TSS.

These parameters provide a broad view of the overall physical, chemical, and biological conditions present in the watershed. This section describes the findings of concentration plotting, the trend analysis, loading calculations, and the compliance analysis for the general parameters.

3.5.1 General Parameter Concentrations

Concentration trends for general parameters across the watershed are shown on box plot figures C2-16 through C2-26 in Appendix C2. Time series plots of the general parameters are presented in three groups. Alkalinity, dissolved oxygen, hardness, pH, and specific conductivity are presented in Appendix C1, Figures C1-61 through C1-80. TDS, temperature, TSS, and sulfate are presented in Figures C1-81 through C1-100. TOC time-series plots are presented in Figures C1-21 through C1-40. Spatial and seasonal concentration patterns are summarized as follows:

- **Temperature and dissolved oxygen** generally show expected seasonal and spatial patterns across the watershed. Temperature shows a general increasing trend from upstream to downstream (Figure 47), reflecting natural warming patterns. Dissolved oxygen concentrations show a slight decrease from upstream to downstream (Figure 48), largely reflecting decreased saturation levels due to increasing water temperature. Dissolved oxygen in the C-BT canal system, however shows a small increase from upstream to downstream, likely reflecting re-saturation of slightly depressed dissolved oxygen concentration (relative to M20) upon entry to the watershed (C10; Figure 48). VT05 in the Little Thompson River exhibits lower median dissolved oxygen concentrations as compared to the Big Thompson River just upstream at M150 (Figure 48). This corresponds to higher temperatures also (Figure 47). In spite of the lower dissolved oxygen concentrations in the Little Thompson River, comparison to standards (discussed in Section 3.5.4) indicates that there are currently no concerns for dissolved oxygen at VT05.

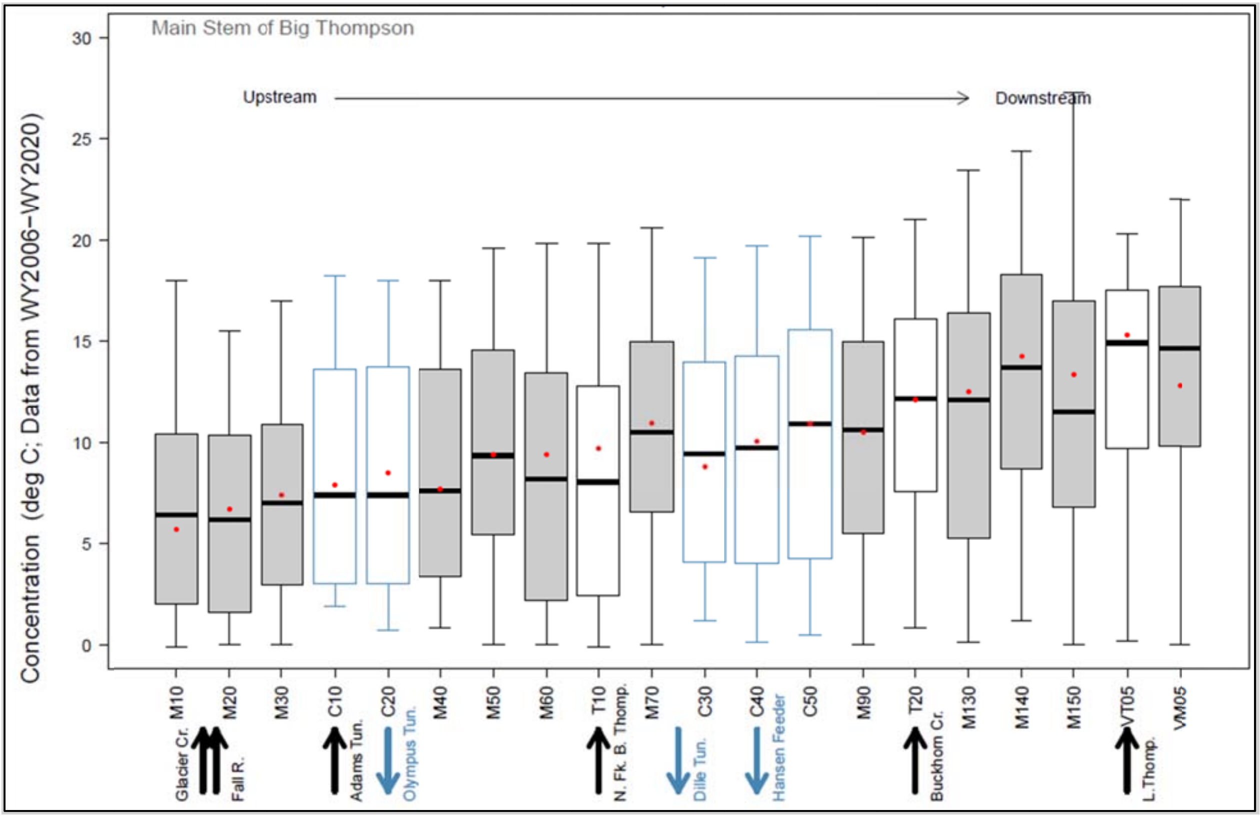

Figure 47. Box Plot of Water Temperature (°C) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the linear scale.

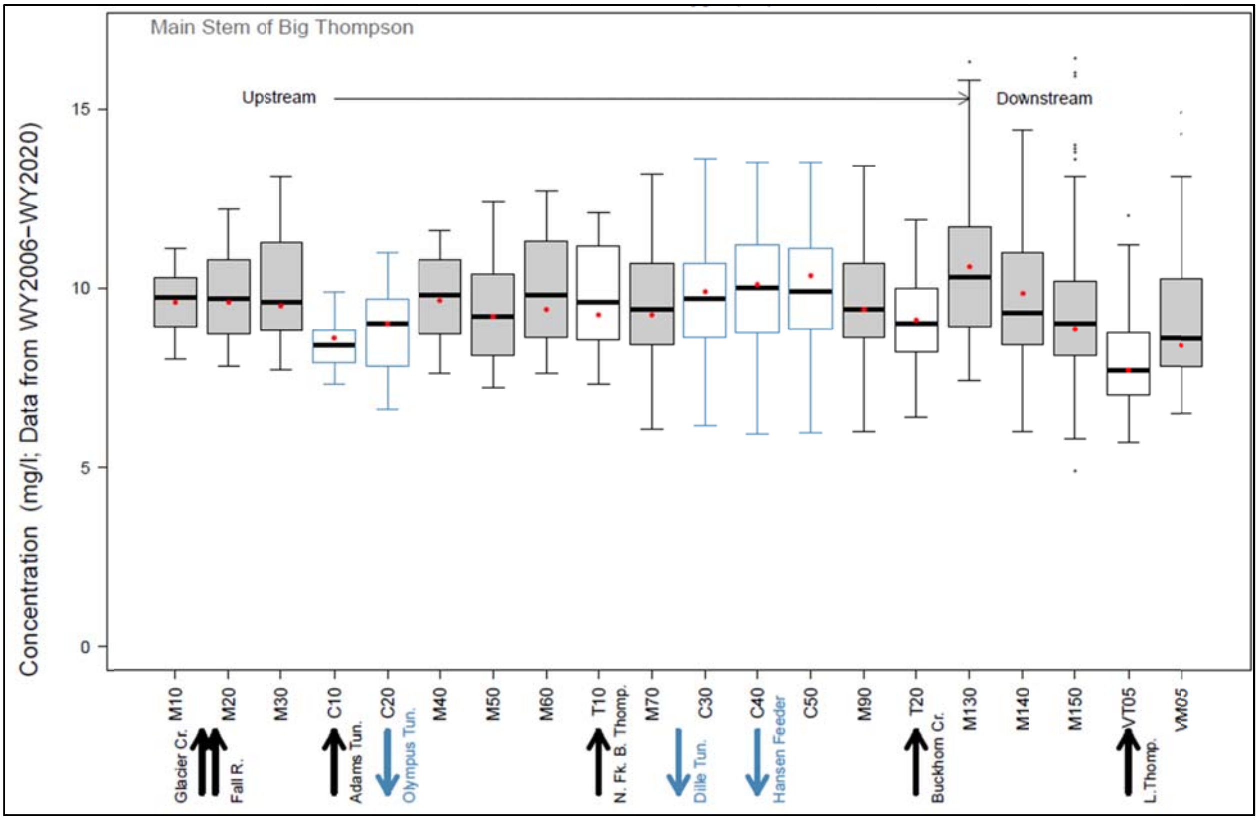

Figure 48. Box Plot of Dissolved Oxygen (mg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the linear scale.

- **Specific conductivity, hardness, and alkalinity** are all different measures of dissolved species in solution. These parameters show similar relative patterns across the watershed, with the lowest values in the upper-most watershed (M10, M20, M30, and T10) and a sharp increase in concentrations at Buckhorn Creek (T10) and in the lower watershed starting at M130 (e.g., Figure 49). The highest concentrations of specific conductivity, hardness, and alkalinity are observed at VT05 at the end of the Little Thompson River (e.g., Figure 49). All of the locations with elevated specific conductivity, hardness, and alkalinity are located in areas of sedimentary bedrock geology (Figure 3). Additionally, there are several quarries in the Buckhorn Creek watershed (e.g., Arkins Park Stone Quarry, Colorado Flagstone Quarry, and Old Wild Gypsum Quarry) that might help explain the observations at T10. Gypsum (calcium sulfate, $CaSO_4 \bullet 2\ H_2O$) is a common and soluble evaporite mineral in sedimentary rocks that may contribute to these elevated values.

Seasonally, specific conductivity, hardness, and alkalinity are higher in winter and early spring across the watershed. The concentrations of these parameters drop in the late spring / early summer due to dilution by the snowmelt runoff waters.

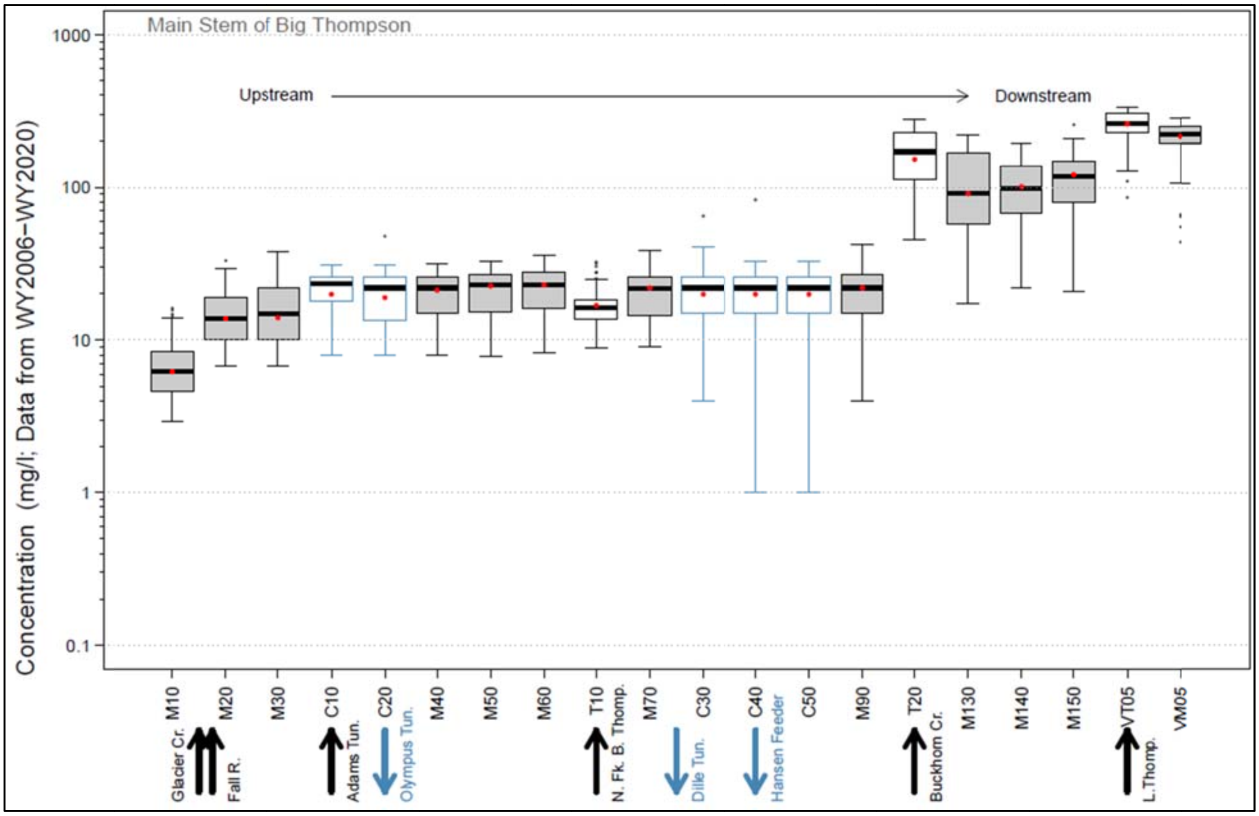

Figure 49. Box Plot of Alkalinity (mg/L as CaCO3) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **Sulfate** concentration patterns (seasonal and spatial) are similar to those noted for specific conductivity, hardness, and alkalinity. These patterns reflect similar sources (evaporite minerals). In addition to being a source of selenium and arsenic, Pierre shale can also be a source of sulfate. The highest sulfate concentrations are observed in the Little Thompson River reflecting the greatest area of Pierre shale and extensive agricultural land use which can exacerbate dissolution and transport of dissolved solids through irrigation and irrigation returns.

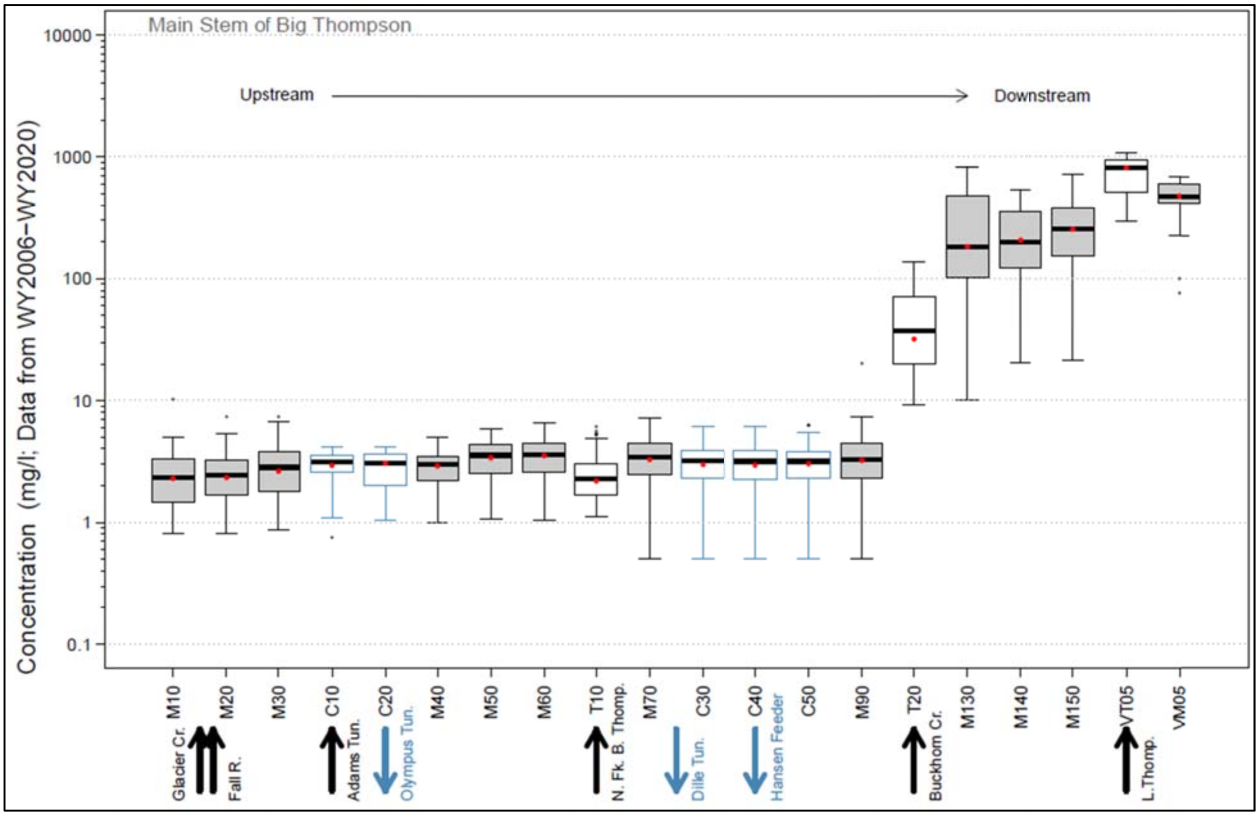

Figure 50. Box Plot of Sulfate (mg/L) in the Big Thompson River, WY2006-WY2020
Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **pH** shows a generally increasing trend from upstream to downstream (Appendix Figure C2-20), with median values ranging from ~7 to ~8 (Figure 51). This follows the expected patterns based on alkalinity across the system (Figure 49). Similarly, seasonality in pH values at most locations shows patterns matching alkalinity, with higher pH in winter and early spring and lower pH in summer.

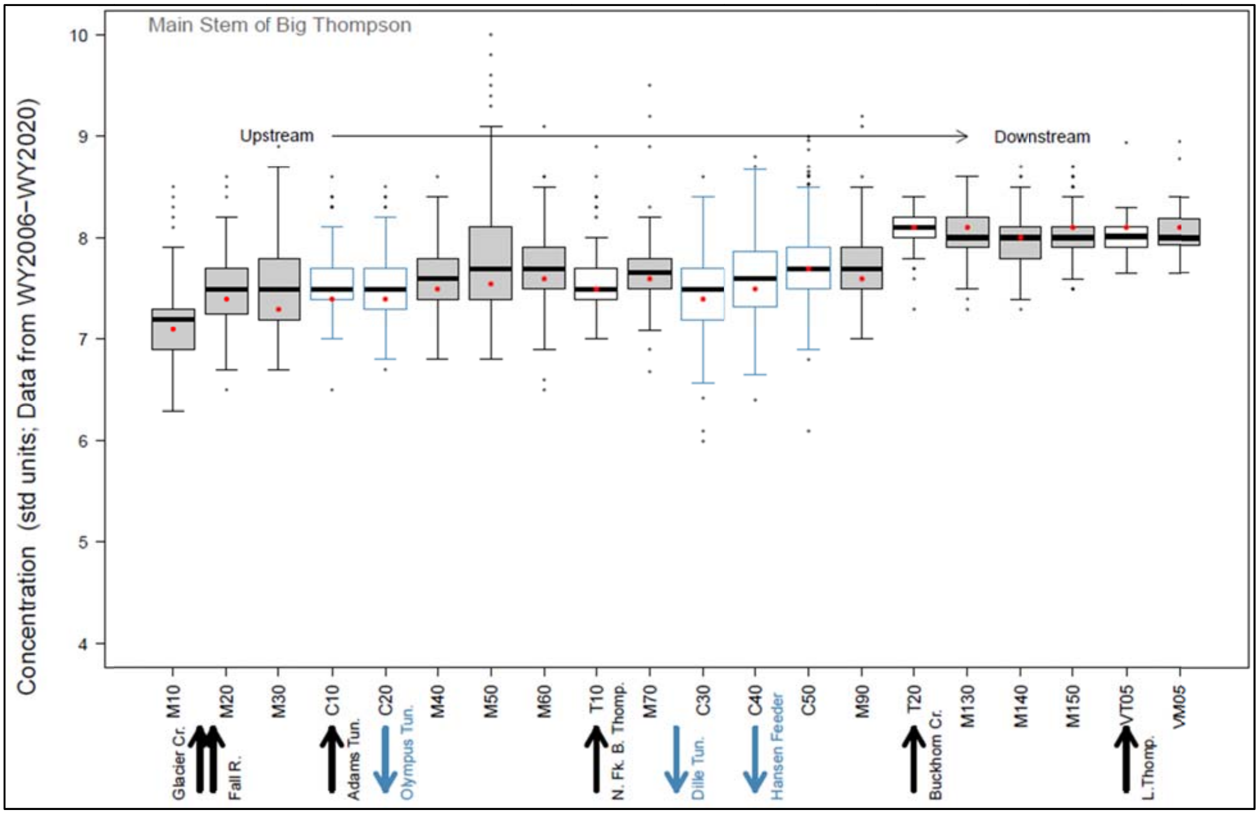

Figure 51. Box Plot of pH in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the linear scale.

- **TSS** is a measure of solids in suspension in the river. In spite of the limited dataset for TSS, there are some apparent patterns worth noting. First, TSS concentrations entering the Big Thompson River from the CB-T system (C10) are generally low compared to values in the Big Thompson River upstream (M10 and M20; Figure 52). The median concentrations and observed ranges of TSS are fairly consistent across the upper watershed (data from M10 to M90; Figure 52). There is a TSS concentration increase of roughly an order of magnitude in the lower watershed (VT05 and VM05; Figure 52). Due to the lack of TSS data at T20, M130, M140, and M150, it is difficult to evaluate the full pattern and comment definitively on sources behind this sharp increase in solids; however, urban, suburban, and agricultural runoff and changing subsurface geology are possible explanations. Routine collection of TSS data at all stations is recommended for future sampling. This will be particularly critical to support evaluation of post-fire response in the watershed in the coming years.

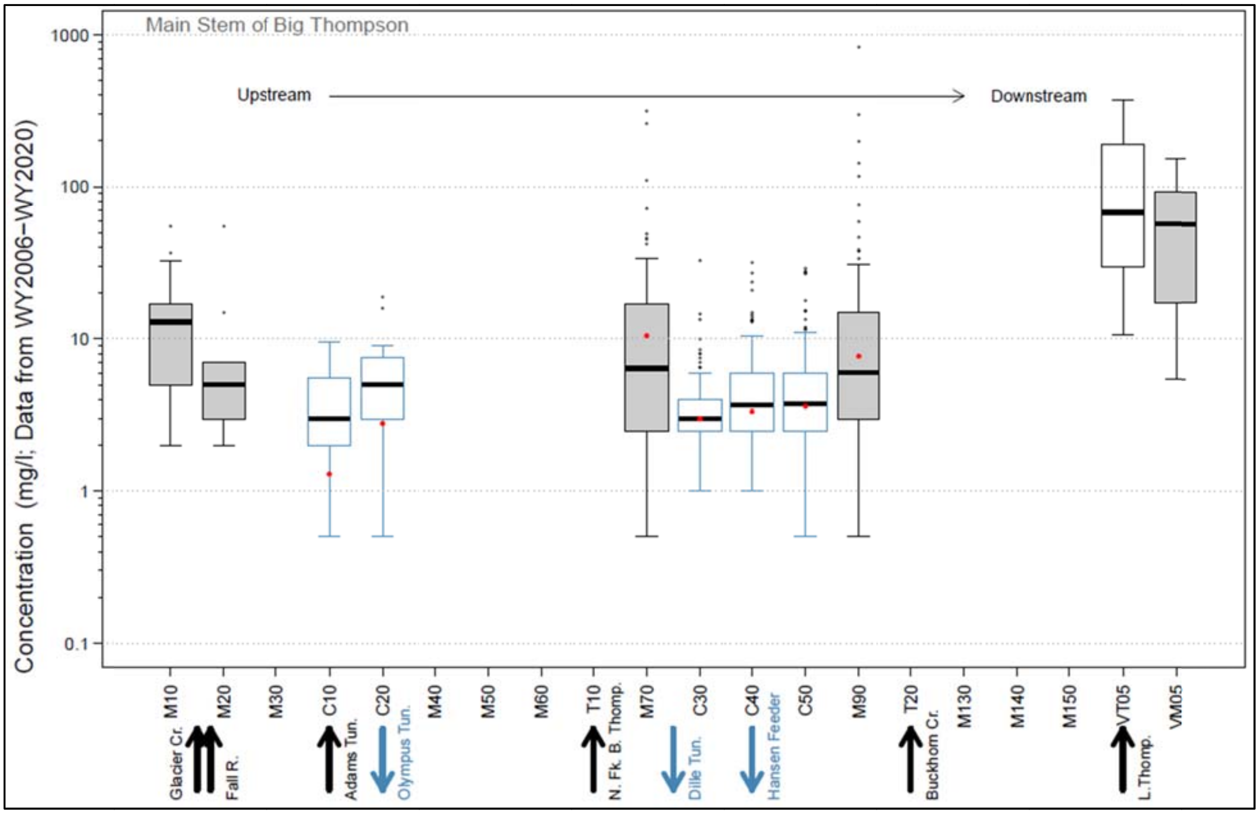

Figure 52. Box Plot of TSS (mg/L) in the Big Thompson River, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

- **TOC** is one of the most important water-quality parameters for the drinking water treatment plants that treat Big Thompson River water and/or C-BT system water. TOC is important 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). DBPs are compounds that are formed when TOC reacts with chlorine at the water treatment plants and include carcinogenic compounds. Water treatment plants have regulatory requirements related to DBP concentrations in treated water. The following TOC concentration patterns are apparent across the Big Thompson River watershed, as shown in (Figure 53):
  - Median TOC concentrations along the Big Thompson River generally increase from upstream to downstream, with a small step increase at M140, due to effluent from the Loveland WWTP.
  - Seasonally, TOC concentrations tend to be highest across the Big Thompson watershed each spring during the snowmelt runoff. In the upper watershed, TOC concentrations tend to be low in winter months; however, in the lower sub-watersheds, particularly beginning at M140, TOC concentrations are also relatively

high in winter months when flows are low and there is a greater relative fraction of treated wastewater effluent.

- Over the full study period (WY2006-WY2020), median concentrations of TOC in the Little Thompson River are comparable to those in the lower portion of the Big Thompson; however, the median TOC in the Little Thompson River has increased in the recent five years (see red dot at VT05 in Figure 53), possibly reflecting population growth.
- TOC concentrations in C-BT water (C10, Adams Tunnel) reflect the conditions of the Three Lakes system on the west slope. The median concentration is higher at C10 (3.5 mg/L) than at M30 (2.8 mg/L). In addition, TOC concentrations from the Adams Tunnel are less seasonally variable due to the dampening effect of mixing and residence time in the Three Lakes, though the highest seasonal concentrations are still observed in the spring during snowmelt runoff.

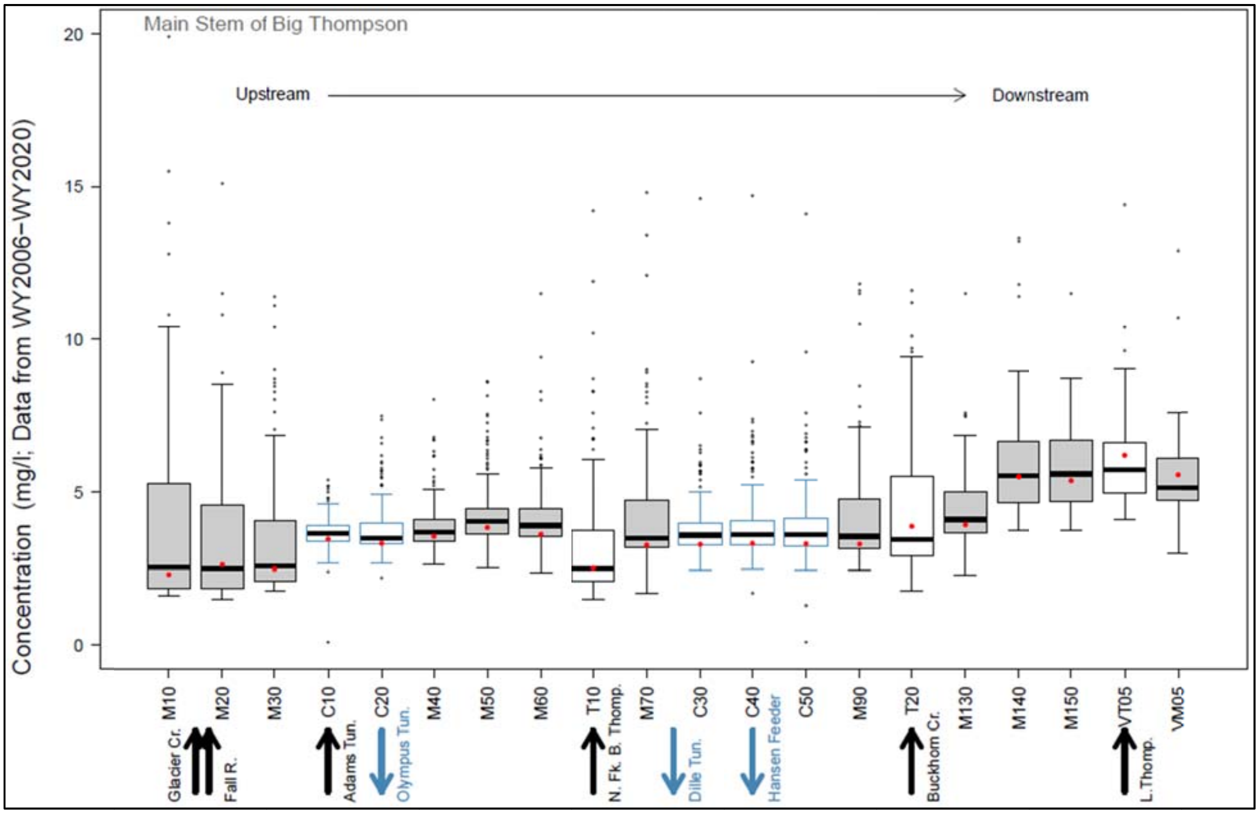

Figure 53. Box Plot of TOC (mg/L) in the Big Thompson River, WY2006-WY2020
Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the linear scale.

The following event-related responses were noted in review of the time-series of general parameter data:

- **2012 Fern Lake Fire and 2013 Flood Effects at M10:** As noted in Section 3.2.1, there was an apparent increase in nitrate concentrations during snowmelt runoff at M10 in the three years following the 2012 fire and 2013 flood. A similar pattern is apparent for general parameter measures of dissolved solids, including alkalinity, hardness, and specific conductivity (e.g., Figure 54). This pattern, which may be vaguely apparent downstream at M20, is not seen elsewhere in the basin, including relatively pristine basins like the North Fork which also experienced the 2013 flood. Based on this, it is expected that the response is the combination of the Fern Lake Fire (October 2012) in the M10 watershed and the 2013 flood. The combination resulted in extensive vegetation and soil disruption and transport. Moraine Park, just upstream of M10, is a natural solids trap, and may have limited the extent of solids transport. The disruption of vegetation cover and exposure and movement of solids, however, could have led to increased contact time for snowmelt water with rock and soil, leading to increased dissolved constituent concentrations.

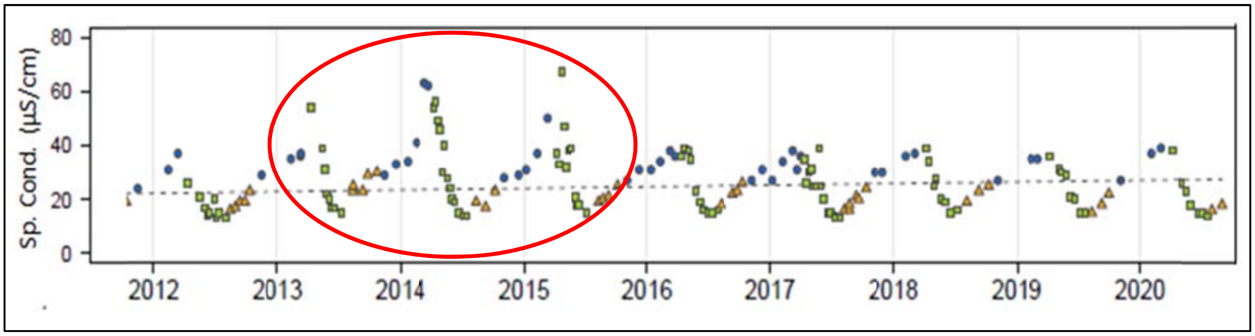

Figure 54. Specific Conductivity (µS/cm) at M10, 2012-2020, Post-Fire and Flood Concentrations Circled

(Symbol colors indicate season; black dashed line indicates long-term linear trend)

- **2013 Flood Effects in the Lower Watershed:** Following the 2013 flood, there was an increase in baseflow rates in the lower watershed which was particularly apparent in winter months for two to three years after the event (discussed in Section 3.1.3). At the same time, winter concentrations for measures of dissolved solids (alkalinity, hardness, sulfate, and specific conductance were lower than in other years at T20, M130, M140, and M150; e.g., Figure 55). The decreased concentrations reflect dilution from greater groundwater inflow (and groundwater from different areas) in these reaches where typical winter concentrations tend to be relatively high. A similar effect is expected at the downstream end of the watershed; however, data gaps in 2015 and 2016 at VT05 and VM05 make it difficult to discern any patterns.

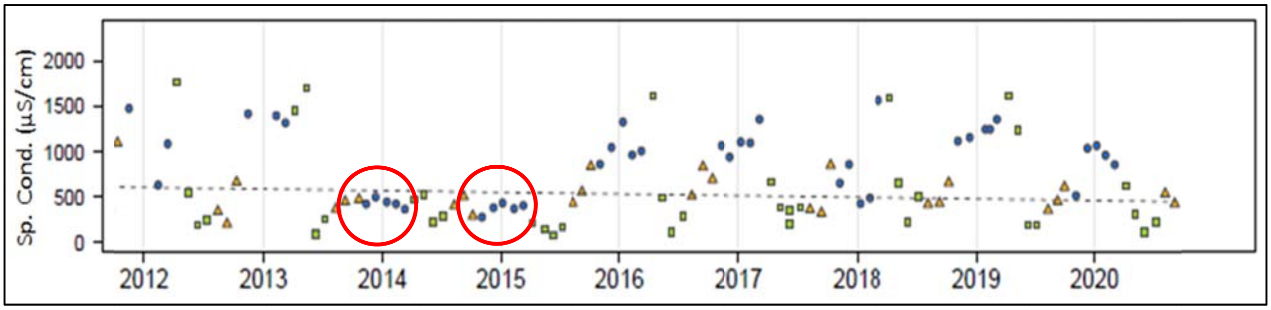

Figure 55. Specific Conductivity ((µS/cm) at M130, 2012-2020, Post-Flood Winter Concentrations Circled

(Symbol colors indicate season; black dashed line indicates long-term linear trend)

- **Post-Flood Road Reconstruction Impacts:** Results for general parameters were reviewed for evidence of adverse effects of post-flood road construction activities; however, no clear impacts are apparent in the Forum dataset. This does not indicate that there were no impacts. Separate studies have documented construction impacts on the river including increased solids (Fayram, 2018). There was also a well-documented fish kill, due to increased pH from a concrete spill in 2016 (CPW, 2016). These are described further in Sections 1.3.4 and 1.3.5. The lack of observed impacts from road construction activities in this dataset likely reflects the transient nature of such impacts, which are unlikely to be seen at the sampling frequency of this program.

3.5.2 General Parameter Concentration Trends

Concentration time series data for the nine general parameters were evaluated for statistically significant trends applying the Seasonal Mann-Kendall approach, as described in Section 2.2.2. Results were first screened against the fairly inclusive criteria of p-values less than or equal to 0.10 (90% confidence level), then reviewed in the time-series plots. Based on this review, several noteworthy trends were identified for discussion. All identified trends are noted on the time-series graphics (Appendix C1) and in tables in Appendix E.

In the previous State of the Watershed Report (Hydros, 2015), an increasing trend of TOC concentrations was noted in the C-BT canal system (C10, C20, C30, C40, and C50), though it was noted to have likely plateaued in the latter years of that study (as of ~2008). The cause of this increase was hypothesized to be the large-scale tree death from the mountain pine beetle epidemic (Hydros, 2015), citing a study by Mikkelson et al. (2013) which noted a similar effect. In this update, however, there is a statistically-significant trend in the opposite direction of a similar magnitude (a decrease of ~0.03 mg/L TOC per year) across the C-BT canal locations. Based on review of the graphic, a slow decrease in concentration from ~2012 through 2020 is apparent (Figure 56). It is unclear at this time if the pattern relates to recovery from Mountain Pine Beetle response, if it is part of a larger cyclical pattern, or if there is another explanation.

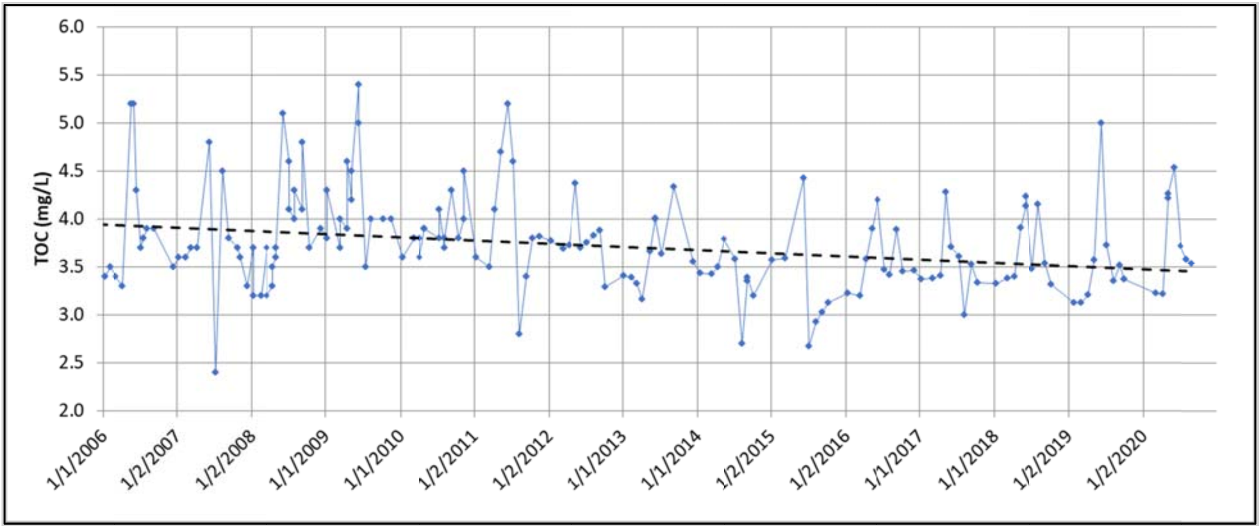

Figure 56. TOC Concentrations (mg/L) at C10 (Trend slope shown as black dotted line)

Statistically-significant trends in TOC concentrations were also identified in the lower watershed. At VT05 (Little Thompson River) and VM05, a trend of increasing TOC (on the order of an increase of 2% per year; ~0.1 mg/L per year) was found through the statistical testing (e.g., Figure 57). These patterns may reflect population growth in the Little Thompson River watershed, leading to a greater fraction of wastewater effluent in the river.

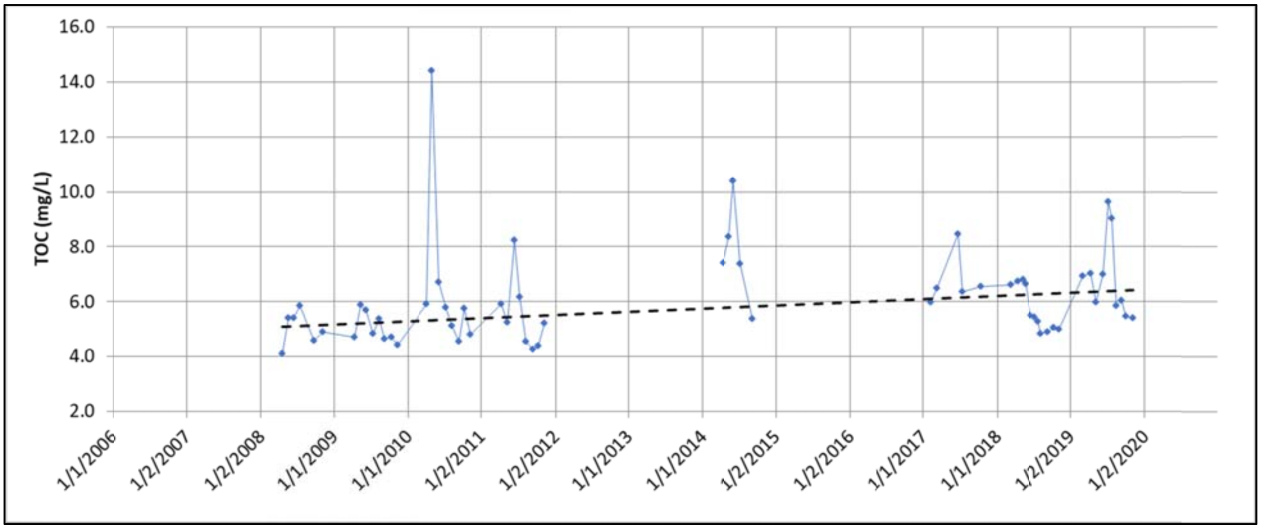

Figure 57. TOC Concentrations (mg/L) at VT05 (Trend slope shown as black dotted line)

Possible trends of decreasing dissolved solids (in terms of alkalinity, specific conductivity, and/or hardness) were identified at various locations in the canal system, upper watershed, and lower watershed. It is unclear whether these reflect actual gradual changes over time, changes in sampling frequency (canals), or post-flood effects (especially in the lower watershed). Patterns should be considered in the next data review for any consistent changes.

Finally, there is a small-magnitude trend of decreasing pH at mainstem stations from M10 through M60 and at most canal locations (C10, C20, C30, and C40). The trend is small, ranging from 0.1 to 0.5 percent of the mean each year (0.01 to 0.04 standard pH units per year), but the same trend was noted in the 2015 State of the Watershed Report at many of the same locations (Hydros, 2015). The cause of this small decrease in pH remains uncertain. The pattern is noted for consideration in ongoing data collection and analysis.

3.5.3 TOC Loading

Of the general parameters, loading was only assessed for TOC. Appendix D1 (Figures D1-8 and D2-8) presents the loading analysis results for TOC. The larger patterns in TOC loading track with annual and seasonal discharge volumes in the canals and rivers (e.g., Figure 58 and Figure 59). In general, relative TOC loads across the system show similar patterns from year to year. The TOC loads at the Adams Tunnel (C10) and the other canal sites are significantly higher than the upper watershed stream sites because of the significantly higher flows. The canals move large volumes of water in the late fall and winter months to fill Carter Lake and Horsetooth Reservoir, resulting in high winter TOC loads in the canals. Flows and, as a result, TOC loads decrease dramatically below M90 due to diversions, including the City of Loveland drinking water treatment plant intake (Figure 58 and Figure 59). Station M140 shows a small relative increase in mean TOC load compared to the upstream station, corresponding to the increased TOC concentrations and flow from the Loveland WWTP effluent.

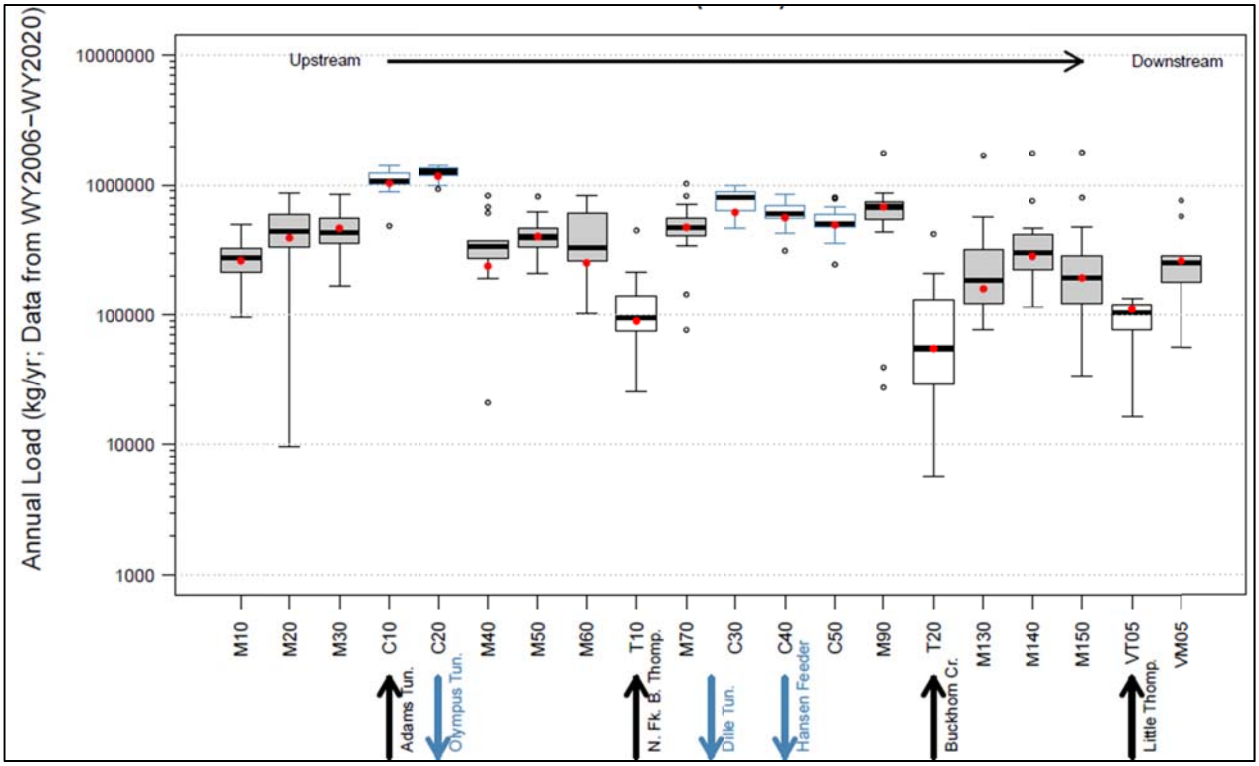

Figure 58. Box Plot of Annual TOC Load (kg/yr) across the Big Thompson Watershed, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

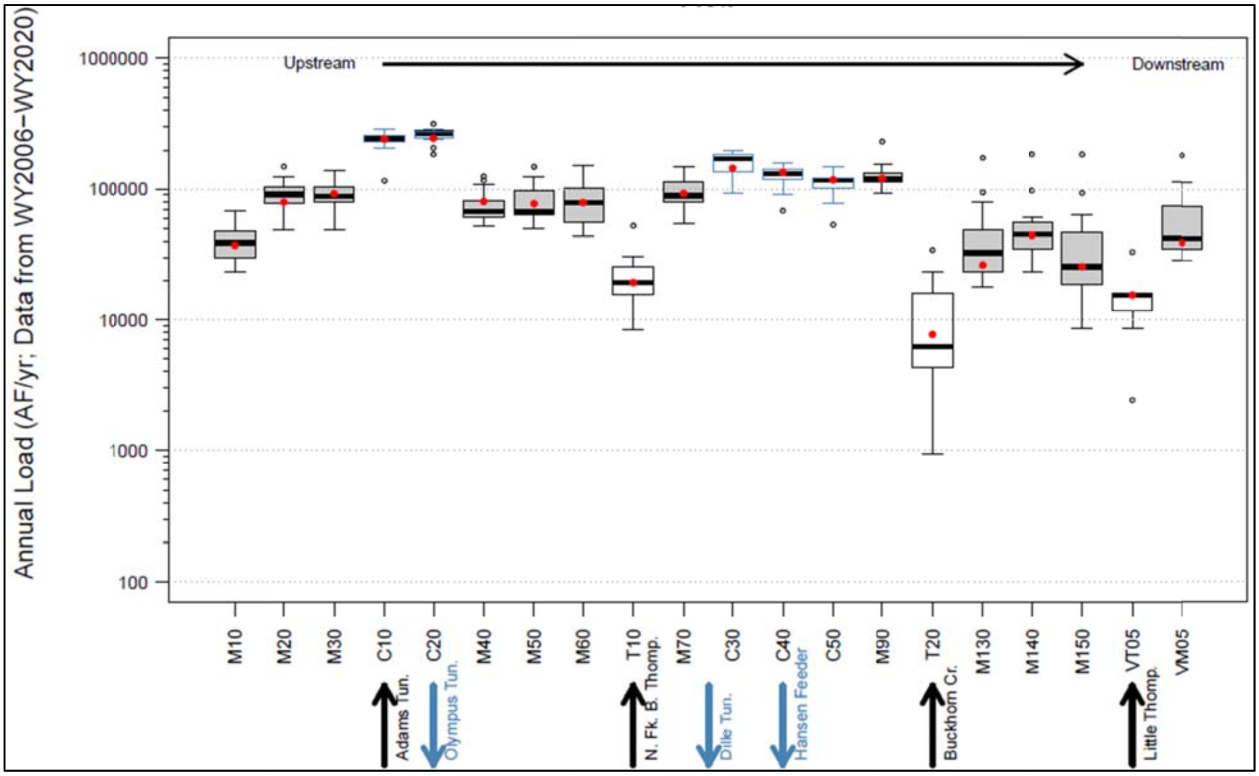

Figure 59. Box Plot of Annual Flow Volumes (AF/yr) across the Big Thompson Watershed, WY2006-WY2020

Grey-shaded boxes indicate mainstem locations. Unshaded boxes indicate non-mainstem sampling locations. Blue outlined boxes indicate canal locations. Red dots indicate the medians for the recent five years of record (WY2016-WY2020). Note the logarithmic scale.

3.5.4 General Parameter Compliance

Of the general parameters, applicable standard values exist for pH, temperature, sulfate, and dissolved oxygen. The compliance analysis results for all years of data are summarized in Appendix F. Findings for each of these parameters are discussed below:

- **pH:** For pH, values below the minimum pH standard (6.5) are occasionally observed in the uppermost watershed at station M10 (there are several cases in the summer and fall months of 2013 and 2017). These cases occur between June and September, corresponding to the time of the lowest seasonal alkalinity at M10, which is also the station with the lowest alkalinity in the watershed. Note that the lowest recorded pH in the study period at M10 was 6.3 in 2013 (which is only slightly below the 6.5 standard value). Observations above the upper pH standard value (9) are also occasionally observed at M50, below the Upper Thompson Sanitation District effluent, though the most recent case of this was ten years ago in 2011. Small magnitude exceedances of the upper standard value are also occasionally seen at M60, M70, and M90, though the most recent case at any of these locations was a pH value of 9.1 in 2012. Finally, the Forum does not have a monitoring station on the short 303(d)-listed segment (Fish Creek below Mary’s Lake) for pH in the upper watershed (Figure 10a), so no comment on that listing can be made here.

- **Sulfate:** Comparison of observed data to the chronic sulfate standards indicates no concerns across the upper watershed (Figure 60). There are, however, frequent observations (>50%) above the sulfate standard in Segment 5 (M150 and VM05), as well as at the end of Segment 9 (the Little Thompson River; 100% of observations are above the standard at VT05). Note that there is no applicable standard in Segment 4, but sulfate concentrations at M150 are comparable to those in Segment 4 (at M130 and M140). In spite of the pattern of sulfate concentrations above the standard in Segments 5 and 9, there are currently no 303(d) listings for sulfate. As discussed in Section 3.5.1, the Pierre shale in the lower watershed may explain the elevated levels of sulfate (relative to the upper watershed).

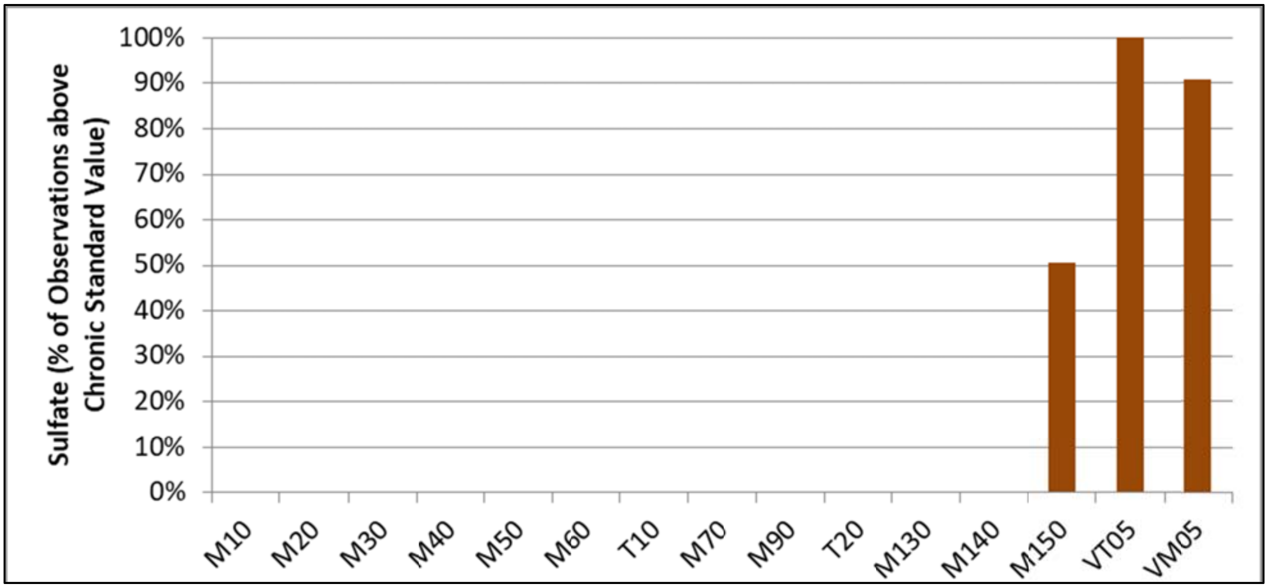

Figure 60. Summary of Data Comparison to Chronic Sulfate Standards, 2006-2020

- **Dissolved Oxygen:** There are no consistent issues relative to the dissolved oxygen standards across the watershed. While there are a handful of observations in the study period that are below the applicable standard, the most recent case is an observation of 6.9 mg/L dissolved oxygen at T20, which is only slightly below the applicable standard of 7.0 at the time.

- **Temperature:** The temperature compliance evaluation should be cautiously interpreted. Continuous temperature data (at least hourly) are needed to appropriately evaluate the river conditions relative to the acute and chronic standards, but there are only discrete measurements in the Forum database. Only comparisons to the acute temperature standard values are made here; however, it is recognized that even these findings are not definitive given the low frequency of observations. No cases of observed temperatures above the acute temperature standards exist in the Forum database for the study period. Given the importance of water temperature to aquatic life and the variable flow rates in the Big Thompson River due to various diversions, it is recommended that continuous temperature gages be installed in several locations across the watershed. These data could help support evaluation of the current 303(d) temperature listings in the watershed (Figure 10c). Alternatively, if such data are being collected through another program, it is recommended that these data be included in the Forum's next five-year data review.

4 SUMMARY OF FINDINGS AND RECOMMENDATIONS

This report, sponsored and supported by the Forum, presents and assesses flow and water-quality data collected at flowing water sites in the Big Thompson watershed from WY2006 through WY2020. This period included wildfires in 2010, 2011, 2012, and 2020. There was also a major flooding event in 2013 followed by many years of road reconstruction activities. The analysis considered nutrients, metals, coliforms, and general water-quality parameters in light of hydrology, geology, population, land use, and water management in the watershed. Data were reviewed for spatial and temporal patterns, long-term trending, loading rates, and concerns relative to regulatory standard values.

Based on the analysis, the state of the Big Thompson watershed varies spatially. The upper watershed is generally in good condition, though there is an imminent threat to water quality in both the upper and lower watersheds from the major fires in the fall of 2020. Conditions in the lower watershed are considered fair, with improving conditions on the mainstem but deteriorating conditions on the Little Thompson River. The basis for this general assessment of the state of the watershed is summarized in the following subsections, including major patterns in the dataset, notable long-term trends, apparent effects of major watershed events, and highlights of the compliance analysis. The final subsection in this summary presents program recommendations generated based on the analysis.

4.1 FLOW AND WATER-QUALITY PATTERNS

Detailed review and analysis of flow and water-quality data from canals, rivers, and tributaries in the Big Thompson watershed reveal some consistent spatial and temporal water-quality patterns for the upper watershed, lower watershed, C-BT canals, major tributaries, and below WWTFs:

Upper Watershed:

- Flow: Flow rates in the upper watershed follow a seasonal snowmelt hydrograph pattern, with peaks between May and June and a falling limb typically extending into September. The lowest flows occur in winter months. Below Lake Estes, the snowmelt hydrograph peaks are still apparent, but are diminished in some years by C-BT diversions to the Olympus Tunnel.

- Water Quality: The upper watershed is generally characterized by good water quality. This reflects the igneous and metamorphic rock of the subsurface geology, low population density, and natural runoff patterns (dominated by the annual snowmelt runoff hydrograph). Concentrations of dissolved solids, metals, nutrients, TOC, suspended solids, and coliforms all tend to be low, especially relative to the lower watershed.

Lower Watershed:

- Flow: There is a sharp drop in annual flow volumes at the top of the lower watershed. This drop in flow volume, due to major irrigation and municipal water diversions including the City of Loveland drinking water treatment plant intake, dampens the annual snowmelt peak in most years across the lower watershed. While flow rates are notably lower in spring and summer in the lower watershed as compared to the upper watershed, winter flows tend to be higher at the downstream end of the watershed due to gains from groundwater and wastewater effluent.

- Water Quality: The water quality in the lower watershed is generally fair. It is characterized by higher (and growing) population density, urban development, agriculture, livestock, WWTF effluent, alluvial groundwater gains, and sedimentary subsurface geology, including Pierre shale. Relative to the upper watershed, the lower watershed exhibits notably higher concentrations of dissolved solids, nutrients, TOC, suspended solids, and coliforms, reflecting the land use and geology. The higher concentrations of TOC, nutrients, and some metals reflect the population and corresponding WWTF effluent, as well as land use. Livestock and urbanization likely explain the higher coliform concentrations. Finally, elevated concentrations of selenium, arsenic, and sulfate are likely due to the underlying Pierre shale, with concentrations exacerbated by agricultural irrigation.

C-BT Canals:

- Flows: The Big Thompson Watershed serves as a conduit for Colorado's largest trans-basin water diversion, the C-BT Project, which brings water from the western slope of the continental divide. Flows from the C-BT system mix with water in the Big Thompson River at Lake Estes and again in the upper watershed at the trifurcation structure located between the North Fork and Buckhorn Creek. The largest average annual flow volumes in the Big Thompson watershed are in the canal and tunnel structures of the C-BT Project.

- Water Quality: Water quality in the C-BT canals is good and reflects the conditions in Grand Lake on the west side of the continental divide. Concentrations from the Adams Tunnel tend to be lower than those in the upper Big Thompson watershed for coliforms, orthophosphate, ammonia, and nitrate, but slightly higher for arsenic, TOC, and dissolved solids (specific conductivity, alkalinity, and hardness). Overall, there is no indication that C-BT water contributes negative impacts to water quality in the Big Thompson River.

Major Tributaries: Major tributaries with sampling data in the Big Thompson watershed for the updated study period include the North Fork, Buckhorn Creek, and the Little Thompson River.

- The North Fork: The North Fork comprises an average of ~20% of the flow in the Big Thompson River at its confluence in the upper watershed. Because it is generally a high-mountain, granitic watershed with low population and primarily forested land use, water quality from North Fork tends to be good and similar to that of the upper watershed on the mainstem of the Big Thompson River. This includes low concentrations of nutrients, metals, TOC, and dissolved solids, particularly compared to the lower watershed.
- Buckhorn Creek***:*** Buckhorn Creek is defined as an upper sub-watershed and is characterized by low population with primarily forested or shrub/scrub land use. At the downstream end of this tributary, however, Buckhorn Creek crosses transitional sub-surface geology, including the sedimentary sandstones and conglomerates that form the hogbacks. These features include gypsum, which contributes to elevated dissolved solids concentrations in Buckhorn Creek. Due to this subsurface geology, water quality from Buckhorn Creek is similar to that of the lower watershed in terms of alkalinity, hardness, pH, specific conductance, and sulfate. For TOC and nutrients, Buckhorn Creek water quality is more similar to the upper watershed.
- The Little Thompson River***:*** The Little Thompson River enters the Big Thompson River just a few miles upstream of the confluence with the South Platte River. This major sub-watershed contributes roughly 25% of the annual flow in the Big Thompson River at its confluence. Water quality from the Little Thompson River tends to be comparable to or worse than that in the lower Big Thompson River upstream of its confluence. Increasing population density, urban and agricultural land use, and the underlying Pierre shale contribute to the water quality issues. Temperature, sulfate, TOC, arsenic, lead, coliforms, ammonia, nitrate, dissolved solids, and selenium all tend to be higher in the Little Thompson River than in the rest of the lower watershed of the Big Thompson River.

Below WWTFs: WWTFs serve an important function in the watershed, treating wastewater and returning water to the river. For many rivers, including the Big Thompson, WWTFs represent major point sources for loading of nutrients, organic matter, and sometimes metals. In the Big Thompson watershed, total nitrogen and total phosphorus concentrations increase at sampling stations below each of the major WWTFs in the watershed: M30 (below the Estes Park Sanitation District effluent), M50 (below the Upper Thompson Sanitation District effluent), and at M140 (below the Loveland WWTP effluent). These increases largely reflect loading of nitrate and orthophosphate, which are forms of nutrients that are readily available for algae and plant growth. Treatment improvements were noted as apparent in downstream water quality at two WWTFs on the Big Thompson River. First, a pattern of decreasing orthophosphate (as well as total phosphorus) upstream of Lake Estes is attributed to ongoing operational and structural improvements at the Estes Park Sanitation District WWTF. Second, a dramatic step change reduction in phosphorus concentrations in the Big Thompson River downstream of the Loveland WWTP reflects upgrades to that facility that went online in 2019. This improvement at the Loveland WWTP reduced phosphorus concentrations in that part of the lower watershed to values below the interim nutrient criteria value for the first time in the observed record.

4.2 LONG-TERM TRENDS

Testing of the 15-year record for statistically-significant trends revealed a few noteworthy findings:

Increasing nutrients and TOC in Little Thompson River: Statistically-significant trends of increasing nutrients and TOC were found at the end of the Little Thompson River (VT05). Increases were seen across seasons for TOC, total phosphorus, orthophosphate, nitrate + nitrite, and total nitrogen. These trends were some of the largest across constituents and sampling locations in terms of rate of increase, including 8% per year for nitrate + nitrite, 15% per year for total phosphorus, and 2% per year for TOC. It is expected that these increasing trends correspond to the rapid population growth rate in the Little Thompson River sub-watershed.

Decreasing lead concentrations across the watershed: Lead concentrations exhibit a statistically-significant decrease at nearly all stations across the watershed with a magnitude of ~6% per year. This may reflect long-term reductions in atmospheric loading of lead from leaded petroleum products.

Decreasing nitrate at the top of the upper watershed: As noted in the previous State of the Watershed Report (Hydros, 2015), statistically-significant long-term trends of decreasing nitrate concentrations were noted in the upper-most portions of the watershed (M10 and C10). In this review, the rate of decline was lower than that noted in the previous report, corresponding to a long-term decreasing trend of 1 to 3 μg/L per year. Over the 15-year period, this corresponds to a decrease of 24 to 67% of the mean nitrate concentration in the upper-most watershed. It is suspected that this decline corresponds to the EPA-mandated decrease in nitrogen oxide emissions from vehicles, industry, and power plants beginning in the early 2000's. The decreasing rate of decline and decreasing spatial extent of the apparent effect (relative to the WY2000-WY2014 analysis) may indicate a diminishing effect over time.

Decreasing TOC in C-BT canals: In the previous State of the Watershed Report (Hydros, 2015), statistically-significant trends of increasing TOC concentrations were found in the C-BT canal system (C10, C20, C30, C40, and C50) as well as in much of the Big Thompson upper watershed mainstem (M20 to M130). The cause of that increase was hypothesized to be the large-scale tree death from the mountain pine beetle epidemic, and the pattern was noted from visual review to have leveled-off in the latter half of that study period. In this update, there is a statistically-significant trend in the opposite direction of a similar magnitude (a decrease of ~0.03 mg/L TOC per year) across the C-BT canal locations. At this time it is uncertain, however, whether the pattern relates to recovery from the Mountain Pine Beetle infestation, whether this is part of a larger cyclical pattern, or whether there is another explanation.

4.3 MAJOR WATERSHED EVENTS

Major watershed events during the study period included wildfires, a flood, and extensive road reconstruction activities.

Fires: There were six major wildfires entirely or partially within the Big Thompson watershed in recent years:

- **Cow Creek Fire:** June 2010 (1,200 acres in the Big Thompson watershed),
- **Crystal Fire:** April 2011 (3,000 acres in the Big Thompson watershed),
- **High Park Fire:** June 2012 (~21,606 acres in the Big Thompson watershed),
- **Fern Lake Fire:** October 2012 (3,500 acres in the Big Thompson watershed),
- **Cameron Peak Fire**: August 2020 (65,162 acres in the Big Thompson watershed), and
- **East Troublesome Fire**: October 2020 (4,894 acres in the Big Thompson watershed).

Of these fires, only the Fern Lake fire shows an apparent water-quality response based on the Forum's database, with increased nitrate and dissolved solids concentrations (including alkalinity, hardness, and specific conductivity) observed at one location just below Moraine Park for the three years following the fire. The post-fire effect below Moraine Park may also reflect the combined effect of the 2012 fire and the 2013 flood. A separate study of the Fern Lake Fire (Billica, 2014) also found that measured impacts were generally short-lived, limited in spatial extent, and not significant enough to impact aquatic life and drinking water supplies. A more significant response may occur following the Cameron Peak Fire (and possibly the East Troublesome Fire) due to its size and intensity. Post-fire water-quality data for these fires are still being collected, with effects expected to be apparent only after the period of record for this study (ends on September 30, 2020); however, there are indications of issues. Specifically, the City of Loveland had to modify its diversion operations from the Big Thompson River at times in 2021 due to ash in the river. Careful evaluation of post-fire response for the Cameron Peak fire and the East Troublesome fire will be needed in the next five-year review of Big Thompson watershed data.

2013 Flood: A week of record-breaking rainfall in September of 2013 resulted in extensive flooding along the Front Range. The flood is estimated to have been a 100- to more than 500-year flood in the Big Thompson and Little Thompson Rivers. Damage from flash flooding and debris flows was extensive.

There was no in-river sampling by the Forum during the 2013 flooding event due to safety and access issues, but some post-flood effects were apparent in the dataset. For two to three years following the September 2013 flood, increased baseflow rates (particularly apparent in winter months) occurred in the lower Big Thompson watershed. The effect was not apparent in the upper watershed, which has minimal alluvium for shallow groundwater storage. The increased baseflow in the lower watershed served to dilute phosphorus and nitrogen from WWTF effluent, lowering concentrations in winter months. Winter concentrations of dissolved solids (alkalinity, hardness, sulfate, and specific conductance) were also lower during those two to three post-flood years, reflecting dilution from greater groundwater inflow (and groundwater from different areas). No lasting adverse water-quality impacts of the flood are apparent in the Forum's dataset.

Post-Flood Road Reconstruction Activities: Extensive reconstruction of roads and infrastructure was needed following the September 2013 flood. A multi-year project, led by the Colorado Department of Transportation (CDOT) Flood Recovery Office, was initiated in 2016, including rebuilding of bridges and repair of nearly 23 miles of U.S. 34, mostly between the City of Loveland and Estes Park. The project was largely completed in early 2019, with some minor repairs continuing into 2020. The project also included critical river restoration work, which will benefit aquatic life in the Big Thompson watershed in the long-term.

While the CDOT-led construction project took all required precautions to protect river water quality during construction, increased erosion often occurs with such large-scale projects. Results for general parameters were reviewed for evidence of adverse effects of post-flood road construction activities; however, no clear impacts are apparent in the Forum dataset. This does not indicate that there were no impacts. Separate studies have documented construction impacts on the river including increased solids (Fayram, 2018). There was also a well-documented fish kill on the North Fork, due to increased pH from a concrete spill in 2016. That release of lime-based concrete occurred during a bridge reconstruction project that was unaffiliated with the larger CDOT project on U.S. 34. The lack of observed impacts from road construction activities in the Forum dataset likely reflects the transient nature of such impacts, which may easily be missed at the sampling frequency of the Forum's program, which is designed for different purposes.

4.4 COMPLIANCE

Comparison of the Forum's water-quality dataset to relevant standard values produced a few noteworthy findings:

Arsenic issues relative to the chronic standard across the watershed: At all sampling stations across the watershed, every detected observation for arsenic is above the 0.02 µg/L chronic standard value (applicable to all Big Thompson segments except Segment 4). Given this pattern across the watershed, from pristine waters in Rocky Mountain National Park (M10) to anthropogenically-influenced waters in the lower watershed, the 0.02 µg/L standard does not appear to be attainable in the Big Thompson watershed. The current 303(d) listings do not include the Little Thompson River or Segment 5; however, based on the observed data, these segments may eventually be listed also under the current chronic standard. Note that there are widespread issues across the state relative to the 0.02 µg/L chronic arsenic standard.

Issue relative to the acute and chronic copper standards at the top of the watershed: There is a high frequency of copper standard exceedances in the upper watershed upstream of Lake Estes. This is not an issue of particularly high copper concentrations. Instead, the naturally low hardness values in this part of the watershed result in very low calculated copper water-quality standards. There are no issues relative to copper standards in the rest of the watershed with one exception. At M90, downstream of the trifurcation structure, 31% of observations in the 15-year dataset are above the chronic standard values and 21% are above the acute standard values for copper. Historically, the City of Loveland occasionally used copper sulfate for algal biomass control in Green Ridge Glade Reservoir (adjacent to their drinking water treatment plant near site M90), which can discharge augmentation water back to the Big Thomson River. This practice was discontinued in 2015, and the time-series plots show that there have been very few cases of values above the copper standards at M90 from 2016 through 2020. Based on this change, it may be appropriate to modify the copper 303(d) listings to exclude Segment 2 downstream of Lake Estes in the future.

Lower watershed issues relative to chronic sulfate and selenium standards: The lower Big Thompson River watershed, including the Little Thompson River, exhibit relatively high frequencies of observations above of the chronic sulfate and selenium standards (e.g., 77% and 91%, respectively at VM05). This reflects the effects of the Pierre shale in this area, exacerbated by irrigation practices. Note that, in spite of the pattern of frequent sulfate concentrations above the chronic standard in Segments 5 and 9, there are currently no 303(d) listings for sulfate in the Big Thompson River or tributaries.

Frequent values above the *E. coli* standard in the lower watershed and Little Thompson River: *E. coli* observations above the standard are infrequent in the upper Big Thompson River. In the lower watershed, beginning with T20 (Buckhorn Creek), the frequency of observations above the standard generally increases moving downstream. The most frequent cases (>65%) are observed on the Little Thompson River (VT05) and at the downstream end of the Big Thompson River (VM05). This may reflect livestock sources of bacteria in these reaches.

Interim Nutrient Criteria review suggests possible future challenges: The interim numeric criteria are only currently applicable in Segment 1 and part of Segment 2 for total phosphorus; however, both total nitrogen and total phosphorus criteria may be considered for adoption as water-quality standards across the watershed prior to or after May 31, 2022, depending on determination by the WQCC. Observed data indicate that the interim criteria would be routinely exceeded in the lower watershed, including the Little Thompson River. Note that 2019 upgrades in phosphorus treatment at the Loveland WWTP have resulted in total phosphorus concentrations at M140 and M150 that are below the interim criteria for the first time in the observed record.

4.5 PROGRAM RECOMMENDATIONS

Overall, the Forum monitoring program is well-conceived and well-managed, generating a very useful dataset to support evaluation of water quality across the watershed. Through the process of developing this report, several recommendations for sampling program improvements were generated for consideration by the Forum:

- **Add total arsenic**: Total arsenic should be added to the sampling and analysis list for all stations in the current Forum sampling program. It is currently missing in data from the 13 stations sampled by the USGS. Total arsenic is needed for an accurate assessment against the chronic arsenic standard, which is the basis for extensive 303(d) listings across the watershed. A method providing a detection limit of 0.05 µg/L or less is recommended.
- **Restart mercury sampling**: Sampling for mercury should be added back into the program across all stations, given widespread 303(d) listings. Sampling was discontinued in 2018.
- **Add zinc at M10 and M20**: It is recommended that dissolved zinc be added to the analyte list for routine sampling at M10 and M20 to support future analyses, in light of the 303(d) listing.
- **Add manganese sampling in lower watershed**: Recognizing the 303(d) listings, the sampling program should include manganese at VT05, M130, M140, M150, and VM05.
- **Add TSS analyses**: Routine collection of TSS data at all stations is recommended for future sampling. TSS should be added to the analysis list for M30, M40, M50, M60, T10, T20, M130, M140, and M150. These data will be particularly critical to support evaluation of post-fire response in the watershed in the coming years.
- **Add continuous temperature gages**: Given the importance of water temperature to aquatic life and the variable flow rates in the Big Thompson River due to major diversions, it is recommended that continuous temperature gages be installed across the watershed. These data would help support evaluation of the current 303(d) temperature listings. Alternatively, if such data are being collected through another program, it is recommended that these data be included in the Forum's next five-year data review.

Additionally, recommendations were generated for modifications to the scope of work for the next five-year review:

- **Discontinue Loading Calculations:** It is recommended that the next report not include analysis in terms of loading for nutrients and TOC. These calculations are time-consuming, include significant uncertainty (given the frequency of water-quality sampling and flow sampling at some locations), and the products do not add much to the analysis, which already includes evaluations of concentration and flow patterns.
- **Exclude temperature if continuous data are unavailable:** Unless hourly temperature data collection is initiated in the watershed, analysis of temperature should be excluded from the next five-year review. The current frequency of observations does not allow for adequate evaluation against either acute or chronic standards and does not support rigorous assessment of variation over time.
- **Update seasons to include spring runoff:** Consider updating season definitions in the next report to attempt to distinguish snowmelt runoff from the "summer" group.

- **Add mercury, iron, and manganese to the list of focus parameters:** Note that the list of metals considered does not include mercury, iron, or manganese, all of which are on the current 303(d) List for flowing sites in the watershed. Future data analysis efforts may benefit from the inclusion of these parameters.
- **Include review of 2020 fire effects**: The next five-year review should include a specific objective to evaluate water-quality response to the major fires that occurred in the fall of 2020.
- **Consider expanding objectives for the next state of the watershed report to include aquatic life health**: This recommendation is based on discussion from the presentation of the draft report to the Forum board members. There was discussion noting continued (since the 2013 flood) deteriorated conditions for sediment and river health from an aquatic life perspective. Because this effect is not apparent in our current dataset, additional data would be needed, possibly including aquatic life surveys (fish and macro-invertebrates) and sediment surveys.

5 REFERENCES

Agency for Toxic Substances and Disease Registry (ATSDR). 2003. Toxicological Profile for Selenium. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

ATSDR. 2004. Toxicological Profile for Copper. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

ATSDR. 2005. Toxicological Profile for Zinc (Update). Atlanta, GA: U.S. Department of Public Health and Human Services, Public Health Service.

ATSDR. 2007. Toxicological Profile for Arsenic (Update). Atlanta, GA: U.S. Department of Public Health and Human Services, Public Health Service; August 2007.

ATSDR. 2008. Toxicological Profile for Cadmium *(Draft for Public Comment)*. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Beggs, K., Billica, J., Korak, J., Rosario-Ortiz, F., McKnight, D., and S. Summers. 2013. Spectral Evacuation of Watershed DOM and DBP Precursors. Journal – American Water Works Association.

Billica, J. 2014. Fern Lake Fire Water Quality Study. Northern Water-Water Quality Program. August 25, 2014.

Billica, J. 2015. Personal communication in draft report comments from J. Billica (Northern Water) to C. Hawley (Hydros). August, 2015.

Bitner, K., B. Gallaher, and K. Mullen. 2001. Review of Wildfire Effects on Chemical Water Quality. Technical Report LA-13826-MS. Los Alamos National Laboratory, Los Alamos, NM, issued May 2001. http://www.osti.gov/scitech/servlets/purl/781455

Birge, E.A. 1992. Modern Microbiology, Principles and Applications. Wm. C. Brown Publishers; Dubuque Iowa.

Bohling, T. 2021. Email Communication from T. Bohling (City of Loveland) to C. Hawley (Hydros Consulting); Re: question regarding City of Loveland Copper Sulfate use. September 24, 2021.

Braddock W.A., and Cole J.C. 1978. Preliminary Geologic Map of the Greeley 1° by 2° Quadrangle, Colorado and Wyoming. United States Geological Survey Open File Report 78-532.

Buirgy, R.R. 2007. Big Thompson Watershed Management Plan. US EPA Grant #CP-97801601-0. Final Report. Big Thompson Watershed Forum. December 1.

CDOT, Larimer County, National Resource Conservation Service, and U.S. Forest Service. 2012. High Park Burned Area Emergency Response (BAER) Report. July 12, 2012. https://larimer.org/highparkfire/bear_report.pdf,

Center for International Earth Science Information Network - CIESIN - Columbia University, 2017. U.S. Census Grids (Summary File 1), 2010.

CH2MHill. 2014. Little Thompson River Hydrologic Analysis. Prepared for CDOT. August 2014.

Chapman P.M., W.J. Adams, M.L. Brooks, C.G. Delos, S.N. Luoma, W.A Maher, H.M. Ohlendorf, T.S. Presser and D.P. Shaw. 2009. Ecological Assessment of Selenium in the Aquatic Environment: Summary of a SETAC Pellston Workshop. Pensacola FL (USA): Society of Environmental Toxicology and Chemistry (SETAC).

Chapman P.M., W.J. Adams, M.L. Brooks, C.G. Delos, S.N. Luoma, W.A Maher, H.M. Ohlendorf, T.S. Presser and D.P. Shaw (eds). 2010. Ecological Assessment of Selenium in the Aquatic Environment. SETAC Press, Pensacola, FL, USA.

CPW (Colorado Parks and Wildlife). 2016. CPW News Release: Fishkill on big Thompson Being Mitigated Through Partner Meetings. April 26, 2016. https://cpw.state.co.us/aboutus/Pages/News-Release-Details.aspx?NewsID=5756.

Colorado Water Conservation Board (CWCB) 2014. Colorado Flood Proofing and Flood Recovery Workshops; Review of 2013 Flood Recovery. Presentation by Colorado Water Conservation Board. September, 2014. http://cwcb.state.co.us/water-management/flood/Documents/2013Response/floodrecovery.pdf.

Duell, J. 2021. Estes Park Sanitation District WWTF Improvements: Email Communication from J. Duell (Estes Park Sanitation District) to C. Hawley (Hydros Consulting); August 12, 2021.

Fayram, A. 2017. 2016 Big Thompson River Water Quality Summary Report. Prepared for the Big Thompson Watershed Forum. https://btwatershed.org/water-quality-reports/.

Fayram, A. 2018. Big Thompson River 2017-2018 Winter Monitoring Summary. Prepared for the Big Thompson Watershed Forum. https://btwatershed.org/water-quality-reports/.

Jacobs. 2014. Hydrologic Evaluation of the Big Thompson Watershed Post September 2013 Flood Event. Prepared for CDOT with support from Muller Engineering Company, Parsons Brinkerhoff, and Ayres Associates. August 2014.

Jacobs. 2015. Lower Big Thompson Watershed: Phase II Hydrologic Evaluation Post September 2013 Flood Event. Prepared for CDOT with support from Muller Engineering Company, Parsons Brinkerhoff, and Ayres Associates. July 2015.

Haby, P. and J. Loftis. 2007. Retrospective Analysis of Water Quality Data in the Big Thompson Watershed, 2001-2006. Prepared for the Big Thompson Watershed Forum, August. This report is available at: www.btwatershed.org.

Helsel, D. and R. Hirsch. 1992. Statistical Methods in Water Resources. Elsevier.

Hydros (Hydros Consulting Inc). 2011. Big Thompson State of the Watershed, 2010 Report. Prepared for the Big Thompson Watershed Forum. February 4, 2011.

Hydros. 2015. Big Thompson State of the Watershed, 2015 Report. Prepared for the Big Thompson Watershed Forum. September 21, 2015.

Jassby, A. D. and C.R. Goldman. 2003. Water Quality of the Upper Big Thompson Watershed. Prepared for the Big Thompson Watershed Forum, November 25. This report is available at: www.btwatershed.org.

Jassby, A. D., J.E. Cloem, and J. Stachelek. 2017. WQ: Some Tools for Exploring Water Quality Monitoring Data. R package version 0.4.9. https://cran.r-project.org/package=wq.

Mast, M. A. Chow, D. W. Baron, J.S. and Wetherbee, G.A. 2014. Links between N Deposition and nitrate Export from a High-Elevation Watershed in the Colorado Front Range. Environmental Science and Technology. 48, 14258-14265.

Mikkelson, K.M, E.R.V. Dickenson, R.M. Maxwell, J.E. McCray, and J.O. Sharp. 2013. Water-Quality Impacts from Climate-*Induced Forest Die-Off. Nature Climate Change, 3, 218–222.*

Neary, D.G., J.D. Landsberg, A.R. Tiedemann, and P.F. Ffolliott. 2005. Chapter 6: Water Quality. In: Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. USDA Forest Service General Technical Report RMRSGTR-42-Vol 4, September 2005, pages 119-134. http://www.fs.fed.us/rm/pubs/rmrs_gtr042_4.pdf

Oropeza, J. and J. Heath. 2013. Effects of the 2012 Hewlett and High Park Wildfires on Water Quality of the Poudre River and Seaman Reservoir, City of Fort Collins internal report dated Sept. 5, 2013.

Ranalli, A.J. 2004. A Summary of the Scientific Literature on the Effects of Fire on the Concentration of Nutrients in Surface Waters, USGS Open-File Report 2004-1296. http://pubs.usgs.gov/of/2004/1296/pdf/OFR2004-1296.pdf

Rhoades, C., Entwistle, D., and D. Butler. The Influence of Wildfire Extent and Severity on Streamwater Chemistry, Sediment, and Temperature Following the Hayman Fire, Colorado. International Journal of Wildland Fire; CSIRO Publishing, v 20, p 430-442.

Rhoades, C., Chow, A., Covino, T., Fegel, T., Pierson, D., and A. Rhea. 2019. The Legacy of a Severe Wildfire on Stream Nitrogen and Carbon in Headwater Catchments. Ecosystems. v. 22. P 643-657.

Rodríguez-Jeangros, N., Hering, A.S., Kaiser, T., McCray, J.E. 2017a. SCaMF–RM: A Fused High-Resolution Land Cover Product of the Rocky Mountains. Remote Sens. 9, 1015. https://doi.org/10.3390/rs9101015

Rodríguez-Jeangros, N., Hering, A.S., Kaiser, T., McCray, J.E. 2017b. 2012 Map from Spatiotemporal Categorical Map Fusion-Rocky Mountain (SCaMF-RM) Project (https://dspace.library.colostate.edu/handle/11124/170731).

Rust, A., Hogue, T., Saxe, S. and J. McCray. 2018. Post-Fire Water-Quality Response in the Western United States. Journal of Wildland Fire. CSIRO Publishing. v 27.

Shelley, Z. 2014. Big Thompson Watershed News; Newsletter of the Big Thompson Watershed Forum, pg 4.

Shelley, Z. 2015a. Personal email communication from Z. Shelley (BTWF) to C. Hawley (Hydros). Discussion at BTWF Board Meeting on September 17, 2015.

Son J.H., Kim S., Carlson K.H., 2015. Effects of Wildfire on river water quality and riverbed sediment phosphorus. Water, Air, Soil, Pollut. 2015 226 (26)

Thorpe, R. and C. Hartenstine. Re: BTWF – Turbidity. Email Communications from Richard Thrope (City of Fort Collins) and Curtis Hartenstine (Northern Water) to C. Haawley (Hydros Consulting). August 16, 2021.

U.S. Census Bureau. 2021. Comparison of 2010 and 2020 Census Data. Retrieved on September 15, 2021. https://www.census.gov/quickfacts/fact/table/johnstowntowncolorado,millikentowncolorado,berthoudtowncolorado,CO,lovelandcitycolorado/PST120219.

USGS (U.S. Geological Survey). 1980. Composition and Properties of the Pierre Shale and Equivalent Rocks, Northern Great Plains Region. Geological Survey Professional

Paper 1064-B. U.S. Department of the Interior. Leonard Shultz, Harry Tourtelot, James Gill, and Josephine Boerngen. 1980.

Walker, D. 1992. *Energy, Plants, and Man.* University Science Books.

Water Quality Control Commission (WQCC). 2012. Regulation No. 93; Colorado's Section 303(d) List of Impaired Waters and Monitoring Evaluation List. Department of Public Health and Environment Water Quality Control Division, CCR 1002-93. Amended: February 13, 2012; EFFECTIVE: March 30, 2012.

WQCC. 2020a. Section 303(d) Listing Methodology 2022 Listing Cycle. Colorado Department of Public Health and Environment Water Quality Control Division. May 2015.

WQCC. 2020b. Regulation No. 93; Colorado's Section 303(d) List of Impaired Waters and Monitoring Evaluation List. Department of Public Health and Environment Water Quality Control Division, CCR 1002-93. Adopted April 13, 2020; EFFECTIVE: June 14, 2020.

WQCC. 2020c. Regulation No. 31 The Basic Standards and Methodologies for Surface Water; 5 CCR1002-31. Colorado Department of Public Health and Environment Water Quality Control Commission; EFFECTIVE: June 30, 2020.

WQCC. 2020d. Regulation No. 38 Classifications and Numeric Standards for South Platte River Basin, Laramie River Basin Republican River Basin, Smoky Hill River Basin; 5 CCR1002-38. Colorado Department of Public Health and Environment Water Quality Control Commission; Effective: December 31, 2020.

Writer, J. and S. Murphy. 2012. Wildfire Effects on Source Water Quality – Lessons from Fourmile Canyon Fire, Colorado and Implications for Drinking-Water Treatment, U.S. Geological Survey Fact Sheet 2012-3095, July 2012.