HAGGARTY CREEK & WEST FORK BATTLE CREEK TMDLS
FOR
COPPER, CADMIUM & SILVER

Wyoming Department of Environmental Quality – Water Quality Division

HAGGARTY CREEK TMDL QUICK SUMMARY

Waterbody IDs	Haggarty Creek, HUC 140500030109
303(d) Waterbody IDs	WYLS140500030109_01
Waterbody Classification	Class 2AB
Location	Carbon County, Wyoming
Pollutants of Concern	Copper (Cu), Cadmium (Cd) and Silver (Ag)
Pollutant Sources	Hardrock mining and Natural
Impaired Designated Uses	Cold-water game fisheries, non-game fisheries and aquatic life other than fish
Type of TMDL	Final
Submittal to EPA	September 2011
EPA Approval	Pending

Target Criteria Dissolved concentrations (µg/L) at 25 mg/L hardness	Acute (CMC)	Cu = 3.6 Cd = 0.5 Ag = 0.3
	Chronic (CCC)	Cu = 2.7 Cd = 0.09 Not applicable to Ag
Existing Conditions for: Cu at Station HC8 Cd and Ag at Station HC14	Annual range of dissolved concentrations (µg/L)	Cu = 80 to 365 Cd = 0.02 to 1.00 Ag = 1 to 6
	Natural Background Load (ton/day)- Based on critical loading condition	Cu = 2.23×10^{-5} Cd = 0.83×10^{-7} Ag = 1.41×10^{-5}
	Total Pollutant Load (ton/day)- Based on critical loading condition	Cu = 9.23×10^{-3} Cd = 8.27×10^{-6} Ag = 3.62×10^{-4}
Total Maximum Daily Load (**TMDL** in ton/day)- Based on critical loading condition		$Cu_{CCC} = 3.05 \times 10^{-5}$ $Cd_{CCC} = 7.75 \times 10^{-7}$ $Ag_{CMC} = 8.98 \times 10^{-5}$
Margin of Safety (**MOS** in ton/day) - 20% of TMDL for all pollutants		Cu = 0.61×10^{-5} Cd = 1.55×10^{-7} Ag = 1.80×10^{-5}
Load Allocation (**LA** in ton/day) - Based on critical loading condition		Cu = 2.23×10^{-5} Cd = 6.20×10^{-7} Ag = 7.18×10^{-5}
Wasteload Allocation (**WLA** in ton/day)- Based on critical loading condition		Cu = 0.21×10^{-5} Not applicable to Cd Not applicable to Ag
Percent (%) Pollutant Reduction Required to Achieve TMDL Target Loads- Based on critical loading condition		Cu = 99.7 Cd = 90.6 Ag = 75.2

WEST FORK BATTLE CREEK TMDL QUICK SUMMARY

Waterbody IDs	West Fork Battle Creek, HUC 140500030109
303(d) Waterbody IDs	WYLS140500030109_02
Waterbody Classification	Class 2AB
Location	Carbon County, Wyoming
Pollutants of Concern	Copper (Cu)
Pollutant Sources	Hardrock mining and Natural
Impaired Designated Uses	Cold-water game fisheries, non-game fisheries and aquatic life other than fish
Type of TMDL	Final
Submittal to EPA	September 2011
EPA Approval	Pending

Target Criteria Dissolved concentrations (µg/L) at 25 mg/L hardness	Acute (CMC)	3.6
	Chronic (CCC)	2.7

Existing Condition for: Cu at Station WFBC1	Annual range of dissolved concentrations (µg/L)	3 to 36
	Natural Background Load (ton/day)- Based on critical loading condition	1.37×10^{-4}
	Total Cu Load (ton/day)- Based on critical loading condition	3.90×10^{-3}

Total Maximum Daily Load (**TMDL** in ton/day)- Based on critical loading condition	1.88×10^{-4}
Margin of Safety (**MOS** in ton/day) - 20% of TMDL	0.38×10^{-4}
Load Allocation (**LA** in ton/day) - Based on critical loading condition	1.37×10^{-4}
Wasteload Allocation (**WLA** in ton/day)- Based on critical loading condition	0.13×10^{-4}
Percent (%) Cu Reduction Required to Achieve TMDL Target Load- Based on critical loading condition	95.2

Cover Photo – Ferris Haggarty Mine site settling ponds (top) and original Haggarty Creek-mine discharge confluence (September 2004).

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LIST OF ACRONYMS

Ag	Silver
AML	Abandoned Mine Land Division
Cd	Cadmium
CFR	Code of Federal Regulations
cfs	cubic feet per second
CRCT	Colorado River Cutthroat Trout
Cu	Copper
CWA	Clean Water Act
FHM	Ferris-Haggarty Mine
gpm	gallons per minute
HC	Haggarty Creek
HC-WFBC	Haggarty Creek-West Fork Battle Creek
HUC	Hydrologic Unit Code
LA	Load Allocation
LDC	Load Duration Curve
MBNF	Medicine Bow National Forest
mg/L	milligrams per liter (equivalent to part per million or ppm)
MOS	Margin of Safety
NFLSR	North Fork Little Snake River
NRCS	Natural Resource Conservation Service
SNOTEL	Snowpack Telemetry
TMDL	Total Maximum Daily Load
µg/L	micrograms per liter (equivalent to part per billion or ppb)
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WDEQ/WQD	Wyoming Department of Environmental Quality, Water Quality Division
WFBC	West Fork Battle Creek
WGFD	Wyoming Game and Fish Department
WLA	Wasteload Allocation
WQC	Water Quality Criterion
WQS	Water Quality Standard
WY RIVPACS	Wyoming River Invertebrate Prediction and Classification System
WSII	Wyoming Stream Integrity Index
WPDES	Wyoming Pollutant Discharge Elimination System

EXECUTIVE SUMMARY

Section 303(d) of the Federal Clean Water Act (CWA) requires states to identify waterbodies with water quality impairments and to develop total maximum daily load (TMDL) plans for each. In compliance with §303(d), the Wyoming Department of Environmental Quality, Water Quality Division (WDEQ/WQD) has developed TMDLs for Haggarty Creek and West Fork Battle Creek. Both streams are headwater tributaries of the Little Snake River in the Green River Basin of south-central Wyoming. For several years, Haggarty Creek and West Fork Battle Creek have been identified as impaired waterbodies that do not fully support their aquatic life and fish uses due to metal contamination (WDEQ/WQD 2010). The purpose of the TMDLs is to calculate the allowable metal loading that each waterbody can assimilate without violating state water quality standards (WQS). The water quality goal is to reduce the metal loading such that both waters are able to fully support their assigned designated uses.

The major source of the copper (Cu) contamination for both streams is the mine drainage water that emanates from the inactive Ferris-Haggarty Mine (FHM), situated in the headwaters of Haggarty Creek. Natural background Cu contributions (non-point sources) in the Haggarty Creek-West Fork Battle Creek (HC-WFBC) drainage are considered negligible. Copper concentrations in Haggarty Creek upstream of the mine and in tributary streams meet water quality criteria. Copper-laden water from the mine's underground workings and surface disturbances have likely discharged into nearby Haggarty Creek since the initiation of mining in 1898. The metal contamination extends for several miles downstream impacting the water quality in West Fork Battle Creek which receives flows from Haggarty Creek. Copper is the primary pollutant of concern, but low levels of cadmium (Cd) and silver (Ag) are occasionally observed in both streams. The Cd and Ag contamination is entirely attributed to non-point sources, including natural background contributions. Evidence gathered to date suggests that the FHM is not a contributing source of Cd or Ag.

While flows in Haggarty Creek provide considerable dilution to the mine effluent, the resultant instream Cu concentrations exceed levels deemed toxic to fish and other aquatic life for several miles downstream. The reduction, or near eradication, of aquatic plant life and benthic macroinvertebrates caused by the direct and indirect effects of metal toxicity are identified as reasons why a thriving fish population is not found in Haggarty Creek. Metal concentrations in the HC-WFBC drainage are well below Wyoming's human health standard, but exceed criteria established to protect aquatic life and

coldwater fish uses. Aquatic life use criteria for Cu, Cd and Ag are considerably lower than drinking water criteria due to the fact that aquatic organisms are highly sensitive to soluble concentrations of these metals.

Copper concentrations consistently exceed aquatic life use criteria in Haggarty Creek and frequently exceed criteria in West Fork Battle Creek. For Haggarty Creek, the target concentration for Cu during all flow periods is about 0.003 milligrams per liter (mg/L). Copper criteria in West Fork Battle Creek are the same as in Haggarty Creek during high-flow conditions, but are less stringent during low-flow periods (due to increases in water hardness), varying from about 0.005 to 0.017 mg/L. Relative to the established criteria, dissolved Cu concentrations in the FHM effluent are about one-thousand times greater, ranging from about 2 to 9 mg/L throughout much of the year. Short-lived surges of 10 to 12 mg/L may be observed just prior to the spring peak discharge in Haggarty Creek. The surges occur in response to precipitation and spring snowmelt runoff events, whereby the infiltration of fresh water flushes copper-enriched water from the underground mine workings to the surface where it discharges into Haggarty Creek. Immediately below the FHM discharge, dissolved Cu concentrations in Haggarty Creek typically range from about 0.080 to 0.365 mg/L. In the four-mile distance between the mine discharge and the USGS Station above the Belvidere Ditch, upstream of State Highway 70, Cu levels in Haggarty Creek decrease roughly 80 to 85 percent (0.015 to 0.085 mg/L). Eleven miles downstream in West Fork Battle Creek, Cu concentrations of 0.003 to 0.036 mg/L are typically observed.

The low-level concentrations of Cd and Ag observed periodically in Haggarty Creek and West Fork Battle Creek are measured at or near the limits of analytical detection (<0.001 mg/L). Nonetheless, the levels of both metals occasionally equal or slightly exceed their respective aquatic life use standards. Dissolved values of Cd range from less than 0.0001 to 0.001 mg/L, while values of Ag range from 0.001 to 0.006 mg/L. All of the WQS exceedances (three Cd and four Ag values) are documented from data collected at USGS water quality monitoring stations several miles downstream of the FHM discharge. No WQS exceedances of Cd or Ag have ever been documented at any site on Haggarty Creek or its tributaries upstream of the Belvidere Ditch diversion. The amounts of Cd and Ag measured in the FHM effluent are negligible or not detected. Sources of both metals are presently unknown.

The TMDLS developed for Cu, Cd and Ag are derived from load duration curve (LDC) models which are also used to calculate predicted daily metal loads. The LDCs are developed from the continuum of daily

flow values generated for a water quality monitoring station and the water quality criterion of interest. The predicted metal load reductions are projected to provide the water quality required for Haggarty Creek and West Fork Battle Creek to achieve WQSs over the full range of flow conditions observed at a station. Because the LDC models include several assumptions and uncertainties, margin of safety (MOS) factors are incorporated into each load reduction estimate.

Load duration curve models are developed for two stations on Haggarty Creek and one station on West Fork Battle Creek. For each station the critical condition, or time period in which aquatic organisms are subject to the greatest metal loading, is identified. Based on the LDC analyses, maximum Cu loading in the HC-WFBC drainage occurs at the onset of peak runoff from late-May to early-June. During this critical loading period, it is predicted that greater than 99 percent of the existing Cu load in Haggarty Creek immediately below the FHM (9.23×10^{-3} ton/day) must be reduced to achieve the TMDL target load of 3.05×10^{-5} ton/day. The background Cu load associated with the critical condition at this location is 2.23×10^{-5} ton/day. At sites further downstream, the amount of Cu reduction required to achieve TMDL target loads decreases as a result of dilution effects and/or diminution of the Cu load in the FHM discharge. Nonetheless, eleven miles downstream in West Fork Battle Creek, a projected 95 percent reduction in the existing Cu load (3.90×10^{-3} ton/day) is still required to achieve the critical TMDL target load of 1.88×10^{-4} ton/day.

Critical conditions assigned to Cd and Ag TMDLs for Haggarty Creek are established from the greatest loading period identified from their respective LDCs. The load reduction estimates for both metals are developed from data collected at the USGS Station above the Belvidere Ditch. With respect to Cd, the critical condition occurs during low-flow periods from about late-July to early-April. To achieve the critical TMDL target of 7.57×10^{-7} ton/day, about 90 percent of the existing Cd load (8.27×10^{-6} ton/day) must be reduced. For Ag the critical loading period occurs during the high flow period from early-May to mid-July. Based on load reduction estimates, about 75 percent of the existing Ag load (3.62×10^{-4} ton/day) must be reduced to achieve the critical TMDL target load of 8.98×10^{-5} ton/day.

According to Wyoming's TMDL Workplan (WDEQ/WQD 2008a), TMDLs are to be reassessed at least every five years. Reassessments are an iterative approach which allows for refinement of the TMDL as new information becomes available or if physical conditions of the watershed change significantly over time. In many instances, full restoration can take decades of implementation. Reassessments of TMDLs

are also important to determine progress made towards attainment of TMDL goals. With this in mind, a monitoring plan to reevaluate the TMDLs and address the assumptions and uncertainties identified in the original TMDL plan and measure the success of any remedial action(s) taken is presented.

In order to achieve the estimated load reductions necessary to meet TMDL targets and goals, a water quality remediation or mitigation plan will need be selected and implemented. That decision requires that the State of Wyoming and its citizens assess the environmental, socioeconomic and aesthetic impacts associated with several remediation alternatives. Several remedial/conceptual water quality improvement alternatives are provided to initiate discussion among stakeholders and the public.

1.0 INTRODUCTION

Section 303(d) of the Federal Clean Water Act (CWA) requires states, territories and authorized tribes to list waterbodies that do not meet the water quality standards (WQS) established to protect their designated uses (i.e., drinking water, fish consumption, aquatic life). Listed waters may have one or more of their designated uses impaired by one or several pollutants. The §303(d) list is made available for public review and submitted to the U.S. Environmental Protection Agency (USEPA) for approval in even-numbered years. Further, the CWA and USEPA regulations require that priority rankings be assigned to all §303(d) waters for developing Total Maximum Daily Loads (TMDLs).

A TMDL specifies the maximum amount of a pollutant that a waterbody can assimilate (loading capacity) or receive without exceeding the WQSs set for it, and allocates the quantity (load) of the offending pollutant(s) among point and non-point sources. Simply stated, it is a water quality improvement plan for a waterbody that does not meet WQSs. Statutory and regulatory requirements of an approvable TMDL are described in 40 CFR Part 130 and §303(d) of the CWA, as well as in EPA guidance documents (USEPA 1991). Technically, a TMDL is defined as the sum of the individual waste load allocations (WLA) for point (discrete) source pollutants, and load allocations (LA) for non-point (diffuse) and natural background sources. A margin of safety (MOS) is included to address analytical uncertainties. The TMDL document provides the technical guidance and information needed to implement appropriate water quality-based controls for restoring and maintaining water resources (USEPA 1991).

The USEPA has oversight authority for the §303(d) Program and is required to review and either approve or disapprove the TMDLs submitted by states. If a TMDL is disapproved and the State does not satisfactorily address the deficiencies, USEPA is required to establish the TMDL. In Wyoming, the Department of Environmental Quality, Water Quality Division (WDEQ/WQD) is responsible for preparing lists of impaired waterbodies under the §303(d) program and TMDL development. Implementation plans for TMDLs developed in Wyoming may include regulatory and non-regulatory actions intended to protect or achieve designated uses. Wasteload permits authorized through the Wyoming Pollutant Discharge Elimination System (WPDES) are issued to control point source pollutants. The Watershed Planning Program of WDEQ/WQD is responsible for a variety of planning and water quality project implementation activities, including the development and approval of WQSs, non-point source planning and §319 grant administration, water quality assessment and monitoring, wetlands protection, TMDL coordination and data quality assurance.

This document presents the required elements and supporting information used in the development of TMDLs for Haggarty Creek and West Fork Battle Creek in south-central Wyoming. Both streams are identified on Wyoming's §303(d) list of impaired waterbodies that do not fully support their designated water uses due to metal contamination. **Table 1** summarizes the §303(d) listing information provided for Haggarty Creek and West Fork Battle Creek in the State of Wyoming 2010 Integrated 305(b) and 303(d) Report (WDEQ 2010). Metal concentrations in both streams are well below Wyoming's human health standard, but exceed criteria established to protect aquatic life and coldwater fish uses. Copper (Cu) is the primary pollutant of concern in both streams but less toxic amounts of cadmium (Cd) and silver (Ag) are occasionally observed. The Cu toxicity in Haggarty Creek has been well-documented over several decades but was more recently documented in West Fork Battle Creek. The primary source of the Cu contamination for both streams is mine drainage water that emanates from the inactive Ferris-Haggarty Mine (FHM) Osceola Tunnel, discharging directly into the upper reaches of Haggarty Creek. The contamination extends for several miles downstream impacting the water quality in West Fork Battle Creek, which originates at the confluence of Haggarty Creek and Lost Creek. Trace amounts of naturally occurring (background) Cu are observed occasionally in Haggarty Creek upstream of the FHM and in some downstream tributary waters. Sources of Cd and Ag in the drainage are unknown and therefore attributed to non-point sources.

Table 1. Impaired waterbodies in the Haggarty Creek-West Fork Battle Creek Drainage, Little Snake River Basin, Carbon County, Wyoming.

Waterbody			Impairment Description				
HUC[1]	Name (Segment)	Class	Impaired Uses[2]	Length (miles)	Causes	Sources	Priority Ranking
140500030109_01	Haggarty Creek (from Ferris-Haggarty Mine downstream to West Fork Battle Creek)	2AB	AL CWGF	5.9	Copper Cadmium Silver	Hardrock Mining	High
140500030109_02	West Fork Battle Creek (from Battle Creek confluence upstream to Haggarty Creek)	2AB	AL CWGF	4.6	Copper	Hardrock Mining	High

[1]HUC = Hydrologic Unit Code. See http://water.usgs.gov/GIS/huc.html for more information regarding the hydrologic unit classification system.
[2]Designated water uses: AL = Aquatic Life; CWGF = Coldwater Game Fish.

Both Haggarty Creek and West Fork Battle Creek are high priority waters targeted for TMDL development. A detailed explanation of the assessment and listing methodology employed by the WDEQ/WQD is provided in Wyoming's Integrated Report (http://deq.state.wy.us/wqd/watershed/Downloads/305b/2010/WY2010IR.pdf).

The intent of the TMDLs developed for Haggarty Creek and West Fork Battle Creek is to establish the water quality targets required for each waterbody to achieve full support of their aquatic life and coldwater fish uses. To achieve the needed pollutant load reductions, remedial/conceptual water quality improvement alternatives are provided to initiate discussion among stakeholders and the public. A monitoring plan to measure the success of any remedial action(s) taken is presented. The remaining sections of the report address each of the required elements of a TMDL, summarized as follows:

Section 2 – Waterbody Characterization and Impairment Description. In this section the Haggarty Creek-West Fork Battle Creek (HC-WFBC) drainage is characterized, including the regional and environmental setting, climate, geology, geochemistry, hydrology and descriptions of the Ferris-Haggarty Mine site and its history. The water quality conditions and pollutant problems in the watershed are assessed. The cause and source of the water quality impairment is identified, including the applicable WQSs and numeric criteria used to define impairment and the designated uses impacted.

Section 3 - Water Quality Targets. The water quality goals or 'targets' required for each waterbody to achieve full support of their designated uses is explained, and the extent to which each currently deviate from those targets are quantified.

Section 4 - TMDL Technical Analyses. Analyses used to estimate the existing metal loading in the HC-WFBC drainage and methods used to establish TMDLs are described. The stressor→response relationship between the rate of pollutant loading and resultant water quality impacts are explained. The total allowable pollutant loads that each waterbody can assimilate without exceeding WQSs are quantified and their available assimilative capacities are apportioned among point, non-point and natural pollutant sources. A MOS is incorporated into each TMDL to address uncertainties in the analyses and provide reasonable assurances that WQSs can be attained. Critical conditions of streamflow, seasonal variability, analytical assumptions and other water quality factors are considered. The TMDLs are expressed in terms of a daily loading rate that account for the natural variability in the system (i.e., seasonal and streamflow factors).

Section 5 – Monitoring Strategy. A monitoring plan is prescribed to assess the progress made towards achieving stated water quality targets and evaluating the effectiveness of load reduction efforts. If monitoring results demonstrate that the TMDL is inaccurate, then allocations will be reevaluated.

Uncertainties in the assumptions made to develop the TMDLs and the process by which new information may be used to refine them are explained.

Section 6 – Public Participation. A description of the public participation process is presented for the purpose of conveying an understanding of the problem and water quality restoration solutions and for soliciting stakeholder input.

Section 7 – Implementation/Remediation Alternatives. Potential water quality improvement solutions and restoration alternatives are discussed.

2.0 WATERBODY CHARACTERIZATION AND IMPAIRMENT DESCRIPTION

2.1 WATERBODY CHARACTERIZATION

This section summarizes the regional and environmental setting of the HC-WFBC drainage and provides a description of the Ferris-Haggarty Mine (FHM) site. Much of the information presented herein is described in reports prepared for the WDEQ-Abandoned Mine Land Division (AML) by Adrian Brown Consultants, Inc. (Adrian Brown 1994) and Knight Piésold (1999). Mine site descriptions and history are drawn from the accounts of several sources. The extent and magnitude of the water quality impairment and applicable WQSs for both streams is described at the end of the section.

Regional Setting

The HC-WFBC drainage lies within the Little Snake River sub-drainage of the Green River and Colorado River Basin in south-central Wyoming (**Figure 1**). The headwaters of Haggarty Creek originate at about 10,800 feet above mean sea level (famsl) west of the Continental Divide in the Sierra Madre Range, about 15 miles west of the Town of Encampment and 30 miles east of the communities of Baggs and Dixon in Carbon County. Haggarty Creek flows southwest for approximately seven miles where it joins Lost Creek (**Figure 2**). At this confluence West Fork Battle Creek originates and merges with Battle Creek another five miles to the southwest at 8,000 famsl. Battle Creek joins the Little Snake River immediately south of the Wyoming-Colorado border.

The HC-WFBC drainage lies within the Subalpine Zone and Montane Forests and Shrublands ecoregions of the greater Southern Rockies level III ecoregion (Omernik and Gallant 1987). These ecoregions are characterized by steep mountainous terrain, open meadows and high-elevation plateaus. Elevations range from 7,500 to 10,800 feet. Alpine tundra and wet meadows give way to coniferous forests skirted by stands of aspen. Dense stands of lodgepole pine, Engelmann spruce and subalpine firs are found in the upper elevations. Lower elevations support stands of limber pine, ponderosa pine, Douglas fir and aspen. Predominant land uses include wildlife habitat, recreation, logging and mineral extraction. Livestock graze open meadows and slopes primarily in the lower elevations during the summer. Irrigation water is diverted from Haggarty Creek into the Belvidere Ditch ½-mile upstream of State Highway 70. Most of the watershed is managed by the U.S. Forest Service, Medicine Bow National Forest (MBNF), but several patented mining claims exist in the upper reaches of Haggarty Creek including the FHM. Mine claim ownership status is discussed by Adrian Brown (1994) and Knight Piésold (1999). Currently, no mining activity occurs in the watershed.

Figure 1. Haggarty Creek–West Fork Battle Creek watershed, Carbon County, Wyoming.

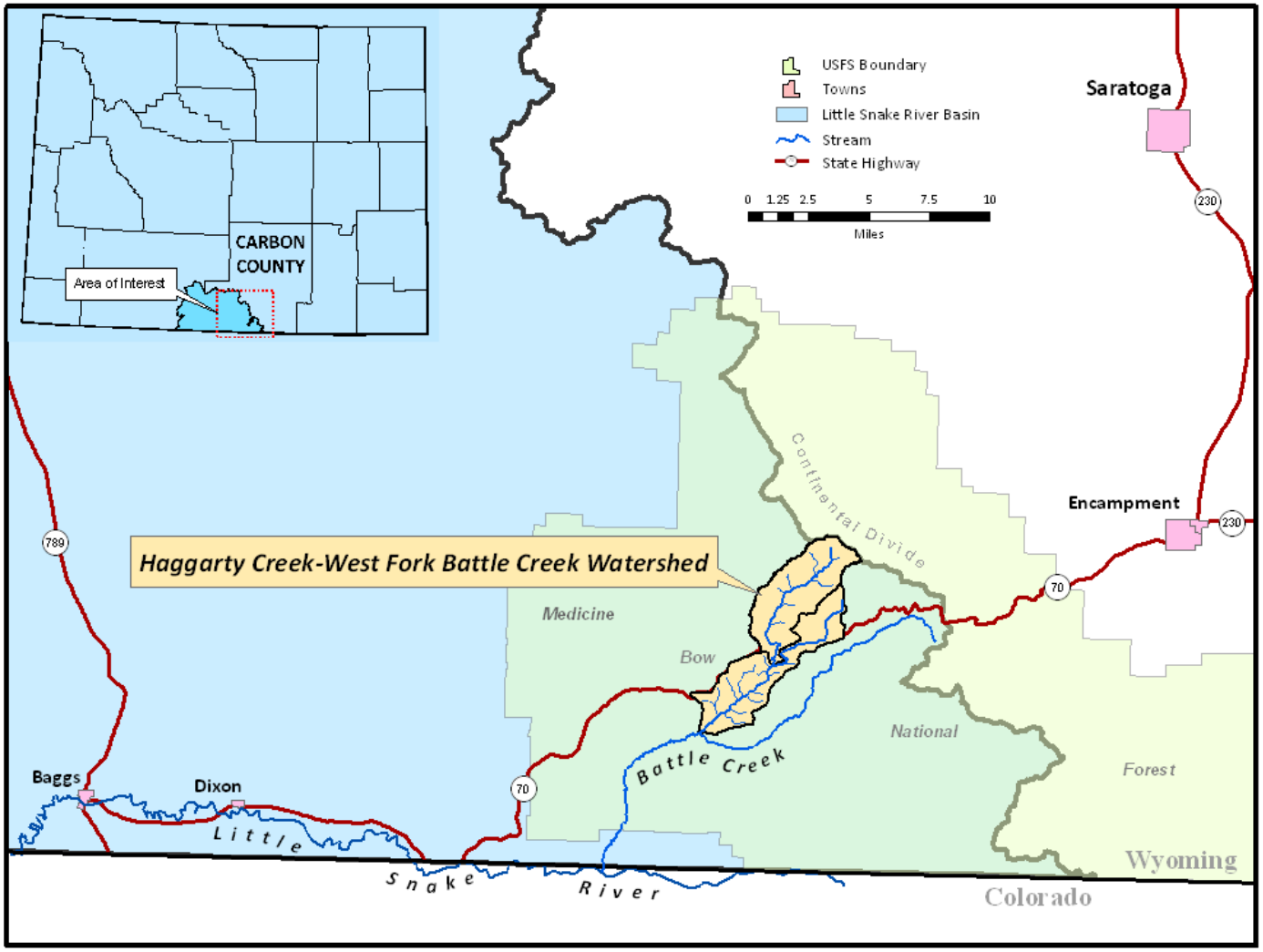
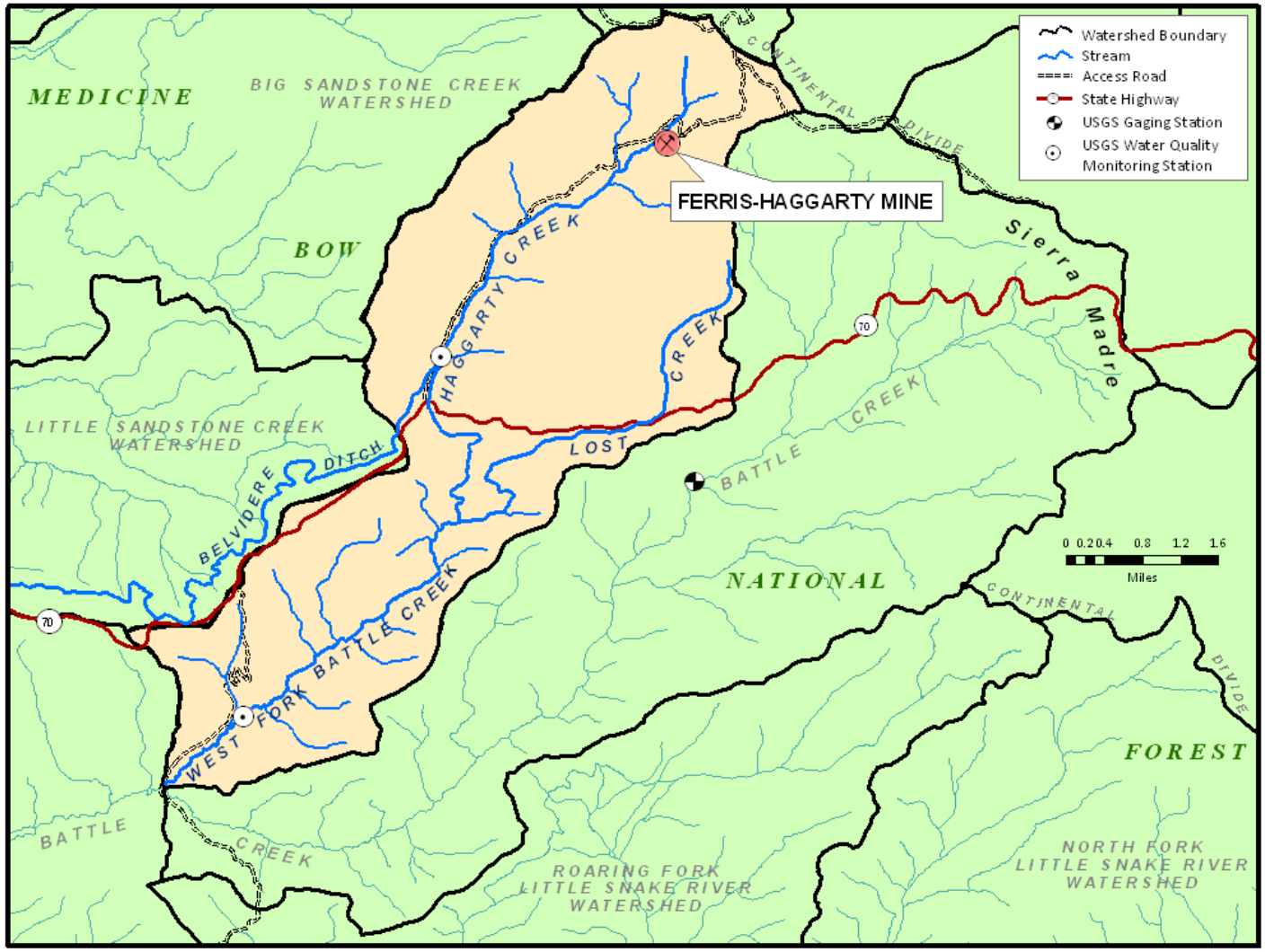


Figure 2. Haggarty Creek-West Fork Battle Creek drainage, Carbon County, Wyoming.



Due to climatic factors and rugged terrain, access to the HC-WFBC drainage is limited to about four months during the year. Access to the upper reaches of Haggarty Creek and the FHM site is provided by a four-mile, four-wheel-drive road off of State Highway 70. The highway is closed from November through May as snow-removal operations are discontinued. Only the lower mile of West Fork Battle Creek is accessible by vehicle via a gravel road maintained by the MBNF. The lower three miles of Haggarty Creek (below Highway 70) and upper four miles of West Fork Battle Creek are confined within a steep, rugged canyon accessible only by foot.

Ferris-Haggarty Mine Site Characterization

The FHM is an inactive, underground copper (Cu) mine situated in the remote upper reaches of Haggarty Creek, about four miles north of Wyoming Highway 70 in Section 16, T14N, R86W (**Figure 2**). At the turn of the nineteenth century it was one of the largest Cu mines in the region, producing an estimated 24 million pounds of Cu from 1898 to 1908 (Adrian Brown 1994). The mine used state-of-the-art mining equipment, including a 16-mile aerial tramway (touted as the largest in the world at the time) for transporting metal ore to a smelter in Encampment.

Underground mining operations at the FHM commenced one year after prospector Ed Haggarty discovered a mineral-rich outcrop near the current mine site. Haggarty and three other financial supporters filed the original 'Rudefeha' Claim, named by combining the first two letters of each partner's last name (Rumsey, Deal, Ferris and Haggarty). The mine was subsequently called the Ferris-Haggarty Mine in recognition of the principal developers. The Cu ore was initially extracted from the underground workings through two vertical shafts driven from the surface and later from a main haulage level (called the "Osceola Tunnel") whereby the ore was transported to the surface using a compressed air locomotive and rail cars. The ore was then transported over the Continental Divide to the smelter in Encampment via the aerial tramway. Mining operations ceased in 1908 presumably as a result of a smelter fire, financial problems, mismanagement and declining Cu prices (Patera 1991).

Knight Piésold (1999) characterized the FHM site by dividing it into three areas: the upper surface area, the surface area within the vicinity of the Osceola Tunnel and the underground mine workings. The upper surface area consists of two large shafts (Shafts No. 1 and No. 2) and adits or horizontal drifts that were driven from the surface to access the underlying ore body. Figure 3-7 in the report prepared by Adrian Brown (1994) shows adit portals at elevations greater than 10,000 famsl. These initial mine access openings were developed on the steep, forested, northwest-facing hillslope east and south of

Haggarty Creek where annual snowpack accumulation can exceed 30 feet. While a substantial amount of surface water runoff occurs on the slope during spring snowmelt, Knight Piésold observed no surface water entering the mine's upper mine openings during their investigations. The upper surface openings no longer provide access to the mine due to collapsed rock material and shaft closure work completed by the AML Program.

The Osceola Tunnel was developed in 1903 for ore haulage and mine dewatering purposes (Spencer 1904). Mine effluent from the tunnel portal discharges directly into Haggarty Creek at about 9,500 famsl. The Osceola Tunnel provides the only presently available access point to the underground mine workings, extending about 1,400 feet into the mountainside (Knight Piésold 1999). Much of the original surface disturbance features still visible at the FHM site (with a footprint of approximately one acre) occur in the vicinity of the portal including a shed, portal entrance enclosed by steel panels with a ventilation stand pipe, the mine waste rock dump, mine effluent discharge channel, building ruins and remnants of the timbers used to construct the aerial tramway.

The underground mine workings consist of six main levels driven outward from two large shafts sunk from the upper surface area (Figure 3-7, Adrian Brown 1994). Shaft No. 2, the deepest, was driven from the surface at 9,900 famsl to a depth of about 250 feet. The Osceola Tunnel was driven into the hillslope about 1,400 feet at about a 1.3 percent uphill grade to where Cu ore was encountered. Several raises and chutes were established at this location for ore extraction. Excluding the tunnel, the lateral extent of the underground mine development is about 700 feet north-south and 700 feet east-west, with a vertical extent of about 700 feet. According to mine plan drawings prepared by the current mine owner, the tunnel was extended another 500 feet to where a winze (vertical shaft) was sunk to access additional ore (Adrian Brown 1994). The lowest elevation to which the network of development and exploration drives extends is about 9,340 famsl. During their tunnel investigations Knight Piésold (1999) was unable to locate the winze due to collapsed rock in the presumed vicinity, but remnants of hoisting machinery used for ore extraction suggest its existence. Knight Piésold considers this winze to be a major source of water inflow to the Osceola Tunnel.

Since the cessation of commercial mining operations, only a limited amount of mineral extraction and exploration activity has occurred at the FHM site. In 1975 the Dos Lomas Mining Company attempted to remove Cu from the Osceola Tunnel effluent using sedimentation and ion-exchange methods (Adrian

Brown 1994, Chervick and Harp 1977). The mine effluent was routed through four sedimentation ponds constructed for this purpose. The ponds were not operational for several years thereafter and were eventually removed in 2005 as part of an AML reclamation project. The mine effluent is now conveyed directly to Haggarty Creek from the tunnel portal through a limestone-lined channel (**Figure 3**).

Figure 3. Ferris-Haggarty Mine Osceola Tunnel portal and effluent channel, September 2008.

Climate

The climate of the Sierra Madre is characteristic of a high-elevation montane environment with short, cool summers and long, cold winters. Precipitation falls mostly in the form of snow remaining on the ground well into the summer months. Over 20 years of climate data have been collected in the Sierra Madre over a range of altitudes at SNOTEL (SNOwpack TELemetry) weather monitoring stations maintained by the Natural Resources Conservation Service (NRCS/USDA 2009). Representative climate stations in the HC-WFBC drainage include Old Battle (WY06H10S: Latitude 41° 9'N, Longitude -106° 58'W at 9920 famsl) and Sandstone RS (WY07H03S: Latitude 41° 7'N, Longitude -107° 10'W at 8150 famsl). From the upper to the lower elevations of the watershed, average summer daily air temperatures typically range from -3 to 20°C (27 to 68°F). Average winter temperatures range from 2 to -23°C (36 to -9°F). From 1983 to 2008 at Old Battle, average annual cumulative precipitation was 51.1 inches (range of 36.8 to 69.5 inches). At the lower elevation Sandstone RS site average annual cumulative precipitation was 29.1 inches (range of 20.6 to 40.2 inches) from 1986 to 2008. The average snow water equivalent of the snowpack (estimated depth of water produced by melting the snowpack) on the first day of June at Old Battle was 36.9 inches (1971-2000), which accounts for slightly more than 70 percent of the total average annual precipitation at the site.

Regional and Local Geology and Ore Deposit Geochemistry

Because the vast majority of the Cu contamination in the watershed originates from the FHM site, much of the geologic information summarized in this section focuses on the upper reaches of Haggarty Creek. Comprehensive literature reviews of the regional and local geology of the FHM site and Haggarty Creek drainage, including discussions on ore mineralogy and critical regional stratigraphic and structural features that influence the local site hydrogeology and geochemistry are provided by Chervick and Harp (1977), Adrian Brown (1994), Bell (1996) and Knight Piésold (2000). Their investigations were conducted with the intent to determine the factors controlling the distribution of Cu in the upper Haggarty Creek drainage and characterize the various forms of Cu that influence the geochemistry of the FHM effluent.

Regional and Local Geology

The Sierra Madre Range is comprised of folded and faulted metamorphic rocks of Precambrian age intruded by igneous rocks of the same age (Short 1958). Haggarty Creek and the upper West Fork Battle Creek drainage flows through metasedimentary and metavolcanic rocks comprised of granite gneiss, pelitic shale, amphibolite schist, quartzite and marble, while the lower reaches of West Fork Battle Creek flow through the Frontier, Niobrara and Steele Shale Formations which are comprised of sandstones, marine shales, limestone and numerous bentonite beds (Love and Christiansen 1985).

Glaciation has shaped the Haggarty Creek drainage as evidenced by the presence of terminal moraine deposits in the valley. Quarternary alluvium in the drainages and talus and colluvium material on the hill slopes overlie Precambrian basement rock. The principal rock types found at the FHM site and within the Haggarty Creek drainage are detailed by Short (1958), but generally consist of quartzite and slaty schist. This rock is host to the Cu ore extracted from the FHM site and found in small amounts throughout the Sierra Madre (Spencer 1904).

The most recent stratigraphic and structural geologic interpretations of the region are presented by Graff (1978) and Houston et al. (1992). Their investigations indicate that the Sierra Madre has undergone extensive deformation within a regional synclinorium that trends from east to west. A limb of the synclinorium dips 45° to the south where the ore-horizon of the FHM follows a conglomerate zone within the quartzite (Spencer 1904, Graff 1978). Several folding events and three groups of faults are superimposed on this regional-scale structure. Based on field visits made by Adrian Brown (1994) and their interpretations of the most recent geologic stratigraphy described by Houston et al. (1992), the FHM mine is placed within the upper Phantom Lake Metamorphic Suite, specifically in the quartzitic

rocks of the upper Silver Lake Metavolcanics. This stratigraphy is overlain by the younger Snowy Pass Group, defined as an erosional unconformity, comprised of quartzite rocks in the lower strata and metasedimentary dolomite, limestone and chert in the upper strata. Subsequent folding and faulting events above and below this unconformity are believed to have isolated the FHM ore body within a structural and stratigraphic wedge which disappears and plunges to the west towards Haggarty Creek.

Copper mineralization at the FHM presumably originated along a fault zone which allowed the intrusion of quartz-rich and mafic (iron- and magnesium-rich) igneous rocks (Spencer 1904). Gabbroic intrusions, which often contain valuable metals including copper sulfides, are also found along fault zones throughout the region (Graff 1978). Adrian Brown (1994) observed that the quartzite rock near the FHM is well-fractured, suggesting that it likely acts as a local aquifer with water movement directed towards Haggarty Creek based on the plunge direction of the strata. They concluded that the stratigraphic and structural features and ore body at the FHM are "…unique and that hydrogeologic conditions for the high concentrations of copper-rich groundwater may be confined to this site."

Ore Deposit Geochemistry

The primary minerals found in the FHM ore body include chalcopyrite ($CuFeS_2$), pyrite (FeS_2) and chalcocite (Cu_2S) with lesser amounts of bornite (Cu_5FeS_4), covellite (CuS) and various Cu-bearing carbonates and oxides (Spencer 1904). The FHM ore body was reportedly greater than 100 feet thick within a high-grade deposit of chalcocite containing as much as 30 to 40 percent Cu (Patera 1991, Adrian Brown 1994). Chalcopyrite is considered to be the principal mineral remaining in the mine from which the copper-enriched mine drainage waters originate (Adrian Brown 1994).

Knight Piésold (2000) examined waters draining from the upper FHM workings at several underground locations within the Osceola Tunnel. Their investigations revealed that the waters are typical of the acid mine drainage from copper-sulfide deposits, but unique with respect to pH and the relative amounts of other metals commonly found in such waters. The drainage is not extremely acidic. The lowest pH value was 3.6, in water draining from one of the ore chutes 1,400 feet from the tunnel portal. Iron levels are also universally low in the drainage, suggesting that highly acidic waters are absent in the upper workings which presumably permits the precipitation of iron oxyhydroxides (Knight Piésold 2000).

As the relatively acidic, copper-rich drainage from the upper mine workings flows out of the Osceola Tunnel it mixes with a larger volume of copper-poor water which exhibits greater alkalinity and pH.

When the mine effluent reaches the portal it has a near-neutral pH. Several copper-bearing precipitates form in the tunnel as the pH in the mine drainage increases. Knight Piésold (2000) identified three different solid phases of Cu:

- malachite [$Cu_2(CO_3)(OH)_2$] – a basic copper carbonate described as a blue-green sludge found throughout the outer 500 feet of the tunnel and in the mixing zone near the ore chutes;
- woodwardite [$Cu_4Al_2(SO4_4)(OH)_{12}\cdot 3H_2O$] – a bright blue, basic copper aluminum sulfate mineral found between the winze area and 500 feet from the portal; and
- chrysocolla [$CuSiO_3\cdot 2H_2O$] – an amorphous copper silicate sludge found with woodwardite.

Knight Piésold observed that the copper sulfates and copper silicates form relatively durable coatings on the rock substrate in the tunnel, whereas the copper carbonate sludge remains in suspension within pools in the tunnel and is readily transported by flow to the portal and outside drainage (**Figure 4**). Adrian Brown (1994) and Bell (1996) analyzed samples of the Cu sludge (described as a "*gelatinous, blue-green colloidal precipitate*") collected from the settling ponds and have different interpretations of its mineral composition. They suggest that it has the same general physical and chemical composition of chrysocolla, a copper silicate, described by Klein and Hurlbut (1985). However, Newberg (1967) notes that chrysocolla has a poorly-defined crystal structure and a composition that can vary significantly for any given sample.

Figure 4. Colloidal copper precipitate in FHM effluent channel outside Osceola Tunnel portal, June 2007.

Geochemistry

Bell (1996) examined water samples from Haggarty Creek between August 1993 and August 1995 to determine the extent of the contamination and Cu toxicity potentials. Bell's investigation was limited to

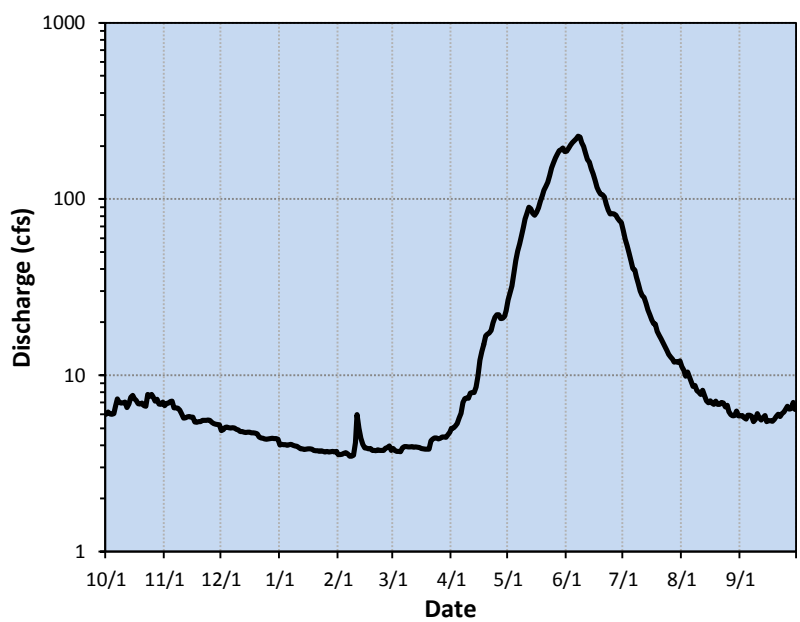
the Osceola Tunnel discharge, nearby springs and Haggarty Creek within ½-mile upstream and downstream of the mine site. Analytical results of Cu samples collected from Haggarty Creek showed that the majority of the Cu is comprised of 81 percent Cu hydroxides, 10 percent free Cu (Cu_2^+) and 9 percent copper-carbonate ($CuCO_3^0$) species (1996). Adrian Brown (1994) reported similar results.

In aqueous solutions, free Cu_2^+ is considered one of the more toxic forms to aquatic organisms (Nielsen and Anderson 1970, Allen et al. 1980). The tightly-bound un-ionized $CuCO_3$ species are potentially toxic if pH levels decrease, releasing Cu_2^+. Although dissolved organic carbon samples suggest that Haggarty Creek contains very little organic matter, some Cu may be bound to organics in the streambed. Copper in the organically-bound or exchangeable forms is potentially the most toxic to aquatic organisms because it can be easily released (Gibbs 1973, Salomons and Förstner 1980, Tessier et al. 1979).

Regional Hydrology

Streamflow gaging data are unavailable for Haggarty Creek and West Fork Battle Creek, but several gaging stations in nearby watersheds provide sufficient flow information to represent flow conditions in the ungaged drainages. Flow data collected by the U.S. Geological Survey (USGS) at Station 09253400, Battle Creek near Encampment is the nearest gage site at 8,375 famsl (**Figure 2**). The hydrograph for this station (**Figure 5**) represents the typical flow regime of high-elevation streams in the Sierra Madre, which is driven primarily by snowmelt. Streamflow increases rapidly beginning in late April to early May with the onset of warm temperatures, peak in late May or early June and recede rapidly as the snowpack diminishes. Outside of the high flow period near steady-state flow conditions are observed. Low flow conditions prevail from about mid-August and December followed by a baseflow period

Figure 5. Annual hydrograph for Battle Creek near Encampment, WY (1956-1963; 1985-1988).

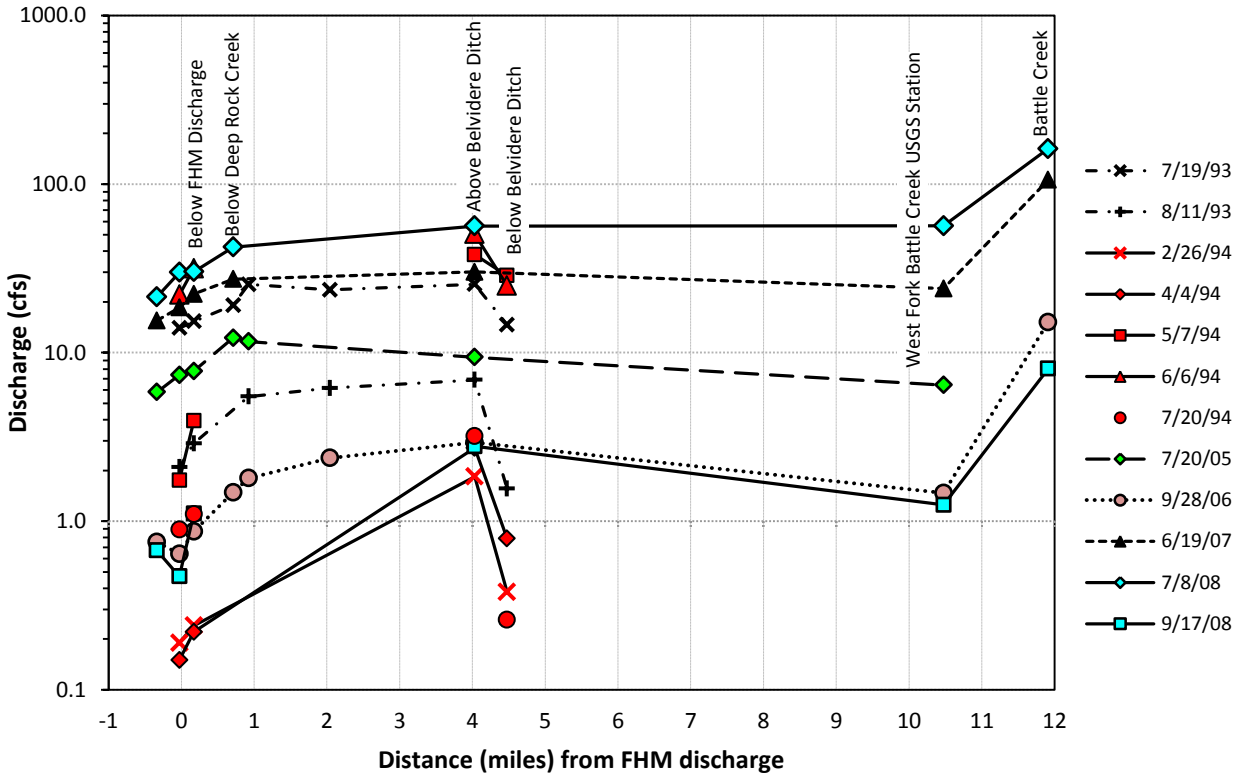


from January to early April. Peak flow conditions in the upper elevations generally occur later than what is observed in the warmer, lower elevations.

Local Hydrology

Instantaneous flow measurements made at various locations on Haggarty Creek by Adrian Brown (1994) in 1993 and 1994 and WDEQ/WQD from 2005 to 2008 show it is a net gaining stream from just above the mine to the Belvidere Ditch diversion one-half mile upstream of Highway 70 (**Figure 6**). Increases in streamflow are largely attributed to small tributary inflows that enter Haggarty Creek downstream of the FHM. Deep Rock Creek, less than a mile downstream of the mine site, contributes a substantial amount of flow to Haggarty Creek, particularly during the snowmelt runoff period. Groundwater inputs from valley alluvium and numerous seeps and springs throughout the drainage contribute lesser amounts of flow.

Figure 6. Seasonal streamflow observations at sites in the Haggarty Creek–West Fork Battle Creek drainage relative to the Ferris-Haggarty Mine discharge (mile 0).



Streamflow reductions observed between Haggarty Creek above the Belvidere Ditch diversion and on West Fork Battle Creek at Battle Creek Campground are the result of withdrawals at the Belvidere Ditch

diversion. Adrian Brown (1994) reported that about 50 percent or more of the flow in Haggarty Creek is diverted to the Belvidere Ditch for irrigation use in the lower basin. According to their 1993-1994 estimates, the amount of flow diverted into the ditch is proportionately greater (70 to 90 percent) during the low flow period from mid-July to early-April than during the peak runoff season. Streamflow increases abruptly at the confluence with Battle Creek which has an unaltered flow regime.

Discharge estimates of the FHM effluent are derived from flow measurements made from 1993 to 2008 by Adrian Brown, Knight Piésold and WDEQ/WQD. Knight Piésold recorded the most complete and continuous flow record of the mine drainage during various periods from 1996 through 1999. Their data supplemented with flow measurements taken in other years provided sufficient information to develop an annual hydrograph for the mine drainage. Annual hydrographs for Haggarty Creek above the FHM site (HC4 in **Table 2**) and the FHM drainage are shown in **Figure 7**.

Table 2. Basin characteristics of Haggarty Creek, West Fork Battle Creek and nearby USGS gaging stations. Data reported by Miller (2003) and StreamStats at http://water.usgs.gov/osw/streamstats/. Units: feet above mean sea level (famsl), feet (ft), miles (mi), square miles (mi^2), inches per hour (in/hr), and cubic feet per second (cfs).

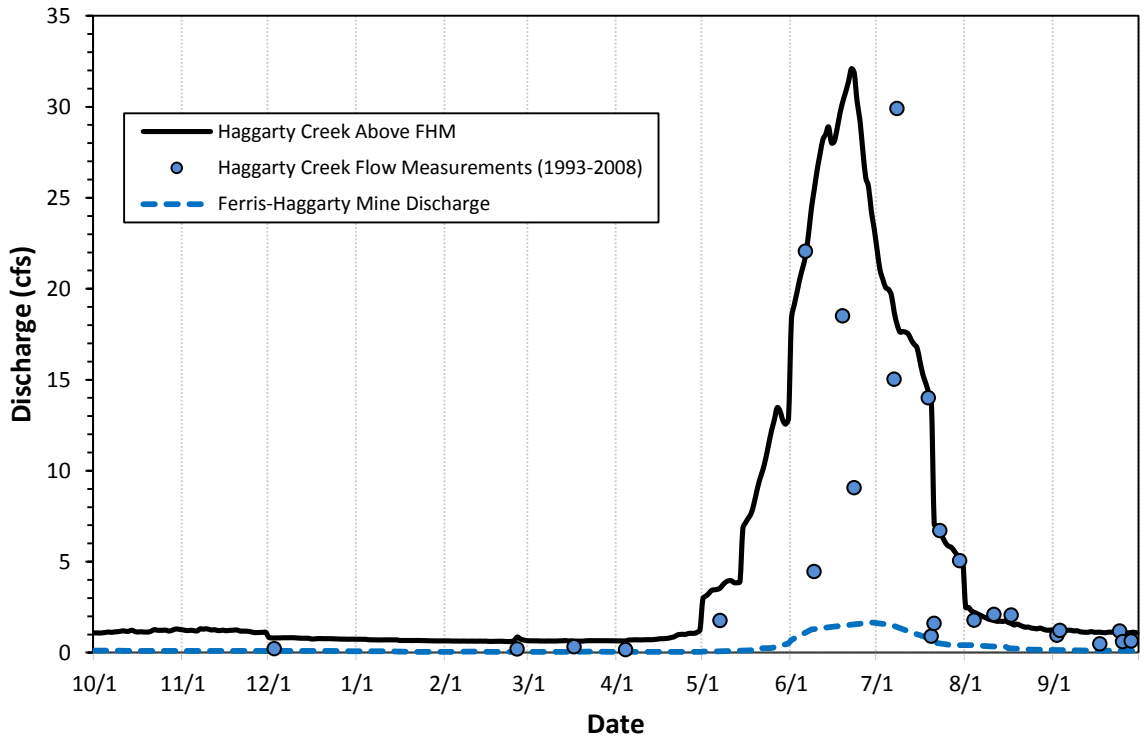
Station Type	Station[1]	Flow Record (Years)	Station Datum (famsl)	Drainage Area (mi^2)	Drainage Density (mi/mi^2)	Channel Maint. Constant (mi^2/mi)	Mean Basin Elev. (famsl)	Mean Basin Slope (ft/mi)	Mean Channel Slope (%)	Mean Annual Precip. (in)	Mean Annual Discharge (cfs)	Discharge/ Unit Area (cfs/mi^2)
	HC4	NA	9560	1.30	1.90	0.53	10250		12.0	53.3	3	2.3
Ungaged	HC14	NA	8440	6.95	2.05	0.49			8.3	37.4	15	2.2
	WFBC1	NA	7280	13.8						28.5	26	1.9
	ER	45→	8270	72.7			9560	1200	2.1	44.9	111	1.5
Gaged	NFLSR	9	8250	12.8	2.44	0.41	9110	1350	7.5	49.8	26	2.0
	BC	10	8375	13.0	2.13	0.47	9590	1210	4.8	48.3	27	2.1

[1] Station names (USGS Station No.): HC4 = Haggarty Creek above FHM; HC14 = Haggarty Creek above Belvidere Ditch near Encampment, WY (09253455); WFBC1 = West Fork Battle Creek at Battle Creek Campground near Savery, WY (09253465); ER = Encampment River above Hog Park Creek near Encampment, WY (06623800); NFLSR = North Fork Little Snake River near Encampment, WY (09251800); BC = Battle Creek near Encampment, WY (09253400).

Mean daily discharge values used to produce the Haggarty Creek hydrograph are adjusted to account for differences in scale (drainage area) and peak runoff timing. Relative to the Battle Creek gaging station, the FHM site has about ten-times less drainage area and is nearly 1,200 ft higher in elevation. Comparisons of high flow measurements to the unadjusted estimates indicate that peak runoff in Haggarty Creek occurs about 15 days later than what is observed in Battle Creek. This difference in peak runoff behavior is likely due to elevation and temperature differences between the gaged and ungaged

sites. Cooler air temperatures at the high-altitude FHM site appear to delay the timing of peak flow in Haggarty Creek. To account for this temporal difference, a lag response is incorporated in the flow data.

Figure 7. Hydrographs for the Ferris-Haggarty Mine drainage and Haggarty Creek above the FHM.



In addition to the scale and temporal adjustments made to the Haggarty Creek data, a period-specific standard deviation is added to each estimated value to account for the variability observed over six distinct flow periods (**Appendix A**). The abrupt changes in flow apparent in the hydrograph reflect these adjustments. Period-specific adjustment factors are also included in the FHM flow estimates.

Based on the estimated flow data, the average annual discharge estimated for Haggarty Creek above the FHM is 4.7 cubic feet per second (cfs). This flow rate is greater than the estimate of 4 cfs reported by Adrian Brown (1994), but they indicate that their measurements likely underestimate the actual flow in Haggarty Creek due to the error associated with measuring flow in streams with cobble/boulder beds (Broshears et al. 1993, Kimball 1997). Given the mean daily flows shown in **Figure 7** are adjusted to account for measurement error and variability, it is reasonable to assume that the estimates are representative of the flow conditions that may be expected in Haggarty Creek.

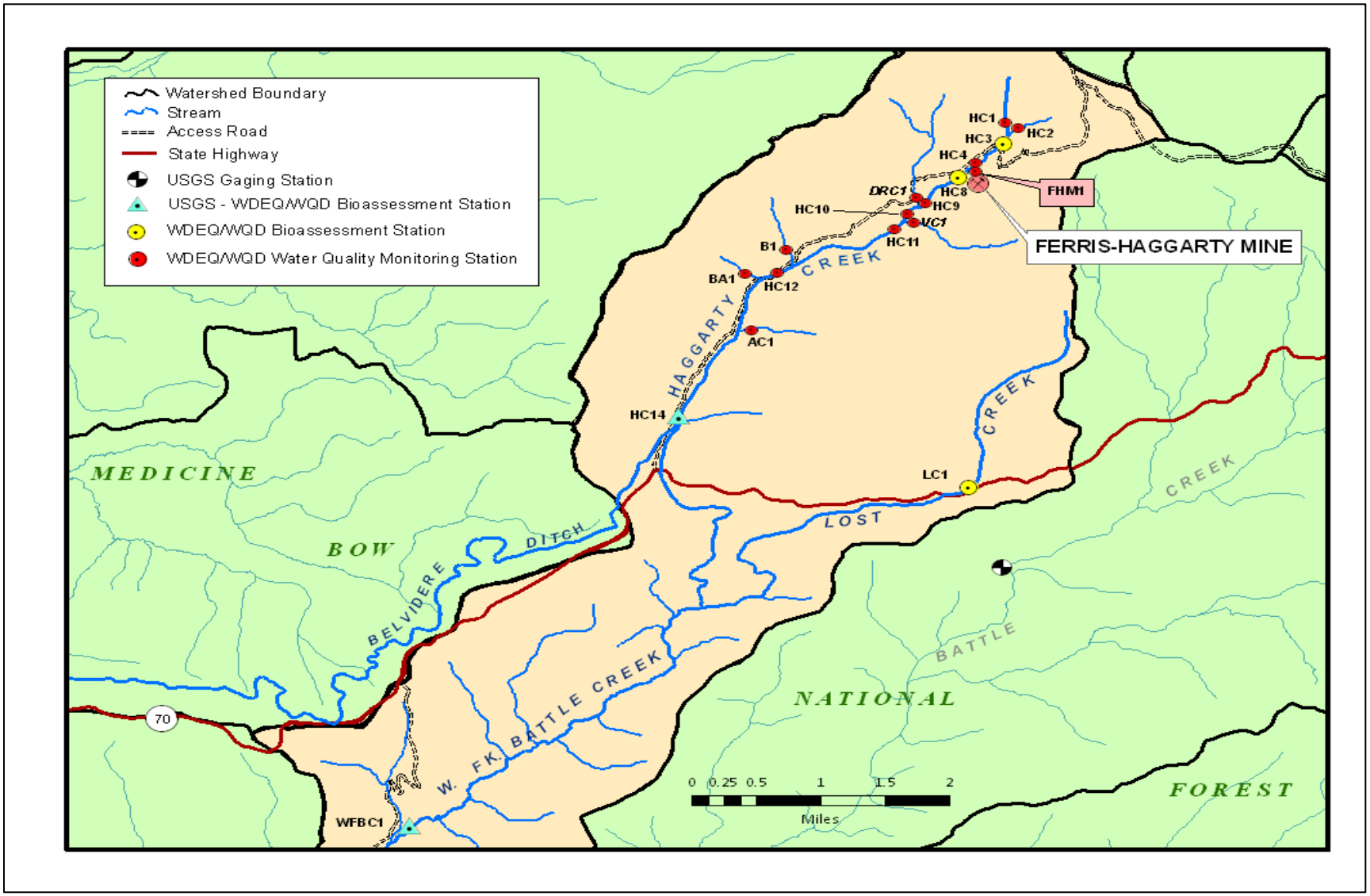
The estimated average annual discharge from the FHM drainage is 120 gallons per minute (gpm), or 0.27 cfs. Minimum and maximum discharge rates are 22 gpm and 747 gpm, respectively. Knight Piésold (2000) estimated that flows at the Osceola Tunnel portal approach 15 gpm during the winter baseflow period, and reach maximum rates of 650 to 700 gpm (1.5 to 1.6 cfs) during the spring snowmelt period. There is some uncertainty in these estimates because of the difficulties encountered with maintaining the automated flow-measuring devices installed inside the tunnel during the winter. The maximum discharge measured at the tunnel portal was 669 gpm on June 23, 1999. They predicted a maximum flow rate of 740 gpm by correlating their 1997 and 1998 peak flow data with the maximum annual snowpack levels recorded from 1983 to 1998 at the Old Battle SNOTEL station.

Based on the few flow measurements made in 1993 and 1994 by Adrian Brown (1994), the estimated ratios of Haggarty Creek flows to FHM drainage flows ranged from about 5:1 to 29:1. Knight Piésold (1998, 2000) reported flow ratios of about 3:1 to 18:1 using Cu concentrations measured in the mine drainage and Haggarty Creek on a few occasions in 1998 and 1999. Except for a period of time that precedes peak runoff (May), flow ratios calculated from the estimated flow data generated for this report are similar to those reported by previous investigators. Flow ratios of Haggarty Creek to FHM drainage flows ranging from about 40:1 to 60:1 may be expected prior to peak runoff.

2.2 CHARACTERIZATION OF WATER QUALITY CONDITIONS AND IMPAIRMENT

This section examines the water quality conditions and the extent of impairment in the HC-WFBC drainage. The pollutants and sources responsible for the impairment and the WQSs used to define the impairment are identified. The applicable water quality and bioassessment data discussed throughout the remainder of the document are presented in **Appendices B and C**. Data are compiled from several sources including Adrian Brown (1994), Knight Piésold (1998, 1999 and 2000), WDEQ/WQD site files and the USGS National Water Information System for Wyoming (http://waterdata.usgs.gov/wy/nwis/nwis). Sampling stations established by the USGS and WDEQ/WQD in the drainage are shown in **Figure 8**. Many of the stations coincide with sites referenced by previous investigators.

Figure 8. WDEQ/WQD water quality and bioassessment sample sites on Haggarty Creek and West Fork Battle Creek. Station identification codes correspond to those listed in the water quality data tables in Appendix B.



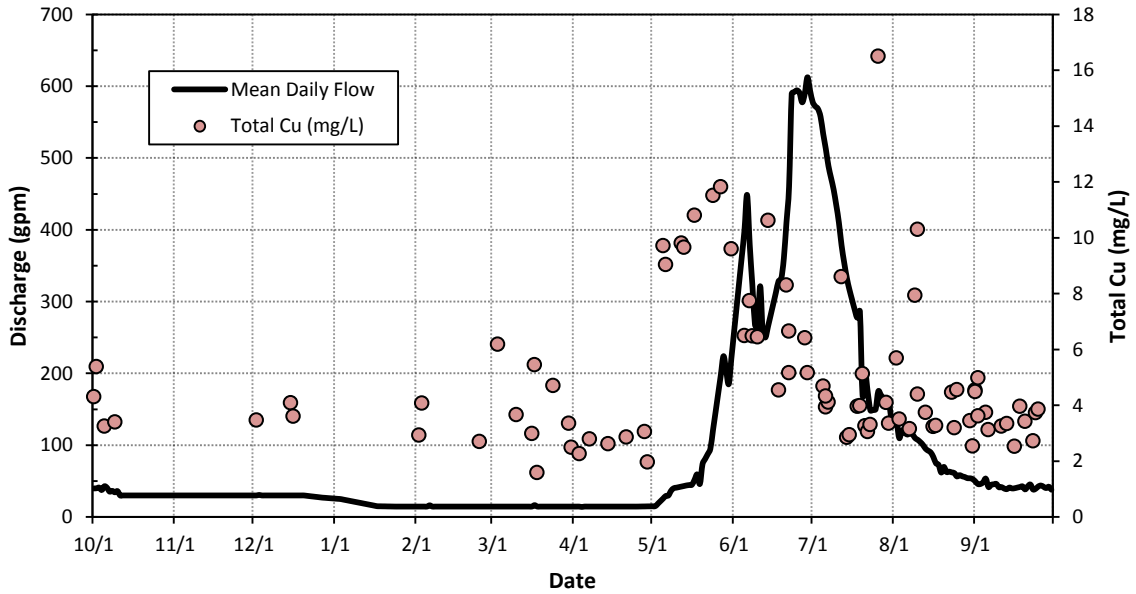
Water Quality Condition

Copper

Copper-enriched water discharging from the underground workings of the FHM has likely impacted water quality in Haggarty Creek since the early 1900's when Cu was first mined in the area. While flows in Haggarty Creek provide considerable dilution to the mine effluent, the resultant instream Cu concentrations exceed levels deemed toxic to fish and other aquatic life for several miles downstream. Elevated levels of Cu are frequently observed 11 miles downstream in West Fork Battle Creek. Cadmium (Cd) and silver (Ag) are periodically detected in the lower reaches of the drainage, but their concentrations are considerably lower than those observed for Cu. The direct and indirect effects from metal toxicity and the reduction, or near eradication, of aquatic plant life and macroinvertebrates are identified as reasons why a thriving fish population is not found in Haggarty Creek.

Total Cu concentrations measured in the FHM effluent from 1993 to 2008 are displayed in **Figure 9** with the hydrograph generated from mean daily flow data collected at the mine portal**.** Concentrations typically vary from about 2 to 9 mg/L (geometric mean = 4.7 mg/L) throughout much of the year, but short-lived peak values of 10 to 12 mg/L may be observed just prior to maximum peak discharge in the spring (late-May to early June). Periodic surges of copper-rich water are also observed in late summer and early spring during sporadic rainfall and snow-melt events.

Figure 9. Mean daily flows estimated for the FHM effluent and total copper concentrations measured from 1993 to 2008.

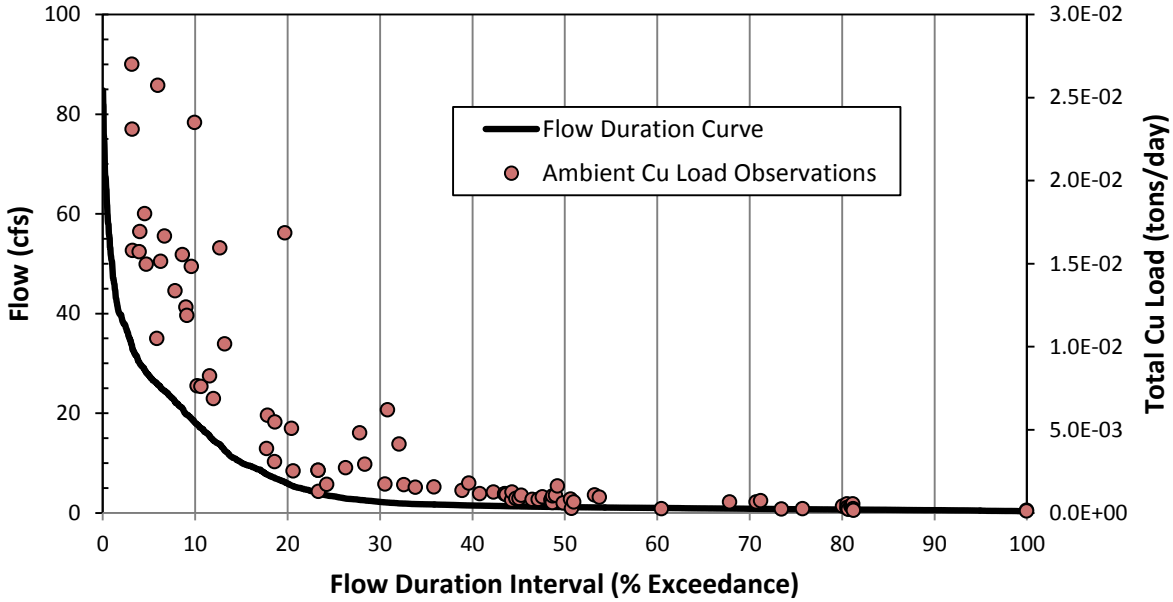


Knight Piésold (2000) proposed that fluxes of Cu in the Osceola Tunnel reach their maximum between the onset of spring snowmelt and the time of maximum discharge at the portal. The process begins with a surge of fresh water infiltrating through the upper mine workings, displacing copper-enriched pore water that has remained undisturbed over the previous ten months. As copper-laden water is flushed from the mine workings, Cu in the portal discharge becomes progressively more dilute until fresh water infiltration through the Cu ore-body diminishes. The process is repeated with successive infiltration events (snowmelt and rainfall). When discharge peaks at the portal in late June, Cu concentrations are similar to those observed during normal low flow conditions.

Although Cu *concentrations* in the mine effluent may reach maximum levels for the year with the initial 'flush' of copper-rich water from the underground mine workings occurring at the onset of the spring snowmelt (**Figure 9**), maximum Cu *loads* (tons/day) in the effluent are typically observed at the time of peak portal discharge. Some of the greatest Cu loads in Haggarty Creek below the FHM are observed during this time frame, as well. **Figure 10** displays Cu load values observed in Haggarty Creek below the FHM. The load values are plotted with the corresponding flow exceedance values derived from the flow duration curve developed for the site. The intent of the plot is not to express a quantitative relationship between flow and Cu loading, but rather to show that Cu loading in Haggarty Creek increases with increasing flow. The greatest Cu load occurs during periods when flows greater than about 10 to 15 cfs are equaled or exceeded (<10 percent flow exceedance). Although short-lived, flows greater than 15 cfs in Haggarty Creek at the FHM site normally occur during the peak snowmelt runoff period and occasionally following large thunderstorm events in the summer (**Figure 7**). Given this information, the greatest Cu loading in Haggarty Creek at the FHM site appears to occur with the onset of peak runoff in late-May and early-June. Data collected at the USGS monitoring stations on Haggarty Creek and West Fork Battle also indicate Cu levels are greater during the spring runoff period than in late summer.

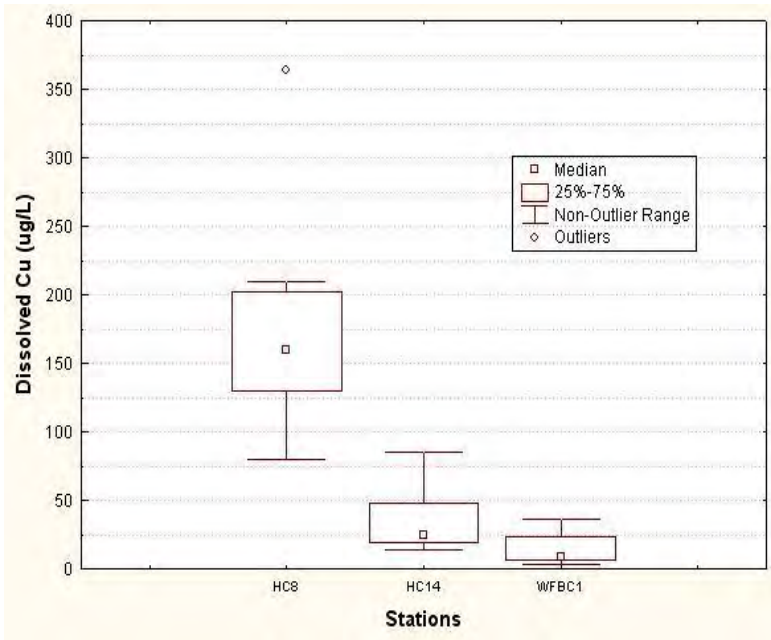
Data collected by Adrian Brown (1994), Bell (1996), Meyer et al. (2004) and WDEQ/WQD indicate that much of the Cu in the mine effluent is in a soluble (dissolved) form. Adrian Brown (1994) reported that precipitation of any of the known inorganic phases of Cu is not favored in Haggarty Creek, but some Cu may exist as low-solubility organic compounds in the streambed sediment. Calculations from available data indicate that about 75 to 80 percent of the Cu remains in solution once mixed with flows in Haggarty Creek.

Figure 10. Flow duration curve for Haggarty Creek below the Ferris-Haggarty Mine site and copper load estimates derived from data collected at the site from 1993 to 2008.



Flows in Haggarty Creek provide a considerable amount of dilution to Cu in the mine effluent. Copper levels continually diminish with distance downstream as tributary inflows provide additional dilution (**Figure 11**). Dissolved Cu concentrations measured below the FHM (HC8 in **Figure 8**) range from about 80 to 365 micrograms per liter (µg/L) with a geometric mean of 158 µg/L). Copper levels estimated from mass balance calculations indicate values near 1 mg/L may be observed in Haggarty Creek below the FHM during the late-May to early-June peak loading period. While concentrations that great are not documented for the site for that time of year, few measurements are available to verify their accuracy. At the

Figure 11. Dissolved copper concentrations observed at stations on Haggarty Creek (HC) and West Fork Battle Creek (WFBC) from 1993 to 2008.



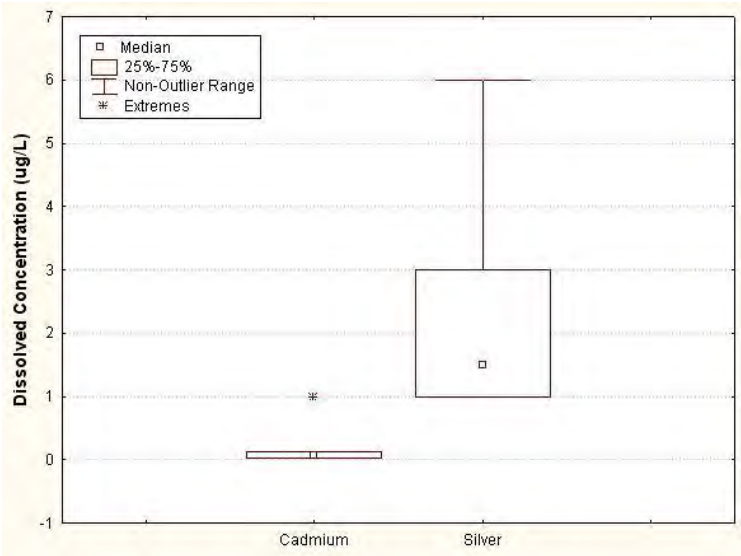
USGS station above Highway 70 (HC14) dissolved Cu varies from about 15 to 85 µg/L (geometric mean = 29 µg/L), a decline of roughly 80 to 85 percent in the four-mile distance between stations HC8 and HC14. Dissolved Cu concentrations at West Fork Battle Creek (WFBC1) are about 90 to 95 percent of values observed at HC8, ranging from 3 to 36 µg/L (geometric mean = 12 µg/L).

Natural or background levels of Cu in the Haggarty Creek watershed are negligible compared to levels in the mainstem of Haggarty Creek below the FHM site. Several tributaries enter Haggarty Creek below the FHM, all of which have no known mining impacts. Based on measurements made during summer flow periods, less than 1 µg/L Cu is observed in the tributary system. Maximum concentrations of 2 µg/L are measured periodically in Haggarty Creek above the FHM site.

Cadmium and Silver

Low-level concentrations of Cd and Ag are observed periodically at the USGS stations on Haggarty Creek (HC8) and West Fork Battle Creek (WFBC1). Concentrations of both metals are typically at or near limits of analytical detection and happen to equal or slightly exceed their respective aquatic life use standards. All of the dissolved Cd (15 values) and Ag (6 values) concentrations measured in the Haggarty Creek-West Fork Battle Creek drainage are shown in **Figure 12**. Dissolved values of Cd range from 0.02 to 1.00 µg/L (geometric mean = 0.08), and values of Ag range from 1 to 6 µg/L (geometric mean = 1.8 µg/L).

Figure 12. Dissolved cadmium and silver concentrations observed in the HC-WFBC drainage (1993-2008).



Past investigators have reported no detectable levels (<1 µg/L) of Cd or Ag in Haggarty Creek or its tributaries (Adrian Brown 1994, Bell 1996, Knight Piésold 1998 and 2000) upstream of HC14. The WDEQ/WQD monitored water quality throughout the HC-WFBC drainage from 2004 to 2008 and also found no detectable levels (<0.1 µg/L) of Cd or Ag in Haggarty Creek or its tributaries. Adrian Brown (1994) and the WDEQ/WQD reported dissolved Cd concentrations of 0.2 µg/L in the FHM effluent in 1993, 2007 and 2008. Silver has

never been detected in the mine effluent. Although past data were collected primarily during low flow conditions, the available evidence suggests that the source(s) of the Cd and Ag detected at the USGS station on Haggarty Creek does not originate from the FHM site.

Biological Condition

While the water chemistry data alone is sufficient to support the impairment listings of Haggarty Creek and West Fork Battle Creek (WDEQ/WQD 2010), the biological evidence provides further confirmation. Based on fish population surveys, trout are not found in Haggarty Creek for approximately four miles downstream of the FHM effluent and few are observed in the lower reaches of the drainage. In addition to metal toxicity, the decline in the fishery may be largely attributed to the apparent collapse of the aquatic food base - the primary producers (algae or periphyton), aquatic insects and other organisms upon which trout rely on to survive.

Coldwater Game Fish

Historical fish population data collected by the Wyoming Game and Fish Department (WGFD) indicates that Haggarty Creek downstream of the mine discharge has been virtually devoid of fish since at least 1975, although anecdotal information suggests that the stream has been sterile throughout the 1900's (Oberholtzer 1987). Fish population survey data from representative, minimally impacted streams in the Battle Creek drainage system indicate that Haggarty Creek has the potential to support a trout population of about 1000 fish/mile or 70 lbs of trout biomass/acre (Oberholtzer 1987, 1990).

In 1983 and 1986 the WGFD discovered remnant populations of genetically pure Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in three small tributaries to Haggarty Creek downstream of the FHM (Oberholtzer 1990). In the past Colorado River cutthroat trout (CRCT) was considered a Category 2 species for formal listing under the Endangered Species Act by the U.S. Fish and Wildlife Service, a sensitive species in Regions 2 and 4 of the U.S. Forest Service, and designated with special status by Colorado, Utah and Wyoming (Johnson 1987). It is currently designated as a species of special concern in its historical range in the upper Colorado River drainage (Hirsch et al. 2005). Declines in the distribution of the species throughout its historical range, including the Little Snake River drainage system, elicited responses from several management agencies to maintain and protect remnant populations. Significant resources have been and continue to be dedicated to its conservation. The CRCT population in the Haggarty Creek drainage is believed to have been isolated as a result of the Cu contamination, acting as a fish migration barrier. Copper toxicity also likely prevents the upstream

movement and colonization of brook trout (*Salvelinus fontinalis*) which compete with the cutthroat for habitat and resources, and rainbow trout (*Oncorhynchus mykiss)* which interbreed with cutthroat reducing its genetic integrity. Management efforts taken to protect and maintain remnant populations of the CRCT in Wyoming and throughout its native range include surveys, angling restrictions, channel modifications and the reintroduction of genetically pure strains of CRCT in isolated headwater streams (CRCT Coordination Team 2006, Young et al. 1996). If in-stream Cu concentrations in Haggarty Creek were reduced to levels that would support aquatic life and fish, the stream could potentially provide additional habitat for the native cutthroat trout.

Adult trout are occasionally observed in the lower reaches of Haggarty Creek (near Highway 70) and in West Fork Battle Creek during late summer when Cu concentrations are typically low. Trout are also observed in the Belvidere Ditch where much of Haggarty Creek's flow is diverted during the irrigation season. These observations suggest that the resident trout population in the drainage is capable of tolerating, to a certain extent, the relatively low-level Cu concentrations observed during the summer low flow period. A majority of the metals in the system at that time of year may also be in forms that are less bioavailable (less toxic) to trout, macroinvertebrates and periphyton. While the presence of trout in the lower reaches of the drainage may be short-lived, it indicates that there is a biological condition gradient that correlates with the observed attenuation of Cu with distance downstream of the FHM effluent. A similar gradient is observed in the benthic macroinvertebrate and periphyton communities found at sites in the lower reaches of the drainage.

Benthic Macroinvertebrates

Because benthic macroinvertebrates are permanent residents in streams, they are useful indicators of cumulative water quality change and impacts. They are subjected to environmental stressors that cannot always be identified from point-in-time chemical and physical sampling data. Several investigators have conducted benthic macroinvertebrate surveys on Haggarty Creek to evaluate the stream's biological condition (Lazorchak et al. 1989, Adrian Brown 1994, Rockwell 2001, and Meyer et al. 2004). The WDEQ/WQD collected macroinvertebrate samples from Haggarty Creek at sites upstream and downstream of the FHM effluent and at one site on West Fork Battle Creek in 1996, 2001 and 2008. The purpose of the surveys was to evaluate spatial and temporal trends in biological condition throughout the drainage. Long-term bioassessment stations established by the WDEQ/WQD in the HC-WFBC drainage are shown in **Figure 8**.

The WDEQ/WQD uses two biological indicator models, the Wyoming Stream Integrity Index (WSII) and the Wyoming River Invertebrate Prediction and Classification System (WY RIVPACS), to interpret benthic macroinvertebrate data and assess aquatic life use-support. Results (scores) from each model are treated as quantitative bio-criteria, however, they are not approved (through formal rule-making) for use as numeric criteria. Rather, the scores generated from each model are used to assign narrative ratings for the purpose of "gauging" aquatic life use support. Narrative ratings of 'full-support', 'indeterminate' and 'partial/non-support' are assigned to a site by comparing its scores to a range of threshold values specific to each model. The narrative ratings from both models are then used in Wyoming's aquatic life use-support decision matrix (WDEQ/WQD 2008) to determine the overall biological condition of a site. Because model results represent water quality conditions over a multi-year period, they generally carry a strong weight when used in a weight-of-evidence approach for making aquatic life use-support determinations (WDEQ/WQD 2008).

The WSII is a regionally calibrated multi-metric model designed to assess aquatic life use support (Hargett and Zumberge 2006). The model calculates a single index score from a set of macroinvertebrate metrics (taxonomic measures of species diversity, community composition, pollution tolerance and functional guilds) derived from a benthic sample. Metrics in the model are selected based on their ability to discriminate between reference and degraded waters within designated bioregions. Each bioregion has its own unique set of metrics. The reference condition for each bioregion is established from macroinvertebrate data collected at several sites within the region considered to be minimally or least-impacted by human disturbance. Biological condition for a site is determined by comparing its index score to threshold values established for the corresponding bioregion. Index scores that fall within the range of expected values imply high biological condition, whereas values that fall below expected numeric thresholds suggest a certain degree of biological degradation. Narrative aquatic life use ratings are assigned to a site's benthic macroinvertebrate community by comparing its biological condition index score to established threshold values.

The WY RIVPACS is a statewide predictive model that compares the macroinvertebrate taxa observed at a site with unknown biological condition to an assemblage of taxa (reference condition) expected to occur in the same bioregion (Hargett et al. 2005 and 2007). The expected reference taxa are compiled from macroinvertebrate data collected at sites that are minimally or least impacted by human disturbance. The model generates ratios of observed to expected taxa, known as O/E values, which are

relative measures of taxa richness used to assess biological condition. Values near 1 imply high biological condition while values <1 imply some degree of biological degradation. Narrative aquatic life use ratings are assigned to a site's benthic macroinvertebrate community by comparing its O/E score to reference condition threshold values.

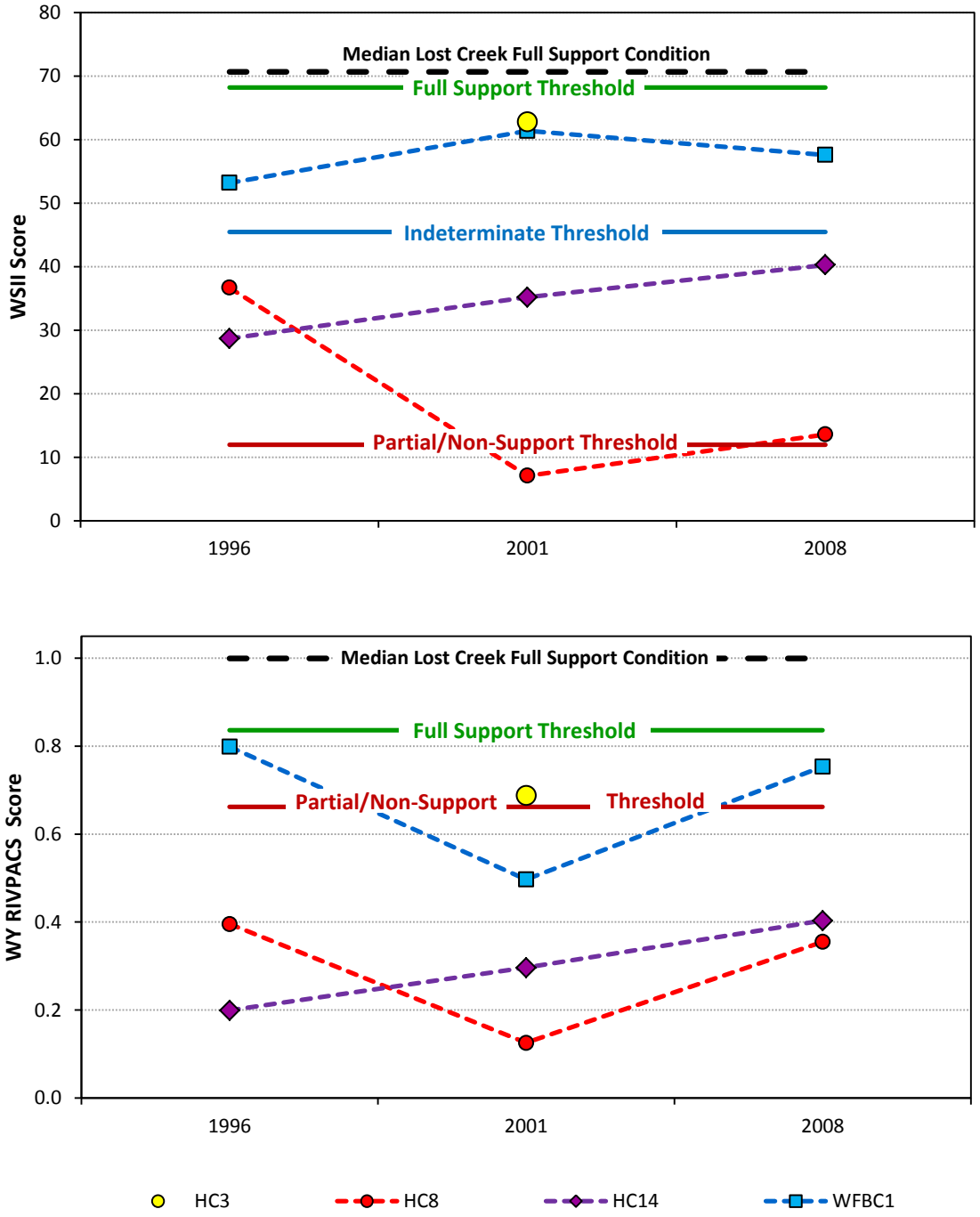
In addition to comparing WSII and WY RIVPACS model results to a regional reference condition, they can be compared to model results of sites with reference-quality or least-impacted characteristics within the same watershed. A bioassessment station established near the US Forest Service campground on Lost Creek (**Figure 8**) is a site within the HC-WFBC drainage where aquatic life uses are considered fully supported. The WSII and WY RIVPACS results derived from four years (1996 and 2001-2003) of macroinvertebrate data collected at this site were used to calculate a median or overall biological condition score for each model. The biological condition of a bioassessment station established on Haggarty upstream of the FHM site provides another relative measure to assess departure in the biological condition observed at sites in the lower reaches of Haggarty Creek and West Fork Battle Creek. Only one benthic macroinvertebrate sample was collected at this site in 2001.

The WSII and WY RIVPACS results for bioassessment sites on Haggarty Creek, West Fork Battle Creek and Lost Creek are displayed graphically in **Figure 13**. While there is some temporal variability in the scores at sites among years, scores for each site follow the same general trend in biological condition over time. Results from both models suggest that the benthic macroinvertebrate community directly below the FHM effluent in Haggarty Creek (HC8) exhibits the greatest degree of biological degradation among all sites in the drainage. Except in 1996, scores increase downstream at HC14 but the low scores still imply that the site experiences a high degree of environmental stress. Among all sites downstream of the FHM site, the macroinvertebrate community in West Fork Battle Creek at WFBC1 appears to experience the least amount of environmental stress.

Based on the combined WSII and WY RIVPACS scores, aquatic life use narrative ratings of 'partial/non-support' are assigned to the macroinvertebrate communities at HC8 and HC14 (**Figure 13**). Various degrees of biological degradation are implied by the model results for WFBC1. Overall narrative ratings of 'indeterminate' are assigned to its 1996 and 2008 communities, but a rating of 'partial/non-support' is assigned to the 2008 community. These variable ratings suggest that biological conditions at West

Fork Battle Creek are not as severe as those observed in Haggarty Creek. Nonetheless, its aquatic life uses are considered to be less than fully supported.

Figure 13. WSII and WY RIVPACS scores for sites on Haggarty Creek (HC), West Fork Battle Creek (WFBC) and Lost Creek.



Scores derived from both models suggest that biological degradation decreases with increasing distance downstream of the FHM. This spatial trend correlates with the observed reductions in Cu concentrations with distance downstream. Changes in elevation between sites may account for some of the differences in scores, but scores for HC3 and at Lost Creek suggest otherwise. For instance, the elevation at the Lost Creek site is not much different than at HC14 on Haggarty Creek where WSII and WY RIVPACS scores fall well below the full support threshold.

A comparison of the WSII and WY RIVPACS scores for sites on Haggarty Creek above and below the FHM effluent indicates that there are considerable differences in the biological condition between the two sites. The disparities in the scores are largely attributed to differences in the total abundance and species richness of organisms observed between the two macroinvertebrate communities. In 2001, the benthic community at HC3 above the mine contained a total of 39 species and nearly 1,500 individual organisms. In comparison, the 2001 community below the mine at HC8 contained only three species and a total of nine individuals (over two orders of magnitude less than the total abundance observed above the mine). Investigators speculate that most if not all of the organisms collected below the mine in years past are not permanent residents of the site. Rather, they are individuals that drifted in the stream current from locations upstream of the mine. This may explain why HC8 received favorable scores in 1996 (**Figure 13**) compared to scores it received in 2001 and 2008.

While the 2001 WSII and WY RIVPACS scores for HC3 are useful for comparative purposes, their use for assessing aquatic life use support is limited. Both models were developed from macroinvertebrate data collected at sites with drainage areas greater than five mi^2 and elevations less than 9,500 famsl. (Station HC3 is at an elevation of 10,000 famsl with a drainage area of less than one mi^2.) As a result, use of the model results to assess aquatic life use support for sites that do not meet these criteria is not recommended.

2.3 APPLICABLE WATER QUALITY STANDARDS & DESIGNATED USES

Water quality standards define the function or goal of a waterbody. The standards consist of criteria and provisions designed to protect and maintain designated water uses. Water quality criteria are numeric values (e.g., contaminant concentrations) or narrative statements that represent a target or quality of water intended to support and protect a particular use. If criteria are met, then there is a reasonable assurance that the water is of sufficient quality to protect designated use(s). If the criteria

(or a criterion) are frequently exceeded, then there is a reasonable degree of certainty that designated uses are threatened or impaired.

Surface waters in Wyoming are classified according to their approved designated uses. Haggarty Creek and West Fork Battle Creek are Class 2AB streams with designated uses that include cold-water fisheries, non-game fisheries, aquatic life other than fish, fish consumption, drinking water, recreation, agriculture, wildlife, industry and scenic value (WDEQ/WQD 2007). For several years, both streams have been identified as impaired waters that do not fully support their aquatic life, non-game fish and cold-water fish uses due to metal contamination. They are currently identified on Wyoming's 2010 §303(d) list of impaired waters (WDEQ 2010).

The applicable aquatic life numeric criteria for the three metal pollutants of concern in the HC-WFBC drainage are derived from hardness-dependent equations (WDEQ/WQD 2007). The criteria vary depending on ambient water hardness concentrations. Hardness is a measure of the mineral content in water (mainly calcium and magnesium) and is expressed in mg/L calcium carbonate [$CaCO_3$]. Over a continuum of hardness, waters may be considered "soft" (i.e., low mineral content of 0 to 60 mg/L) or "very hard" (high mineral content >180 mg/L). For streams with soft water, metals criteria are more stringent than those for streams with hard water. The reason for this is that soft water contains few minerals and other compounds to complex or bind with metal ions. Unbound or free metal ions are generally more toxic to aquatic organisms, thus metals criteria are set at more restrictive levels for waters with low mineral content. The aquatic life use criteria equations for Cu, Cd and Ag are derived from the equations presented in **Table 3**.

Table 3. Equations used to calculate aquatic life use criteria for metals with hardness-dependence[1]. Criteria are expressed as dissolved concentrations (µg/L). From Appendix F, Chapter 1 of the Wyoming Surface Water Quality Standards (WDEQ/WQD 2007).

Parameter	Acute	Chronic
Cadmium (Cd)[2]	$e^{[1.0166(\ln \text{hardness}) - 3.924(CF)]}$	$e^{[0.7409(\ln \text{hardness}) - 4.719(CF)]}$
Copper (Cu)	$e^{[0.9422(\ln \text{hardness}) - 1.700(0.960)]}$	$e^{[0.8545(\ln \text{hardness}) - 1.702(0.960)]}$
Silver (Ag)	$e^{[1.72(\ln \text{hardness}) - 6.52(0.85)]}$	Not Applicable

[1] Total water hardness concentration (mg/L $CaCO_3$). Use 25 for hardness values ≤25 mg/L and 400 for values ≥400 mg/L.
[2] Conversion factors (CF) for cadmium vary with hardness and are calculated using the following equations:

$CF_{acute} = 1.136672 - 0.041838 (\ln \text{hardness})$ $CF_{chronic} = 1.101672 - 0.041838 (\ln \text{hardness})$

Acute and chronic criteria are time-response estimates of the greatest concentration of a material in surface water to which an aquatic community can be exposed without resulting in an unacceptable effect. Acute values represent a response to a stimulus severe enough to induce a rapid reaction, typically in 96 hours or less, while chronic values represent a response to a continuous, long-term stimulus (WDEQ/WQD 2007). The criteria also include averaging periods and frequencies of allowed exceedance. Acute values have a one-hour average concentration and chronic values have a four-day average concentration, which if not exceeded more than once every three years on average should not result in unacceptable effects on aquatic organisms and their uses. Section 21 (b) in Chapter 1 of the Wyoming Water Quality Rules and Regulations (WDEQ/WQD 2007) specifies that the acute and chronic values set for a number of toxicants, including the metals listed in **Table 3**, shall not be exceeded more than once in a three year time period. Because aquatic life criteria are national guidance, they are intended to be protective of the vast majority of aquatic communities in the United States.

3.0 WATER QUALITY TARGETS

The purpose of the TMDLs developed for Haggarty Creek and West Fork Battle Creek is to restore the water quality required for each waterbody to fully support their designated uses. This section identifies the water quality 'targets' established to achieve that goal and describes the extent to which the existing water quality deviates from those targets.

3.1 TMDL TARGETS

The hardness-dependent equations listed in **Table 3** are used to derive the numeric metals criteria that represent the TMDL targets for Haggarty Creek and West Fork Battle Creek. Given water hardness has a significant influence on metal availability and toxicity, it plays a significant role in establishing TMDL target levels and in determining the metal load reductions required to achieve full support of the aquatic life and fisheries uses in the watershed.

The water in Haggarty Creek is considered "soft" (0 to 60 mg/L), rarely exceeding 20 mg/L and is as low as 2 to 3 mg/L during high flow conditions. The lowest hardness concentration that can be used to derive metals criteria is 25 mg/L (WDEQ/WQD 2007); consequently, the aquatic life metals criteria for Haggarty Creek are set at the most restrictive levels for Wyoming surface waters. In West Fork Battle Creek, water hardness rarely exceeds 25 mg/L during high flows and ranges from about 50 to 120 mg/L during low flow conditions when minerals tend to concentrate. Due to the greater mineral content in West Fork Battle Creek during low flow conditions, metals criteria are less stringent than during high flow conditions when minerals are diluted.

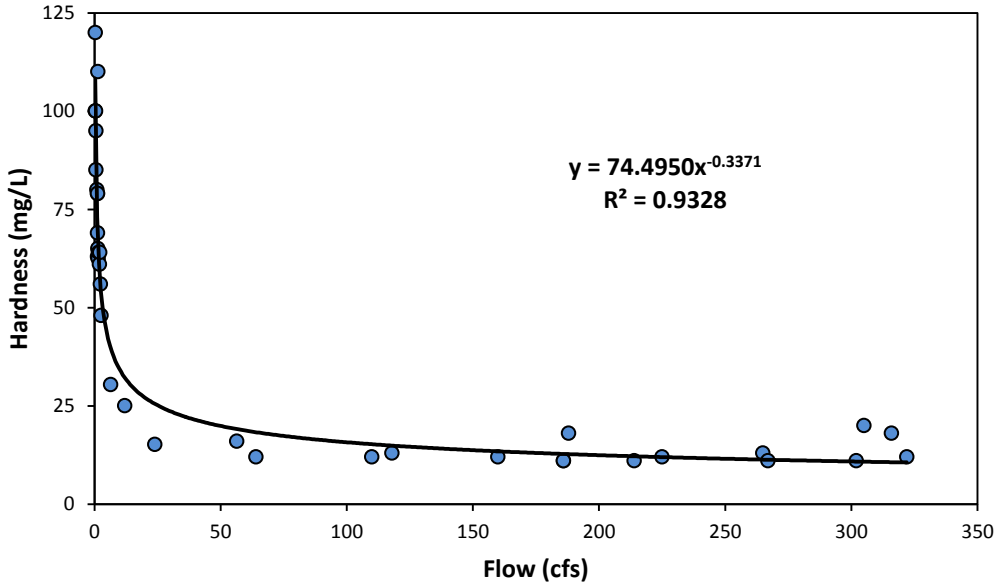
Metals criteria applicable to the full range of hardness concentrations observed in Haggarty Creek and West Fork Battle Creek are presented in **Table 4.** Because hardness concentrations greater than 25 mg/L are not observed in Haggarty Creek, the aquatic life metals criteria at that concentration represent the target loads for Haggarty Creek at all flow levels. However, Cu criteria for West Fork Battle Creek vary with flow and corresponding hardness levels.

Table 4. Aquatic life use metals criteria (TMDL targets) for the range of hardness concentrations observed in Haggarty Creek and West Fork Battle Creek. Values in dissolved concentrations (µg/L).

Water Hardness (mg/L)	Cadmium (Cd)		Copper (Cu)		Silver (Ag)	
	Acute	Chronic	Acute	Chronic	Acute	Chronic
25	0.5	0.09	3.6	2.7	0.3	Not Applicable
50	1.0	0.15	7.0	5.0	1.0	
75	1.5	0.20	10.2	7.0	2.1	
100	2.0	0.25	13.4	9.0	3.4	
125	2.5	0.29	16.6	10.8	5.1	

Figure 14 depicts the relationship between observed flow and water hardness levels in West Fork Battle Creek at the USGS water quality monitoring station. The equation derived from the relationship can be used to compute hardness values, given a flow measurement or estimate is available. Based on the equation, hardness concentrations are predicted to exceed 25 mg/L at flows less than about 25 cfs. Given this prediction, it is reasonable to assume that the Cu criteria for West Fork Battle Creek are the same as those established for Haggarty Creek at flows >25 cfs. During low flow conditions (≤25 cfs), the criteria are less restrictive as hardness concentrations increase as flows decrease. When ambient hardness values exceed 25 mg/L, the Cu criteria that apply to West Fork Battle Creek are calculated from the hardness-dependent equations in **Table 3**.

Figure 14. Relationship between flow and water hardness concentration in West Fork Battle Creek at USGS Station 09253465 (WFBC1).



3.2 EXTENT OF WATER QUALITY IMPAIRMENT

Water quality standards for Cu are consistently exceeded in Haggarty Creek. Although flows in Haggarty Creek provide considerable dilution to the copper-laden mine effluent and further dilution is provided by downstream tributary inflows, Cu concentrations exceed aquatic life use criteria year-round from the mine effluent confluence to the Belvidere Ditch diversion four miles downstream. Regular exceedances of the Cu criteria are observed in West Fork Battle Creek, 11 miles downstream of the mine discharge. Cadmium and Ag standard violations also occur in the HC-WFBC drainage, but on a much less frequent basis than observed for Cu.

Water quality standard exceedances are well-documented from data collected on Haggarty Creek at USGS Station 09253455 above Belvidere Ditch upstream of Highway 70 (HC14) and on West Fork Battle Creek at USGS Station 09253465 at the Battle Creek Campground (WFBC1). Data collected at each station consist of semi-annual measurements made during spring high flow and summer low flow periods. Locations for both stations are shown in **Figure 8**. Standard exceedances are also documented at other water quality monitoring stations established in the HC-WFBC drainage (**Appendix B**).

All Cu concentrations measured over the 16 year period-of-record at HC14 exceeded the acute aquatic life criterion of 3.6 µg/L (25 mg/L hardness). At WFBC1 all Cu concentrations measured during the spring high flow period exceeded the acute criterion (3.6 µg/L), and nearly 50 percent of the values observed during the summer low flow period exceeded the chronic criterion of 2.7 µg/L (25 mg/L hardness). Copper toxicity is moderated in West Fork Battle Creek during the summer low flow period as hardness levels increase with diminishing streamflow.

Only a handful of Cd and Ag standard exceedances in the HC-WFBC drainage are documented. Most of the measured values are near limits of analytical detection that equal or slightly exceed their respective aquatic life use criteria (at 25 mg/L hardness). At the USGS station on Haggarty Creek (HC14), dissolved Cd concentrations of ≤1 µg/L exceeded the acute criterion (0.5 µg/L) twice, in 1993 and 1994, and the chronic criterion (0.09 µg/L) once in 1993. Dissolved Ag concentrations (1-6 µg/L) exceeded the acute criterion (0.5 µg/L) on four separate occasions in 1995, 1996 and 1997. Except for one exceedance of the Ag standard, the observed Cd and Ag exceedances in Haggarty Creek occurred during the summer low flow period.

Two standard exceedances each for Cd and Ag are documented at WFBC1. The dissolved Cd concentrations (0.13 and 1 µg/L) are slightly greater than the acute criterion. Dissolved Ag concentrations of 2 and 3 µg/L measured in 1994 and 1995, both exceeded the acute criterion of 0.3 µg/L. Unlike Haggarty Creek, the Cd and Ag exceedances observed in West Fork Battle Creek occur during the spring high flow period. Given these metals are observed in the two streams during different seasonal flow periods, there is reason to suspect that there may be separate sources of Cd and Ag in the drainage system.

Based on the frequently acute levels of Cu observed in the HC-WFBC drainage, it is considered the primary pollutant of concern in the drainage. The FHM drainage is the primary source of the Cu contamination for both streams. Other minor contributing sources of Cu may include seepage from the tailings rubble outside the portal (**Figure 3**) and soluble inorganic and organic Cu compounds in streambed sediments downstream of the FHM. The FHM drainage waters from the portal and surrounding mine disturbance area combined comprise the waste load allocation of Cu in the HC-WFBC drainage. The load allocation is comprised of natural background levels of Cu. Natural background contributions are considered negligible, based on measured Cu levels ≤2 µg/L in Haggarty Creek above the FHM and its tributaries.

While there is some uncertainty associated with reported low-level concentrations of Cd and Ag and their proximity to analytical detection limits, the possibility that some natural or unknown sources exist in the drainage system cannot be ruled out. Although the data has limitations (sampling frequency, seasonality, sampling/measurement error, etc.), there is no evidence to date to suggest that the FHM drainage is a contributing source of Cd and Ag to Haggarty Creek. Maximum Cd concentrations of 0.1 to 0.2 µg/L are periodically detected in the FHM effluent, but flows in Haggarty Creek provide more than adequate dilution such that detectable levels of the metal are not observed below the effluent. No detectable levels of either metal have been observed in Haggarty Creek or its tributaries upstream of the USGS station at the Belvidere Ditch. At this time the sources of the Cd and Ag measured at the USGS station on Haggarty Creek are unknown.

4.0 TMDL TECHNICAL ANALYSES

This section describes the technical approach and analyses used to develop TMDL target loads and to estimate metal loading in the HC-WFBC drainage. The total allowable metal loads that each waterbody can assimilate without exceeding WQSs are quantified and their available assimilative capacities are apportioned among point, non-point and natural pollutant sources. A MOS factor is incorporated into each TMDL to address uncertainties in the analyses and provide reasonable assurances that WQSs can be attained. Critical conditions of streamflow, seasonal variability, analytical assumptions and other water quality factors are considered.

4.1 TECHNICAL APPROACH

The TMDLs and load estimates for Cu, Cd and Ag are derived from load duration curves (LDCs). Load duration curves are analytical tools used to evaluate the relationship between streamflow and water quality (USEPA 2007, Cleland 2002, Stiles 2001). Given metal concentrations in the HC-WFBC drainage are regulated by changes in streamflow, LDCs are appropriate tools for examining potential loading mechanisms, critical conditions and patterns of water quality impairment.

The LDC is a graphic representation or plot of the amount of a pollutant (load) that a stream transports over its full range of flows. It is an extension of the flow duration curve, which is a cumulative frequency analysis of historic flow data (Leopold 1994). Pollutant loads are calculated by multiplying the concentration of the pollutant by the flow at which the concentration is measured, giving a mass per unit time value (loading rate). From this computation the loading capacity (TMDL target) for a pollutant is expressed in terms of a load by multiplying the water quality criterion (acute and chronic aquatic life concentrations) by the continuum of flows historically observed at a site. Instantaneous loads calculated from ambient measurements or estimates of flow and pollutant concentration data are plotted with the loading capacity curve (TMDL target) to determine compliance with the water quality standard. Ambient load values that lie above the TMDL target represent water quality standard violations (acute or chronic criteria exceedances), whereas those that lie below the curve represent values of compliance. Thus, the ambient load values at various flows can be used to examine the patterns and extent of impairment over the full range of flow conditions observed at a site.

The following sections provide a summary of the technical approach used to develop the Cu, Cd and Ag TMDLS for Haggarty Creek and West Fork Battle Creek.

Flow Duration Curves

Flow duration curves provide the foundation upon which LDCs are built. The flow duration curve is a plot that shows the percentage of time that a specified flow is equaled or exceeded (exceedance frequency) at a stream site. It is typically developed from the full range of mean daily discharge data collected at a stream gaging station, sorted from highest to lowest, and plotted with their corresponding exceedance frequency values. Discharge rate (cfs or gpm) is read on the ordinate (y-axis) and typically presented on a logarithmic scale. The exceedance frequencies, or flow duration intervals, are displayed as percentage values (%) on the abscissa (x-axis). Exceedance values represent the percentage of historical flow observations that exceed a particular flow of interest. The flow duration intervals range from 0 to 100 percent, with zero representing the maximum stream discharge (extreme flood event) on record and 100 representing the minimum (drought conditions). The median flow occurs at a flow exceedance frequency of 50 percent.

Flow duration curves may be developed from at least one year of flow observations, but a multi-year period-of-record is preferable to account for flow variability. To provide a reasonable degree of confidence in estimating flows at a site, at least 10 years of continuous flow data is recommended to encompass intra-annual and seasonal variation. Observations during drought and flood periods are also beneficial to better understand changes in water quality. For this reason, the long-term flow data collected at gaging stations operated by the USGS are ideal.

Because streamflow gaging data does not exist for Haggarty Creek and West Fork Battle Creek, the flow data used in the TMDL analyses are derived from basin area ratio estimation methods (**Appendix A**). The estimates are derived from gaged flow data collected at USGS Station 09253400, Battle Creek near Encampment, WY (**Figure 2**). Battle Creek is located in the watershed adjacent to West Fork Battle Creek and has basin characteristics and a flow regime similar to the impaired waters (**Table 2**). Flow data collected at Battle Creek covers a combined 10-year time period from 1956-1963 and 1985-1988. Although the period-of-record is discontinuous and dated, it is considered to accurately represent the flow regime observed in the HC-WFBC drainage, encompassing years in which the region experienced both drought and above normal precipitation conditions.

The TMDLs presented herein are developed from the estimated flow duration curve data for three water quality monitoring stations in the HC-WFBC drainage- stations HC8 and HC14 on Haggarty Creek and station WFBC1 on West Fork Battle Creek, identified in **Figure 8**.

Load Duration Curves - TMDLs

Load duration curves are produced from the flow duration curve data associated with a stream monitoring station and the water quality criteria of a pollutant. Instead of reading units of discharge on the y-axis of the flow duration curve plot, the units on a LDC plot are expressed as a pollutant load (tons/day). The plot is created by matching load values (flow x concentration) with their corresponding percent (%) exceedance values read on the x-axis. The individual load values are calculated as follows:

$$\textbf{TMDL (tons/day)} = \textbf{WQC} * \textbf{Flow} * C_1 * C_2 * C_3 * C_4$$

Where:

WQC = water quality criterion (acute or chronic concentration) in milligrams per liter (mg/L)

Flow = cubic feet per second (ft^3/s)

C_1 = unit conversion factor of 0.0000022046 pound (lb)/mg

C_2 = unit conversion factor of 0.0005 ton/lb

C_3 = unit conversion factor of 28.31685 L/ft^3

C_4 = unit conversion factor of 86,400 seconds/day

$C_1 * C_2 * C_3 * C_4 = 0.002697$

The LDCs that represent the Cu, Cd and Ag TMDLs for monitoring stations on Haggarty Creek and West Fork Battle Creek are developed from the continuum of flow values generated for each station and the WQC of interest. The individual load values are then adjusted by the appropriate volumetric and time unit conversions to produce a TMDL curve expressed in tons of metal per day, representing the loading capacity for each metal over the entire flow regime at a site.

As described in Section 3, the aquatic life use criteria for metals vary with water hardness concentration. The hardness-dependent equations (**Table 3**) used to derive metals criteria are valid only for hardness values that fall between 25 and 400 mg/L (as $CaCO_3$). In Haggarty Creek, hardness concentrations are observed at levels <25 mg/L. Therefore, all of the hardness-dependent metals criteria that apply to Haggarty Creek are set at the lowest possible levels determined at 25 mg/L hardness (**Table 4**). Based

on this information, the equations used to derive the acute and chronic aquatic life use targets for Cu, Cd and Ag at all stations on Haggarty Creek are simply expressed as follows:

$$\mathbf{Cu_{chronic}\ TMDL\ (tons/day) = 0.0027\ mg/L*Flow*0.002697}$$

$$\mathbf{Cu_{acute}\ TMDL\ (tons/day) = 0.0036\ mg/L*Flow*0.002697}$$

$$\mathbf{Cd_{chronic}\ TMDL\ (tons/day) = 0.000094\ mg/L*Flow*0.002697}$$

$$\mathbf{Cd_{acute}\ TMDL\ (tons/day) = 0.0005\ mg/L*Flow*0.002697}$$

$$\mathbf{Ag_{acute}\ TMDL\ (tons/day) = 0.0003\ mg/L*Flow*0.002697}$$

As described in Section 3.1, the metals criteria in West Fork Battle Creek vary over its flow regime due to changes in water hardness (**Figure 14**). Based on the relationship between observed hardness and flow in West Fork Battle Creek, hardness values greater than 25 mg/L are not observed until flows drop below 25 cfs. Given an estimated or measured flow value in cfs, hardness values can be predicted at the USGS monitoring station (WFBC1) from the following equation:

$$\mathbf{Water\ Hardness\ (mg/L\ as\ CaCO_3) = 74.4950*Flow^{-0.3371}}$$

The predicted hardness values are used to derive the acute and chronic aquatic life use metals criteria for WFBC1 using the hardness-dependent equations listed in **Table 3**. For the copper LDC analyses that apply to West Fork Battle Creek, the hardness-dependent equations are employed for streamflow values less than 25 cfs. At this flow stage water hardness levels greater than 25 mg/L are observed, requiring adjustments in the criteria. The array of Cu criteria generated from these calculations are then multiplied by their corresponding flow values and conversion factor to produce the TMDL target loads used to produce the LDC at WFBC1. For flows greater than the 25 cfs threshold value, the same equations used to derive the acute and chronic aquatic life use Cu targets for Haggarty Creek are applied in generating the target loads at those flows for West Fork Battle Creek.

4.2 MARGIN OF SAFETY

Federal regulations [40 CFR §130.7(c) (1)] require that TMDLs include a MOS. The MOS is a conservative measure incorporated into the TMDL equation that is intended to account for the uncertainty in the relationship between pollutant loads and water quality of the receiving water body. It can be provided explicitly by reserving a portion of loading capacity and/or implicitly through analytical assumptions. The TMDLs presented herein include both explicit and implicit MOS measures.

An explicit MOS is provided for each metal pollutant in the HC-WFBC drainage. Due to the high degree of uncertainty associated with the metal loading estimates and the restrictive water quality targets that must be achieved to protect designated uses, a conservative MOS is incorporated into each TMDL. The explicit MOS for each metal amounts to 20 percent of their respective TMDL target loads. Thus, the chronic aquatic life use criterion target concentration of 2.74 µg/L established for Cu in Haggarty Creek is essentially reduced to 2.19 µg/L. Similar MOS factors are applied to the metal target loads at all water quality monitoring stations. The MOS load duration curves are depicted as green dashed lines in the plots generated for each metal. The MOS measures for Cu and Cd are represented by the chronic criterion since it is the most restrictive value that must be met to achieve WQSs. For Ag, the MOS is applied only to the acute criterion. The net effect of the explicit MOS is that the assimilative capacity of the watershed is reduced, representing a total loading capacity that is 80 percent of the loading capacity based on the water quality targets identified in Section 3. The MOS load at any given percent flow exceedance in the HC-WFBC drainage, therefore, can be defined as the difference in loading between the TMDL and the TMDL reduced by 20 percent.

The implicit MOS elements incorporated into each TMDL consist of several conservative measures. Those measures include:

- Flow estimates that account for temporal variability and the error associated with flow measurements in streams with cobble/boulder beds,
- The use of dissolved instead of total recoverable metal criteria to establish TMDL target loads,
- The use of upper 80 to 95 percent prediction limits to establish existing Cu loads,
- The use of the 90th percentile of observed Cd and Ag loads from the critical loading condition to calculate load reduction estimates,
- Selection of error-adjusted load reduction percentage values identified from critical loading conditions to achieve TMDL targets over the entire flow regime, and
- Natural background Cu concentrations and loads for HC8 established from the 95th percentile of all measured values, which is about the same as the maximum value measured in the tributaries to Haggarty Creek and above the FHM.

In using conservative analytical assumptions, load reduction estimates and a 20 percent explicit MOS, several protective measures are built into the TMDLs to ensure that WQSs can be achieved and maintained.

4.3 EXISTING METAL LOADING AND DEPARTURES FROM TARGET LOADS

Load duration curves are developed for Cu at two water quality monitoring stations on Haggarty Creek (HC8 and HC14) and one station on West Fork Battle Creek (WFBC1). The locations of each station are shown in **Figure 8**. These stations have sufficient water quality data available to develop the LDCs and are positioned within the watershed such that changes in metal loads can be evaluated. As described previously, HC14 and WFBC1 correspond to USGS monitoring stations where instantaneous flow and water quality data was collected on a semi-annual basis from 1993 to 2008.

Load duration curves for Cd and Ag are developed only for HC14 on Haggarty Creek, the location associated with the original §303(d) listing for these metals. Because total recoverable concentrations were not collected at the station, the LDCs for Cd and Ag are derived from dissolved concentrations with the assumption that they closely approximate total values. A majority of the observed (ambient) load values for both metals are calculated from non-detect values that are reduced to 50 percent of their reported values. Several non-detect values are excluded from the analyses because their reported values exceed the water quality criterion of each metal.

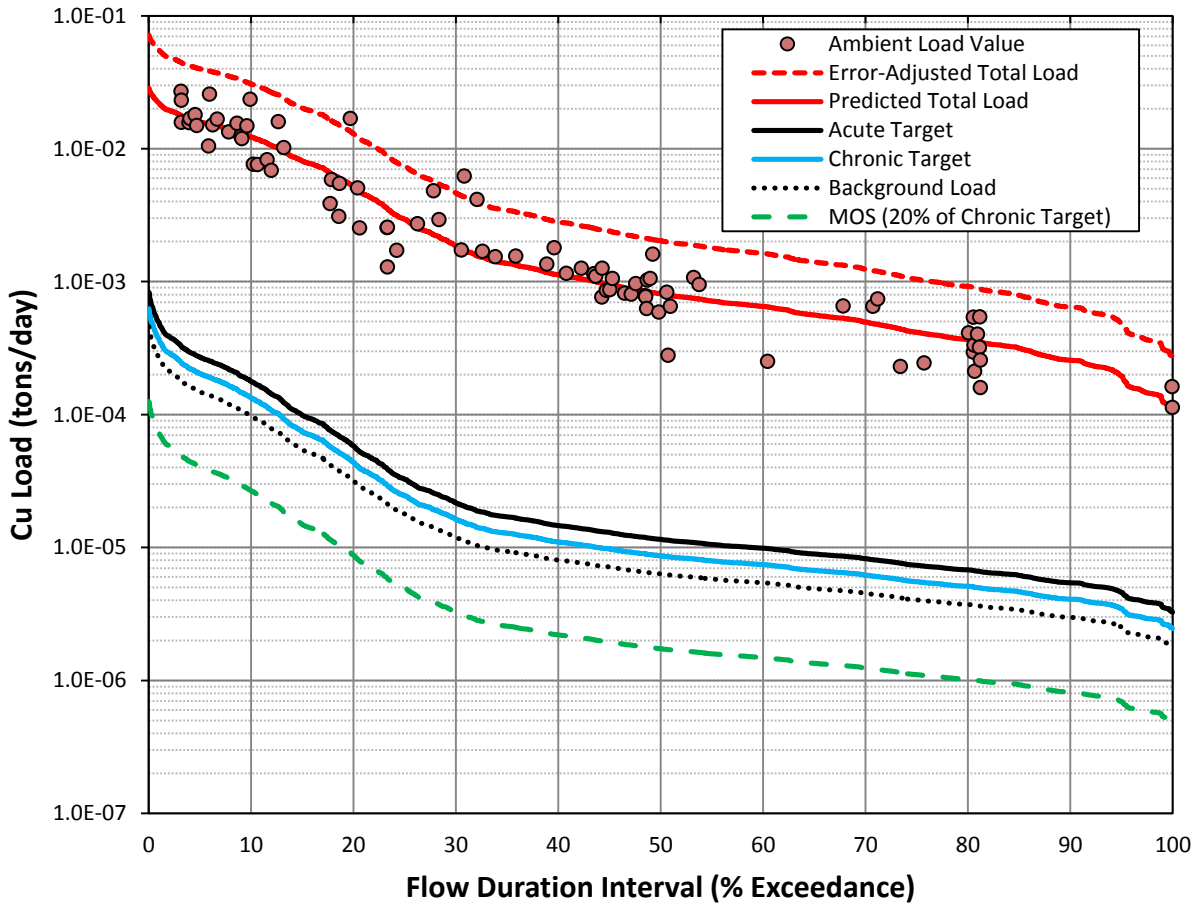
The original data used to develop the LDCs at each station are provided in **Appendices A and B**. All data used to produce the LDCs for Cu, Cd, and Ag are available upon request.

Copper Load Duration Curves

Copper LDCs for HC8 on Haggarty Creek are depicted in **Figure 15**. Two water quality criterion targets are shown; one each derived from the acute and chronic dissolved Cu criteria. The two curves represent the total quantity of Cu (loading capacity, or TMDL target in tons/day) that the stream at this location can assimilate without violating water quality criteria. Included in the plot are LDCs that represent the MOS and background Cu loads. The green dashed line that lies below the acute and chronic target curves represents the MOS load which, as described in Section 4.3, is set at 20 percent of the chronic criterion. The black dotted line that lies above the MOS curve represents the natural background Cu load derived from an estimated concentration of 2 µg/L. Also shown are ambient load values calculated

from observed Cu concentration and flow data. These values represent the existing, instantaneous Cu loads observed at the station from 1993 to 2008. The predicted LDC (solid red line) fitted through the ambient load values represents the estimated Cu load over the entire flow regime at HC8.

Figure 15. **Copper LDCs and ambient load values for station HC8 on Haggarty Creek below the FHM.**

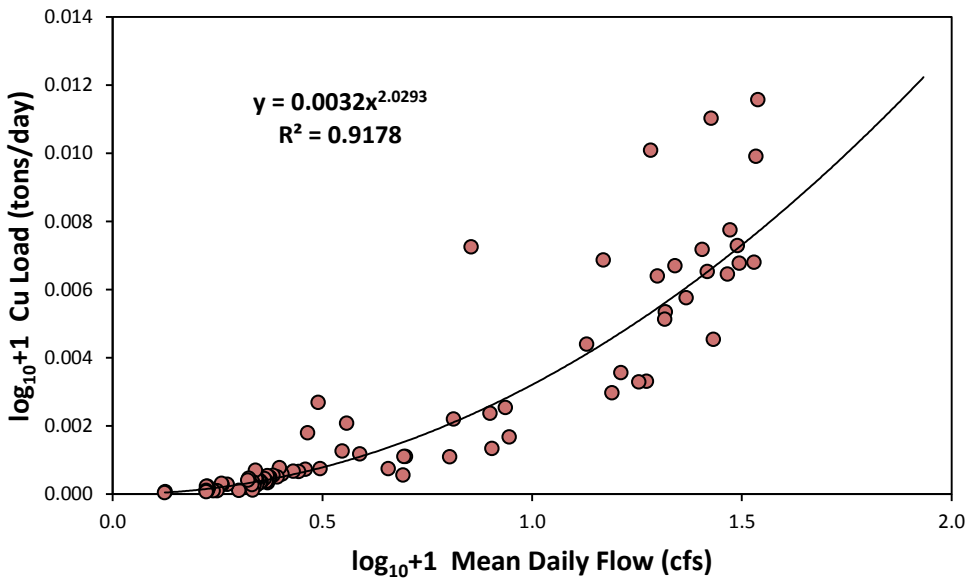


The predicted curve is generated from a power curve model developed from $\log_{10}(x+1)$ transformations of the paired ambient Cu load and flow data. The transformed data and power curve equation used to back-calculate the predicted load values are shown in **Figure 16**. The error-adjusted LDC (red dashed line) above the predicted LDC is used to estimate the percent load reduction considered necessary to ensure that water quality standards are achieved. The difference between the predicted and error-adjusted load values (calculated as a percent reduction) represents an additional MOS factor.

The error-adjusted LDC is generated from an adjustment factor applied to the predicted load values. The adjustment factor originates from a linear regression relationship between the paired observed and

predicted load values (**Figure 17**). Since much of the variability in the observed data appears to lie between the 0-40 percent flow exceedance intervals of the LDC (**Figure 15**), only paired data bounded by this region are used in the regression. The adjustment factor is obtained from the 95 percent predicted limits of the linear regression, depicted by the red dashed lines. The unit difference between the 95 percent prediction limits and the regression line fitted through the transformed data is used to calculate the adjustment factor. Based on this model, 0.0035 units separate the regression line and prediction limits. This value converted back to a load value (0.0081 tons/day) is added to the predicted load associated with the 20 percent flow exceedance frequency (i.e., mid-point of the 0 to 40 percent intervals). The percent difference between the predicted and error-adjusted predicted values at this flow exceedance frequency represents the adjustment factor applied to all predicted values to generate the error-adjusted LDC shown in **Figure 15**.

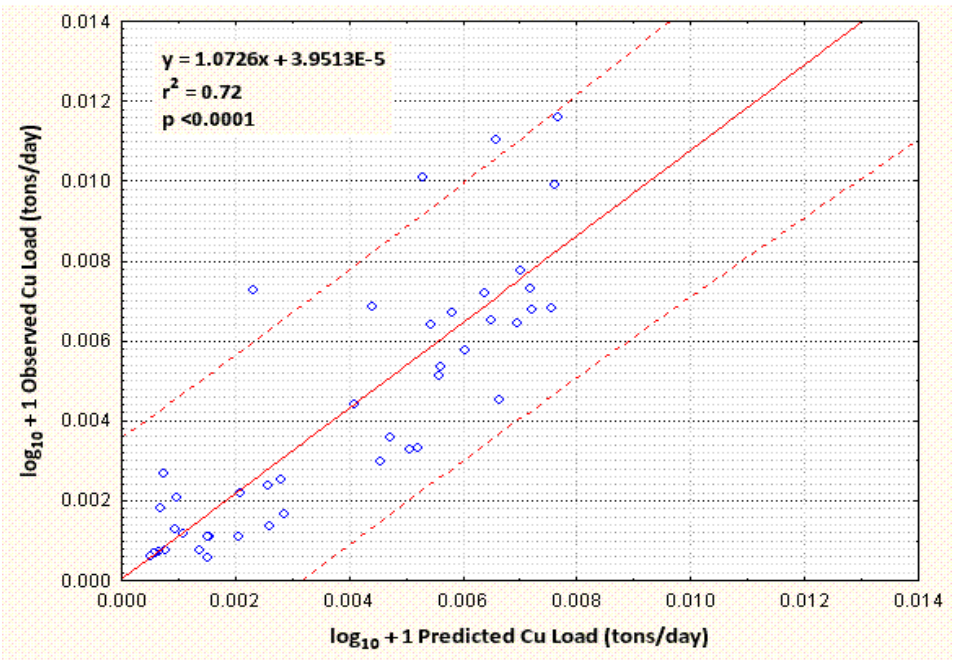
Figure 16. **Power curve model developed from log (x+1) transformed flow and copper load data for station HC8 on Haggarty Creek below the FHM.**



From the LDCs shown in **Figure 15**, it is apparent that a considerable amount of the Cu load at HC8 must be reduced to attain the aquatic life use support goal. Percent load reduction values needed to achieve water quality targets for every 5th flow exceedance interval of the LDC are listed in **Table 5**. Based on the predicted LDC, the quantity of Cu at station HC8 is about two-orders of magnitude greater than the chronic TMDL target load. Using the predicted LDC as a reference, the Cu load would need to be

reduced by about 98 to 99 percent to achieve the chronic TMDL target load. The greatest estimated load reduction is observed between the 20th and 25th flow exceedance intervals. It is noteworthy to mention that although the error-adjusted load is about 2.5-times greater than the predicted load for any given flow exceedance value, the percent load reduction estimated from the error-adjusted LDC is not much greater than that calculated from the predicted LDC. The relatively small differences between the two percent load reduction estimates reflect the magnitude of the Cu load that exists in Haggarty Creek and the mitigation efforts needed to meet WQSs.

Figure 17. Linear regression of log (x+1) transformed observed and predicted Cu load data for station HC8 on Haggarty Creek below the FHM. Red dashed lines represent 95 percent prediction limits.



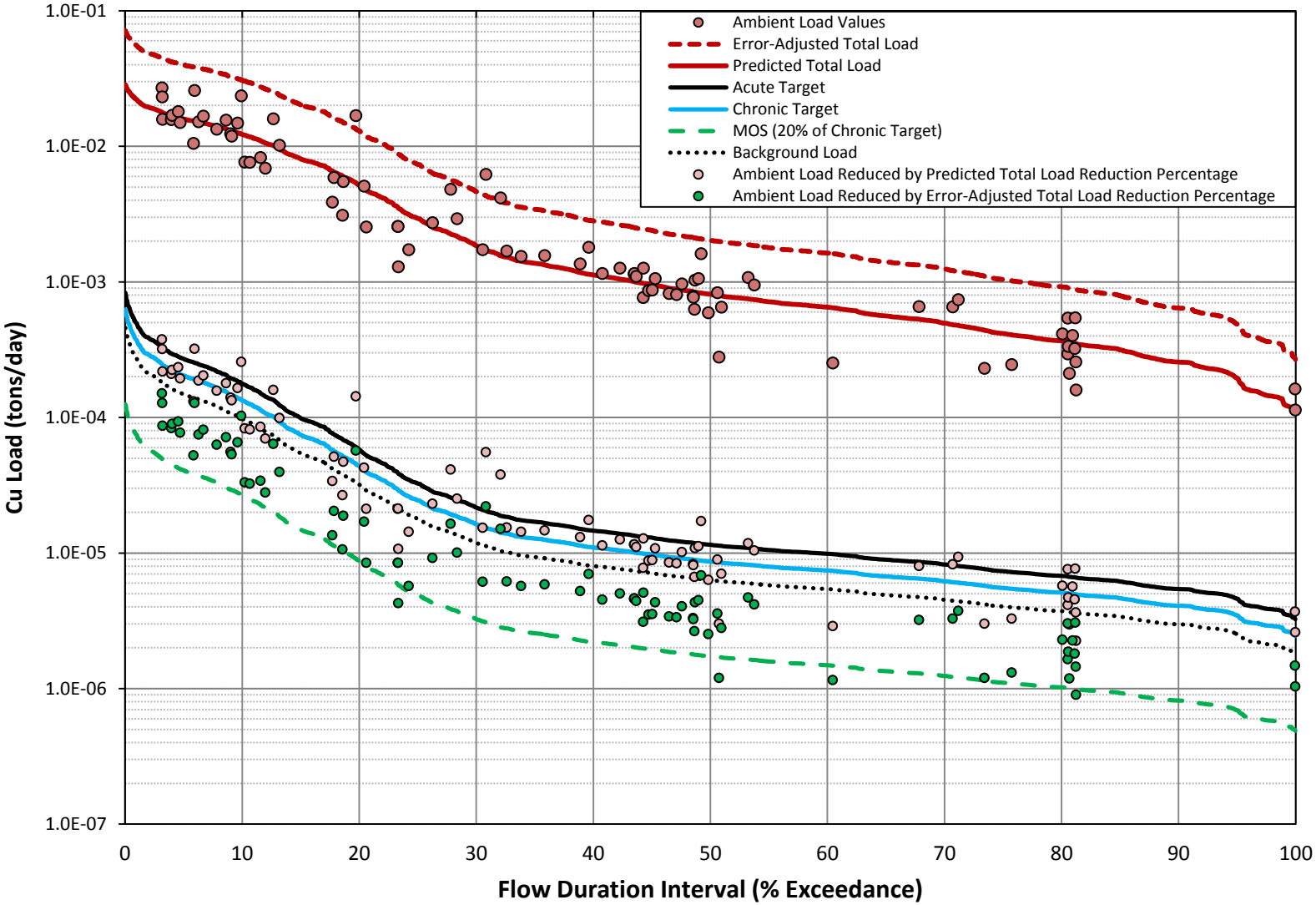
To determine the amount of Cu load reduction considered necessary to achieve TMDL target loads at HC8, all ambient load values shown in Figure 15 are reduced by the percent load reduction values calculated from their corresponding predicted and error-adjusted load estimates. **Figure 18** shows where each 'reduced' ambient load value lies with respect to water quality targets. Based on the predicted Cu load reduction estimates, it is apparent that much of the reduced ambient load exceeds both the acute and chronic TMDL target loads. Conversely, the reduced ambient load generated from the error-adjusted percent load reduction calculations indicate that all but one or two of the reduced values fall below TMDL target loads. While this amount of load reduction may seem overly conservative, it provides a greater degree of certainty that WQSs can be achieved during excessively

high loading periods. In addition, it comes closer to satisfying the requirement that the water quality criteria for Cu not be exceeded more than once in a three year time period as explained in Section 2.3. Considering that over 97 percent of the predicted Cu load for all flow conditions must be reduced just to achieve the acute target level (**Table 5**), the additional one to two percent reduction calculated from the error-adjusted load estimates is comparatively insignificant, and results in achieving the desired chronic TMDL target.

Table 5. **Copper load reduction (%) estimates calculated from predicted and error-adjusted LDCs for Station HC8 on Haggarty Creek below FHM. Data are provided for every 5th flow exceedance interval.**

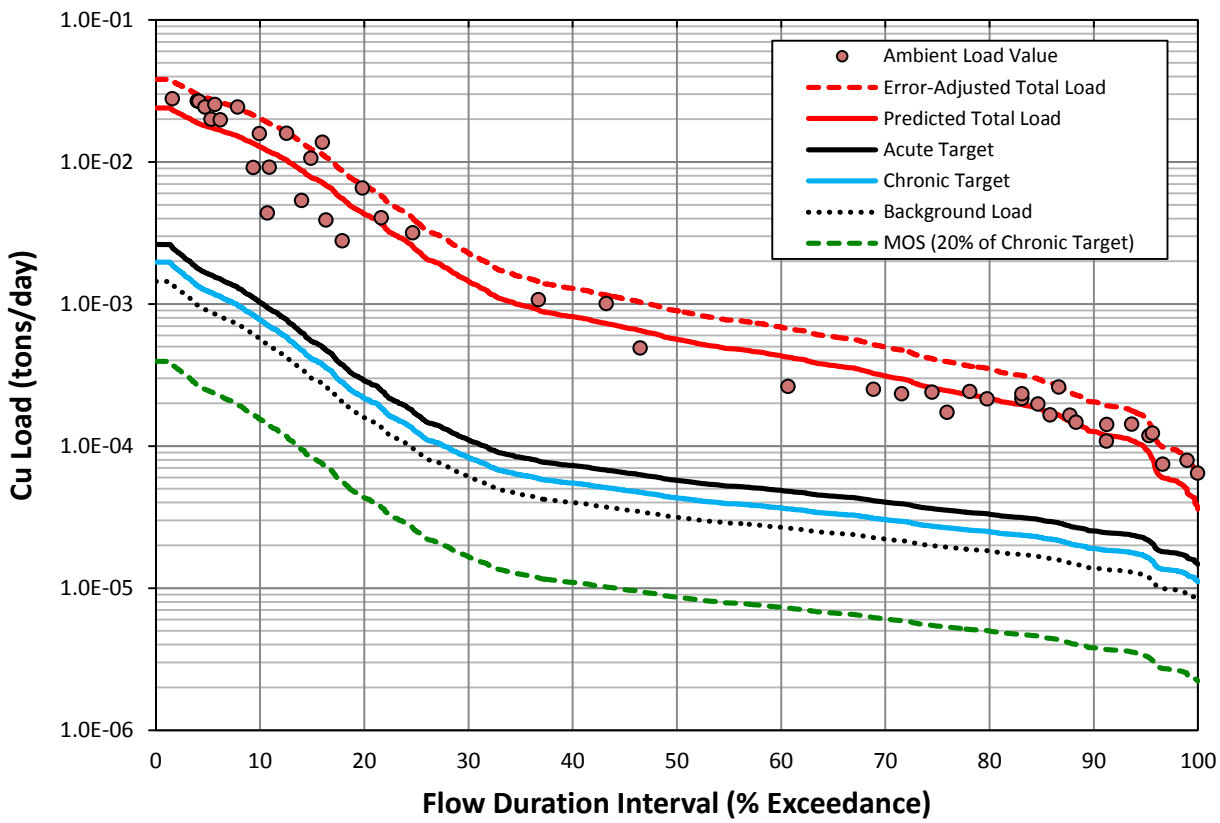
Mean Daily Flow (cfs)	Flow Exceedance Frequency (%)	Predicted Reduction Required to Achieve Acute Target Load	Predicted Reduction Required to Achieve Chronic Target Load	Error-Adjusted Reduction Required to Achieve Chronic Target Load
85	0	97.1	97.8	99.3
28	5	98.3	98.7	99.6
18	10	98.6	98.9	99.7
10	15	98.8	99.1	99.7
5.9	20	98.9	99.2	99.7
3.3	25	98.9	99.2	99.7
2.2	30	98.8	99.1	99.7
1.7	35	98.8	99.1	99.7
1.5	40	98.7	99.0	99.7
1.3	45	98.6	99.0	99.7
1.2	50	98.6	98.9	99.7
1.1	55	98.5	98.9	99.6
1.0	60	98.5	98.9	99.6
0.91	65	98.4	98.8	99.6
0.84	70	98.3	98.8	99.6
0.75	75	98.2	98.7	99.6
0.69	80	98.2	98.6	99.6
0.63	85	98.0	98.5	99.5
0.55	90	97.9	98.4	99.5
0.47	95	97.6	98.2	99.4
0.33	100	97.0	97.7	99.3

Figure 18. Ambient copper load reduction projections based on two load reduction scenarios and associated LDCs for station HC8 on Haggarty Creek below the FHM.



Copper load duration curves developed for HC14 at the USGS Station on Haggarty Creek and WFBC1 on West Fork Battle Creek are shown in **Figures 19 and 20**, respectively. The ambient load values shown in each figure are derived from instantaneous discharge and dissolved Cu data collected at each station from 1993 to 2008. Dissolved Cu concentrations are converted to total-recoverable values using a power curve relationship developed from the available paired dissolved and total concentration data collected at HC14 [$Cu_{Total} = 1.1076(Cu_{Diss}^{0.9935})$; r^2=0.99]. This relationship is assumed to be the same at WFBC1.

Figure 19. Copper LDCs and ambient load values for station HC14 on Haggarty Creek.



For flows that occur less than 50 percent of the time (>5.8 cfs), the ambient Cu load at HC14 (**Figure 19**) is about one-order of magnitude less than the load observed at HC8. Additional reductions in Cu load are observed at lower flows (>50 percent exceedance frequency, <5.8 cfs), but nonetheless, all ambient load values exceed water quality targets by a considerable amount. Much of the Cu attenuation is attributed to dilution, but some likely precipitates and settles out of solution in the four-mile distance between the stations. The predicted and error-adjusted LDCs for HC14 are generated from the same

calculation procedure described for HC8, except that the 90 percent prediction limits are used to derive the adjustment factor.

While the predicted load at HC14 is less than that at HC8, a substantial amount of load reduction is still required to achieve water quality targets. Based on the predicted LDC, Cu loads at HC14 would need to be reduced from about 75 percent at the lowest flow levels to 95 percent at the higher flows to achieve the chronic TMDL target (**Table 6**). Based on the more conservative error-adjusted load reduction calculations, about 84 to 97 percent of the existing Cu load over the entire flow regime at HC14 would need to be reduced to achieve the TMDL target.

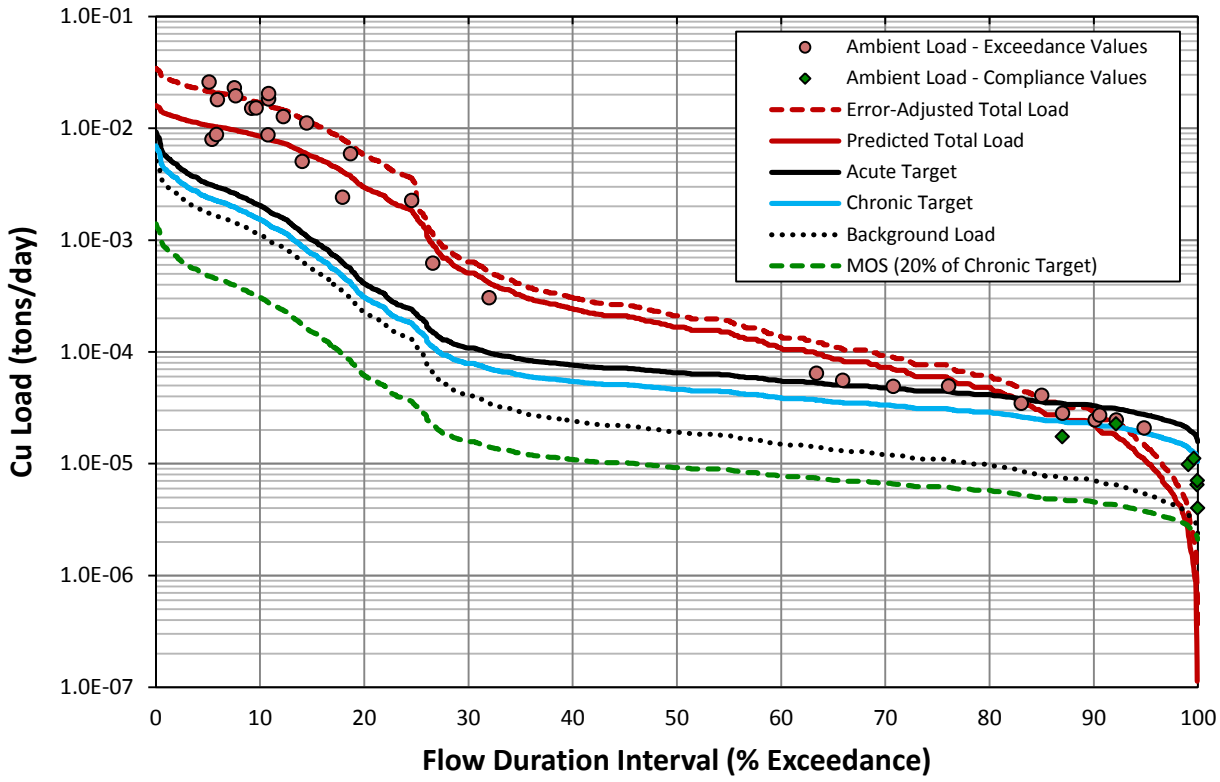
Table 6. Copper load reduction (%) estimates calculated from predicted and error-adjusted LDCs for station HC14 on Haggarty Creek. Data are provided for every 5th flow exceedance interval.

Mean Daily Flow (cfs)	Flow Exceedance Frequency (%)	Predicted Reduction Required to Achieve Acute Cu Target Load	Predicted Reduction Required to Achieve Chronic Cu Target Load	Error-Adjusted Reduction Required to Achieve Chronic Cu Target Load
267	0	89.7	92.2	95.0
167	5	91.2	93.4	95.8
105	10	92.3	94.2	96.3
56	15	93.2	94.9	96.7
29	20	93.5	95.1	96.9
17	25	93.3	95.0	96.8
11	30	92.7	94.5	96.4
8.5	35	91.9	93.9	96.1
7.4	40	91.5	93.6	95.9
6.6	45	91.0	93.2	95.6
5.8	50	90.4	92.8	95.3
5.3	55	89.8	92.3	95.1
5.0	60	89.4	92.0	94.9
4.5	65	88.7	91.5	94.5
4.1	70	87.9	90.9	94.2
3.7	75	86.8	90.1	93.6
3.4	80	85.9	89.4	93.2
3.1	85	84.7	88.5	92.6
2.6	90	82.0	86.4	91.3
2.2	95	79.3	84.4	90.0
1.5	100	66.7	74.9	83.9

The total Cu load in West Fork Battle Creek at WFBC1 is less than that observed in Haggarty Creek at HC14. The predicted LDC shown in **Figure 20** indicates that during high flow conditions the Cu load at WFBC1 is substantially greater than the desired target load, but as flows recede to less than 20 cfs (25 percent flow exceedance interval) the load diminishes considerably. This reduction is largely due to the

flow withdrawn from Haggarty Creek into the Belvidere Ditch following the peak runoff period. Further reductions in streamflow and Cu load become more apparent in West Fork Battle Creek as a greater proportion of Haggarty Creek's flow is diverted for irrigation use.

Figure 20. Copper LDCs and ambient load values for station WFBC1 on West Fork Battle Creek.



Also apparent in **Figure 20** is that the degree of separation between the background load and target load increases as flows recede (at the 25 percent flow exceedance interval) and water hardness concentrations increase. The net effect of the flow recession results in less restrictive water quality targets (i.e., water quality criteria increase with increases in hardness). The increasing 'gap' between the background Cu load and TMDL target load values represents increases in the available assimilative capacity (i.e., the amount of Cu that may be added without exceeding water quality criteria). In addition to the increases in assimilative capacity, the 'gaps' between the existing Cu load and the water quality targets decrease as flows recede. For flows that occur more than about 90 percent of the time (<1.31 cfs), much of the observed Cu load at WFBC1 do not exceed water quality criteria (shown as green dots in **Figure 20**).

The predicted Cu load at WFBC1 (**Figure 20)** decreases considerably during low flow periods (<20 cfs, >25 percent exceedance frequency). For this reason, the error-adjusted LDC is developed from two different adjustment factors. One adjustment factor is applied to predicted load values that lie within the high flow region, bounded by the 0 to 25 percent exceedance intervals. The other factor is applied to predicted values bounded by the 25 to 100 percent exceedance intervals. The adjustment factor applied to the high flow predicted values is derived from the 95 percent prediction limits of the observed vs. predicted linear regression relationship. For predicted load values associated with lesser flows (>25 percent exceedance frequency), the adjustment factor is derived from the 80 percent prediction limits. The resultant error-adjusted LDC is considered to provide more accurate load reduction estimates compared to a single error-adjustment applied over the highly variable flow regime. Using the error-adjusted LDC as a reference, about 82 to 95 percent of the Cu load at WFBC1 would need to be reduced during high flow conditions (<25th flow exceedance interval) to achieve the TMDL target (**Table 7**). For lower flows (25th to 90th flow exceedance intervals), load reduction requirements range from about 37 percent to 92 percent. No load reduction would be required during extreme low flow conditions (< 1 cfs or >95 percent flow exceedance).

Table 7. Copper load reduction (%) estimates calculated from predicted and error-adjusted LDCs for station WFBC1 on West Fork Battle Creek. Data are provided for every 5th flow exceedance interval.

Mean Daily Flow (cfs)	Flow Exceedance Frequency (%)	Predicted Reduction Required to Achieve Acute Cu Target Load	Predicted Reduction Required to Achieve Chronic Cu Target Load	Error-Adjusted Reduction Required to Achieve Chronic Cu Target Load
945	0	55.9	66.8	82.3
324	5	74.3	80.6	89.7
207	10	78.8	84.1	91.5
102	15	83.8	87.8	93.5
42	20	87.2	90.3	94.8
21	25	87.3	90.5	92.3
7.5	30	80.2	85.6	88.4
5.4	35	75.3	82.2	85.6
4.5	40	71.5	79.6	83.5
4.1	45	69.2	78.0	82.2
3.5	50	65.0	75.1	79.9
3.3	55	62.8	73.7	78.7
2.8	60	55.3	68.5	74.5
2.4	65	49.1	64.2	71.0
2.2	70	43.8	60.6	68.1
2.0	75	37.1	56.1	64.4
1.8	80	28.4	50.1	59.6
1.5	85	4.3	33.8	46.4
1.3	90	0	22.1	36.9
1.0	95	0	0	5.1
0.44	100	0	0	0

Reasonable Assurance

While the error-adjusted Cu waste load is a good, conservative predictor of Cu loads, the question needs to be asked whether these load reductions that are called for would actually bring the stream into compliance with WQSs. The following example examines the resultant load from applying error-adjusted waste load reduction estimates to observed loads, and whether or not that load would meet WQSs further downstream at HC14.

Of all the observed Cu load values at HC8 (**Figure 18**), the value requiring the greatest load reduction lies at the 30.83 percent flow exceedance interval. The flow rate and Cu concentration used to calculate that load (0.00621 ton/day) are 2.09 cfs and 1.101 mg/L, respectively. The error-adjusted load reduction estimate corresponding to that flow is 99.64 percent. Reduced by this amount, the resultant ambient load amounts to 0.0000221 ton/day (Cu concentration = 0.00397 mg/L). Using a simple mass-balance calculation, a determination can be made as to whether this reduced load at HC8 equates to a water quality standard violation at HC14. The mass-balance equation is expressed as follows:

$$QrCr = QsCs + QbCb$$

Where,
QrCr = Receiving water flow (Qr) x concentration (Cr) = Cu load in ton/day at HC14
QsCs = Upstream Cu load in ton/day at HC8
QbCb= Background Cu load in ton/day (contributions from tributaries and other drainage inflows)

Based on information provided from the example, the following is known:
Qr = 10.71 cfs (flow associated with 30.83 percent flow exceedance interval at HC14)
Qs = 2.09 cfs
Cs = 0.00397mg/L
Qb = 8.62 cfs (difference between Qr and Qb)
Cb = 0.0005 mg/L (maximum reported non-detect value from all tributary samples reduced by 50%)

To solve for Cr, the equation is rearranged to:

$$Cr = (QsCs + QbCb) / Qr$$

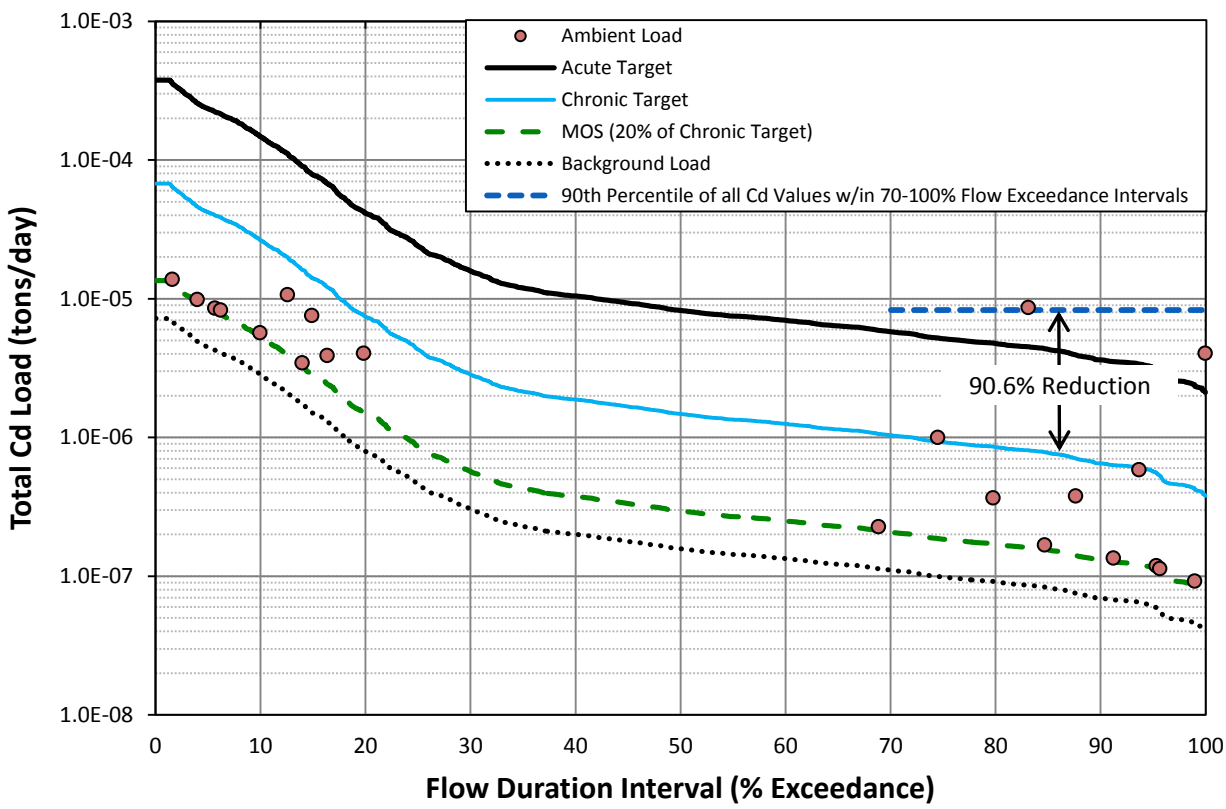
Based on this equation, the resultant Cu concentration observed at HC14 following the load reduction described above is 0.00118 mg/L or 1.18 µg/L. This concentration is less than the chronic criterion of 2.74 µg/L. Assuming this level of Cu reduction can be achieved at HC8, it stands to reason that WQSs would be met further downstream in the HC-WFBC drainage.

Cadmium Load Duration Curves

Cadmium (Cd) LDCs developed for HC14 are shown in **Figure 21**. Similar to the LDCs plotted for Cu, two water quality criterion targets are shown- one each derived from the acute and chronic dissolved Cd

criteria of 0.5 µg/L and 0.09 µg/L, respectively. The TMDL target load, represented by the solid blue line, is derived from the chronic criterion concentration. The background Cd load is calculated from an assumed total concentration of 0.01 µg/L (derived from the lowest measured concentration at HC14 reduced by 50 percent). Ambient load values are calculated from the paired concentration and flow data collected at HC14. Because data for mid-range flows are lacking and most of the ambient load values shown in the plot are derived from transformed, non-detect concentrations, predicted LDCs are not generated for the station.

Figure 21. Cadmium LDCs and ambient load values for station HC14 on Haggarty Creek.



Only three of the ambient Cd load values shown in **Figure 21** exceed water quality criteria. All three values lie within the low flow range of the LDC, between the 70 and 100 percent flow exceedance intervals (flows less than 4.1 cfs). The greatest load value, calculated from the maximum Cd concentration (1 µg/L) measured at HC14, lies near the 85 percent flow exceedance interval. No water quality exceedances are observed in the high flow region of the plot. Based on the existing load, it is apparent that Cd load reduction efforts should focus on the low flow period.

Instead of using a predicted LDC to estimate the percent load reduction required to achieve the Cd TMDL target, load reduction estimates are derived from the 90th percentile statistic calculated from all the observed Cd concentrations that lie between the 70 and 100 percent flow exceedance intervals (**Figure 21**). The 90th percentile Cd concentration calculated from these data is multiplied by the flow rate at the mid-point of the intervals (in this case, the 85percent flow exceedance interval) to calculate an existing load value. This single load value is assumed to represent the existing Cd load over the entire low flow regime. The existing load is then used to estimate the load reduction required to achieve the TMDL target load.

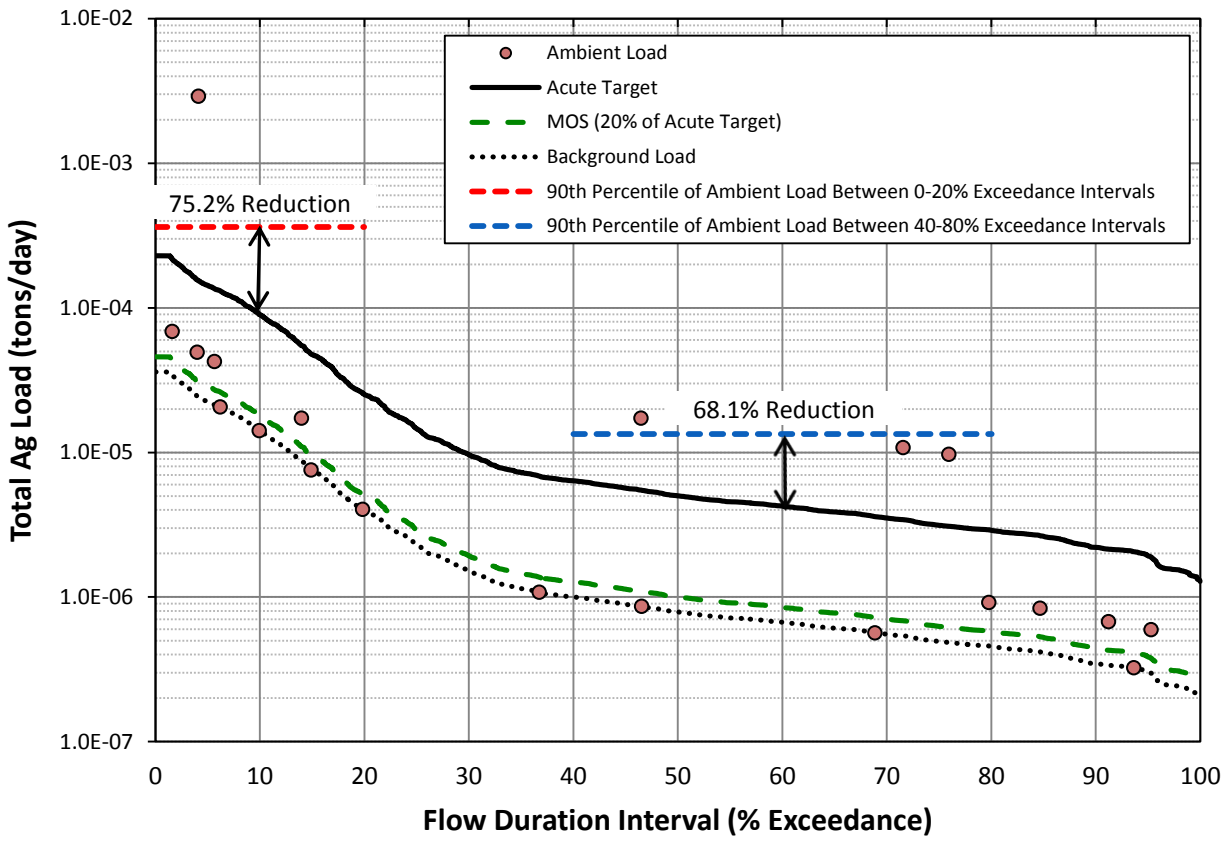
The 90th percentile calculated from all the Cd concentrations observed between the 70 and 100 percent flow exceedance intervals at HC14 is 0.1 µg/L. The estimated mean daily flow at the 85 percent flow exceedance interval is 3.1 cfs. Based on these data the existing Cd load, depicted by the blue dashed line in **Figure 21**, amounts to 8.27E-6 ton/day. At this rate, the existing Cd load observed during the low flow period would need to be reduced 90.6 percent (7.50E-6 ton/day) to achieve the TMDL target load of 7.75E-7 ton/day.

Silver Load Duration Curves

Silver LDCs developed for HC14 are shown in **Figure 22**. All but four observed values are derived from non-detect data (reported values of ≤0.1 µg/L reduced by 50 percent). Since a chronic criterion does not exist for Ag, the water quality target is represented by the acute criterion set at 0.3 µg/L. The MOS LDC is set at 20 percent of the acute criterion load. The background Ag load is derived from an assumed total concentration of 0.05 µg/L, determined from the non-detect concentrations reported for samples collected in upstream tributaries reduced by 50 percent.

All four of the Ag load values measured at HC14 exceeds the acute TMDL target (**Figure 22**). The greatest ambient load value (derived from a concentration of 6 µg/L) lies within the high flow range of the LDC near the 5th percentile. The lesser load exceedances lie between the 40 and 80 percent exceedance intervals, characterized as mid-range flows. Because there appears to be two separate critical loading rates for Ag at HC14, two load reduction estimates are provided. One estimate is calculated from load values that lie within the high flow region of the LDC, between the 0 and 20 percent exceedance intervals, while the other is calculated from values in the mid-range flow region. The estimates are based on the same calculation procedures described for Cd.

Figure 22. Silver load duration curves and ambient load values for station HC14 on Haggarty Creek.



The Ag load reduction estimates for the high and mid-range flow regions are presented in **Table 8**. The flow rates and 90th percentile statistics of the Ag concentrations and load values corresponding to the flow exceedance interval at the mid-point of each critical hydrologic region are included in the table. The existing Ag load in the high flow (red dashed line) and mid-range flow (blue dashed line) regions **(Figure 22)** would need to be reduced by 75.2 and 68.2 percent, respectively, to achieve TMDL target loading rates.

Table 8. Silver load reduction estimates for high flow and mid-range flow conditions at station HC14 on Haggarty Creek.

Hydrologic Region (%Exceedance)	Mean Daily Flow (cfs)	90th Percentile Concentration (µg/L)	90th Percentile Load Estimate (ton/day)	TMDL Acute Target Load (ton/day)	Load Reduction Required to Achieve TMDL Target	
					Percent (%)	ton/day
High Flows (0 - 20%)	105	1.28	3.62E-04	8.98E-05	75.2	2.72E-04
Mid-Range Flows (40 - 80%)	5	1.00	1.34E-05	4.26E-06	68.2	9.12E-06

4.4 CRITICAL CONDITIONS

EPA regulations and 40 CFR 130.7(c)(1) require that TMDLs take into account critical conditions to ensure established pollutant load allocations will achieve WQSs. The critical condition is considered generally to be a time period in which a waterbody is subject to the greatest potential adverse impact(s) resulting from the interaction of a pollutant with the chemical, physical and/or biological characteristics of the waterbody. The intent of this requirement is to ensure that the water quality of a waterbody is protected when its uses are most vulnerable to pollutant loading and other perturbations.

The critical conditions for the TMDLs described in this document are identified by comparing the error-adjusted LDCs developed for each metal pollutant to their respective TMDL target loads. The critical condition corresponds to the greatest difference between the TMDL target and error-adjusted load values generated for each station. Percent Cu load reduction estimates relative to every 5th flow exceedance interval for each station are summarized in **Tables 5, 6, and 7**. Flow rates corresponding to the flow exceedance interval at which the critical condition occurs are used to identify when those flows are observed on an annual basis (i.e., the annual hydrograph).

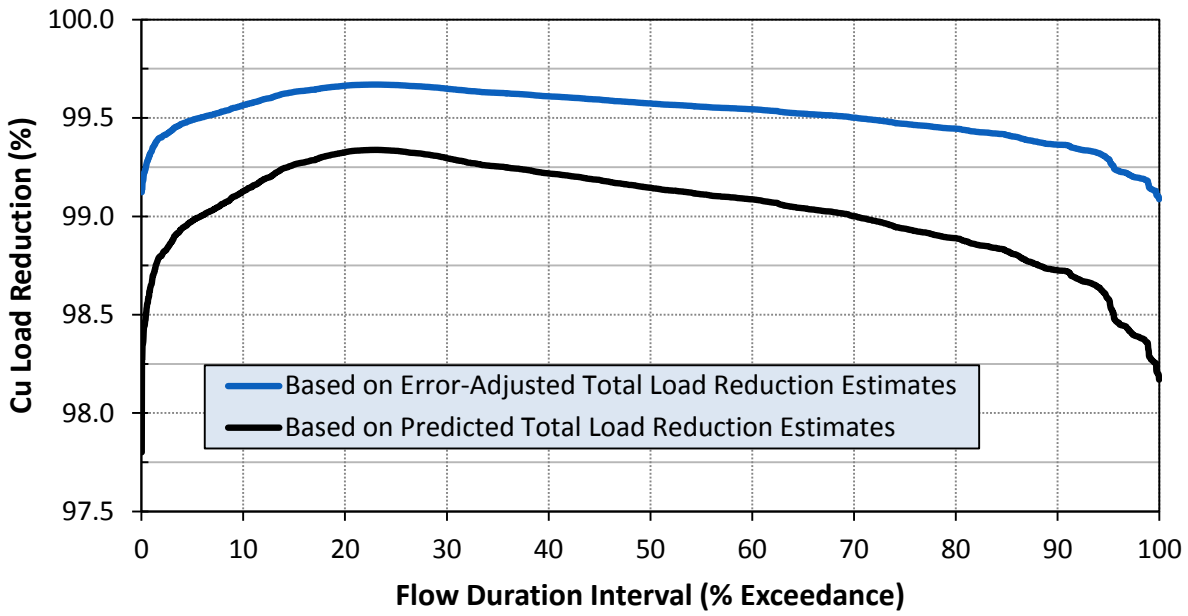
Copper

From the LDC analyses presented in the previous section, it is apparent that the greatest Cu load reduction required for achieving TMDL targets at all stations on Haggarty Creek and West Fork Battle Creek is observed during high flow conditions. To illustrate this, the percent load reduction estimates derived for Haggarty Creek below the FHM (HC8) are graphically displayed in **Figure 23**. Some of the data used to generate the graph are summarized in **Table 5**. Load reductions derived from both the error-adjusted and predicted Cu load estimates are provided to show relative differences between the two load reduction scenarios. The difference between the two curves represents one of the implicit MOS elements described in Section 4.2.

From a review of all the load reduction estimates made at HC8, the maximum load reduction occurs at the 23 percent exceedance interval (mean daily flow = 4.1 cfs). The greatest Cu loads are also observed near the same interval at stations HC14 and WFBC1 (summary data provided in **Tables 6 and 7**). Flow rates observed at this interval are typically observed at the onset of peak runoff at the FHM site in late-May and early-June. As discussed in Section 2.2, copper-enriched water is flushed from the underground mine workings of the FHM at near-maximum discharge rates into Haggarty Creek during

this period. At the same time, flows in Haggarty Creek are increasing but have not yet reached peak levels to provide maximum dilution to the Cu load it receives. While short-lived, the aquatic life in Haggarty Creek is subjected to the maximum Cu loading rate at this time.

Figure 23. Error-adjusted and predicted copper load reduction estimates for station HC8 on Haggarty Creek below the FHM.



Based on the load reduction estimates calculated for each station on Haggarty Creek and West Fork Battle Creek, the critical condition for the Cu TMDLs occurs between the 20th and 25th percent flow exceedance intervals. The Cu load and estimated percent load reduction estimates corresponding to the critical condition for each of the LDCs generated at each station are shown in **Table 9**. Load reduction estimates are based on the amount of error-adjusted Cu load that must be reduced to achieve the TMDL target load.

Table 9. Copper load and estimated percent reduction values corresponding to the critical condition identified for stations on Haggarty Creek and West Fork Battle Creek.

Station	Mean Daily Flow (cfs)	Error-Adjusted Load (ton/day)	Predicted Load (ton/day)	Acute Target Load (ton/day)	Chronic Target Load (ton/day)	Background Load (ton/day)	Error-Adjusted Reduction Estimated to Achieve Chronic Target Load	
							Percent (%)	ton/day
HC8	4.13	9.23E-03	3.68E-03	4.05E-05	3.05E-05	2.23E-05	99.67	9.20E-03
HC14	28.8	6.81E-03	4.37E-03	2.83E-04	2.13E-04	1.55E-04	96.87	6.60E-03
WFBC1	25.4	3.90E-03	2.08E-03	2.50E-04	1.88E-04	1.37E-04	95.18	3.71E-03

Cadmium and Silver

Critical conditions assigned to the Cd and Ag TMDLs are determined from the greatest loading period identified from their respective LDCs developed for Station HC14 on Haggarty Creek. With respect to Cd, the critical condition occurs between the 70 and 100 percent flow exceedance intervals (**Figure 21**). The median value for this hydrologic condition class is the 85th flow exceedance interval. Cadmium exceedances are limited only to this region of the flow duration curve, with corresponding flows of 4 cfs or less. These flows are typically observed at HC14 from about late-July to early-April, but it is notable to recognize that all of the documented Cd exceedances occurred in September (**Appendix B**). As described previously, the Cd load reduction estimated for the low flow region of the LDC is 90.6 percent (**Figure 21**).

Based on the existing Ag loading and percent reduction estimates calculated for the two different critical loading regions shown in **Figure 22**, the greatest percent reduction required to achieve the Ag TMDL target lies within the high flow region of the LDC. This region encompasses flows that are observed less than 20 percent of the time, or greater than about 29 cfs. Flows of this magnitude are typically observed from early May to mid-July during the peak runoff period at HC14. From the load reduction estimates presented in **Table 8**, about 75 percent of the existing Ag load would need to be reduced to achieve the acute Ag criterion target.

4.5 POLLUTANT ALLOCATION

A TMDL is defined as the total quantity of a pollutant (loading capacity) that a waterbody can assimilate without violating WQSs. It is expressed as the sum of all waste load allocations (WLAs) for point sources, load allocations (LAs) for non-point and natural background sources, and includes an appropriate MOS to account for uncertainties and assumptions in the analyses. The definition of a TMDL is expressed by the following equation:

$$\mathbf{TMDL = \Sigma\ WLA + \Sigma\ LA + MOS}$$

The purpose of the TMDL is to estimate allowable pollutant loads and to allocate those loads among known pollutant sources so that appropriate control measures can be implemented to achieve WQSs. The TMDLs may be expressed in terms of mass per time, toxicity or other appropriate measure [40 CFR § 130.2 (1)]. The TMDLs developed for the metal pollutants in this document are expressed in tons per

day (tons/day), representing the maximum one-day load that the stream can assimilate without exceeding WQSs. Percent (%) load reduction recommendations are provided for three water quality monitoring stations in the HC-WFBC drainage to indicate the level of metal load reductions considered necessary to achieve WQSs.

Allocations for Cu in the HC-WFBC drainage are based entirely on loading estimates calculated from the LDCs developed for HC8 on Haggarty Creek below the Ferris-Haggarty Mine (FHM). As discussed in Section 3.2, the mine drainage water that emanates from the FHM site is considered the sole source of the Cu contamination in both streams. Assuming that the existing Cu load at HC8 can be reduced by the amounts specified in **Table 5**, further reductions in Cu are expected at downstream locations through attenuation processes (i.e., dilution, organic complexation and precipitation). Load allocations for Cd and Ag are based on loading estimates calculated from the LDCs developed for HC14 on Haggarty Creek.

Waste Load Allocation

There is no waste load allocation for Cd and Ag since the load is attributed entirely to unknown non-point sources and natural background sources, and because there are no permitted facilities within the watershed that discharge Cd or Ag.

The Cu waste load allocation is allocated entirely to the contaminated mine drainage waters from the FHM site. As stated in Section 3.2, this mine drainage includes the Cu-rich discharge water from the portal as well as seepage waters from the surrounding mine disturbance area. Adrian Brown (1994) reported that groundwater seepage from the underground mine workings may enter Haggarty Creek outside of the portal area, as well as surface water seepage from the tailings dump. For this reason, HC8 on Haggarty Creek is established well below the mine effluent and tailings dump in order to evaluate the total impacts to water quality from the combined mine drainage inputs.

Load Allocation

Cadmium and Silver are attributed to unknown non-point sources and natural background, which comprise the load allocation. Load allocations assigned to Cd and Ag are derived from the difference between their respective TMDL targets and Margins of Safety for HC14 on Haggarty Creek. For Cd the critical loading condition occurs during the low flow period, designated by the 85 percent flow exceedance interval (**Figure 21**). The LA for Cd at this interval is 6.20E-8 ton/day. For Ag the critical

loading condition occurs during high flow periods, designated by the 10 percent flow exceedance interval (**Figure 22**). At this interval the LA for Ag is 7.18E-5 ton/day.

The Cu load allocation in the HC-WFBC drainage is attributed entirely to natural background contributions. Load allocations for each water quality monitoring station on Haggarty Creek and West Fork Battle Creek are derived from the natural background load estimates represented by their respective LDCs. Existing, or predicted total, load values are obtained from the full array of flow exceedance intervals displayed along the *x-axis* of each LDC plot. Predicted total loads include both the FHM drainage water and natural background contributions combined. For example, the predicted Cu load associated with the 50 percent flow exceedance interval at HC8 (**Figure 15**) is 8.11E-4 ton/day. This amount of Cu loading is 8.03E-4 ton/day in excess of the TMDL target load of 8.67E-06 ton/day, which allocates 6.33E-6 ton/day to natural background sources (LA), 1.73E-6 ton/day to an explicit MOS and 6.06E-7 ton/day to an allowable waste load (WLA). The associated load reduction goal amounts to 98.9 percent. This amount of load reduction is less than the recommended amount calculated from the more conservative error-adjusted LDC (99.6%). Percent Cu load reduction estimates calculated from the predicted and error-adjusted LDCs developed at stations on Haggarty and West Fork Battle Creek are summarized for every 5th flow exceedance interval in **Tables 5, 6 and 7**.

From the discussion in Section 4.3, the critical conditions identified from the Cu LDCs generated for each water quality monitoring station occur somewhere between the 20 to 25 percent flow exceedance intervals. The Cu load reduction estimates based on the error-adjusted LDCs at this flow region are shown for each station in **Table 9**. The error-adjusted load reduction estimates are recommended goals intended to provide reasonable assurances that the aquatic life uses in Haggarty Creek and West Fork Battle Creek are fully supported. For loads corresponding to the critical condition, these goals represent the maximum amount of load reduction required over the entire range of flows observed at a station. For the critical condition at HC8, 9.20E-3 ton/day of Cu would need to be removed (99.67 percent reduction) to achieve the TMDL target. This estimate accounts for the implicit and explicit MOS factors described previously. The background Cu load (LA) associated with the critical condition is estimated at 2.23E-5 ton/day.

Margin of Safety

Both implicit and explicit MOS factors are used for all the metal TMDLs developed for Haggarty Creek and West Fork Battle Creek. Several implicit MOS elements are incorporated into each of the LDCs,

primarily consisting of conservative estimates of stream discharge and metal loading. The explicit MOS amounts to 20 percent of the TMDL target loads established for each metal. The net effect of this factor represents a 20 percent reduction in the available assimilative capacity of each metal (i.e., a reduction in the allowable metal load that the waterbody can assimilate without violating WQSs). Relative to the critical condition identified at HC8, the explicit MOS for Cu is 0.61E-5 ton/day. For Cd and Ag the MOS loads corresponding to their respective critical conditions at HC14 amount to 1.55E-7 ton/day and 1.80E-5 ton/day, respectively.

Summary of Load Allocations

Nearly the entire Cu load in the HC-WFBC drainage is allocated to the mine drainage waters from the FHM. Based on the critical condition identified at station HC8, 99.7 percent of the total Cu load (9.20E-3 ton/day) must be reduced to achieve WQSs. A minor amount of the total load is comprised of conservative analytical assumptions which account for the uncertainty in the load estimates. The remainder of the total Cu load (0.3 percent) is comprised of the TMDL target load (3.05E-5 ton/day).

All of the Cd and Ag in Haggarty Creek are allocated to non-point sources upstream of HC14. Sources of Cd and Ag have yet to be identified, but all evidence to date suggests that the mine drainage water from FHM is not a major contributing source of these metals. Of the existing Cd load estimated from the critical condition at HC14, a 90.6 percent load reduction is assigned to unknown sources. From the critical condition identified for Ag, a 75.2 percent load reduction is assigned to unknown non-point sources (**Table 10**).

Table 10. TMDL load allocation summary for stations on Haggarty Creek and West Fork Battle Creek. All values correspond to the critical condition identified for each pollutant.

		Critical Condition							Load Reduction Required	
Pollutant	**Station**	**Flow Exceedance Interval (%)**	**Mean Flow (cfs)**	**Existing Load (ton/day)**	**TMDL (ton/day)**	**WLA (ton/day)**	**LA[1] (ton/day)**	**MOS (ton/day)**	**Percent (%)**	**ton/day**
Copper	**HC8**	23	4.13	9.23E-3	3.05E-5	0.21E-5	2.23E-5	0.61E-5	99.7	9.20E-3
	HC14	20	28.8	6.81E-3	2.13E-4	0.15E-4	1.55E-4	0.43E-4	96.9	6.60E-3
	WFBC1	24	25.4	3.90E-3	1.88E-4	0.13E-4	1.37E-4	0.38E-4	95.2	3.71E-3
Cadmium	**HC14**	85	3.1	8.27E-6	7.75E-7	N/A	6.20E-7	1.55E-7	90.6	7.50E-6
Silver	**HC14**	10	105	3.62E-4	8.98E-5	N/A	7.18E-5	1.80E-5	75.2	2.72E-4

[1] Natural background load

A summary of the existing and allocated loads, and associated load reductions needed to achieve the TMDL targets established for Cu, Cd and Ag in the HC-WFBC drainage is presented in **Table 10**. As explained previously, the load reduction goals presented in the table represent the maximum amount of load reduction required over the full range of flows observed at a station. Less load reduction is required for flows that fall outside of the critical loading periods.

5.0 MONITORING STRATGEY

Monitoring plays an important role in assessing the progress made towards achieving stated water quality targets and evaluating the efficacy of load reduction/remediation efforts. Data collected from the monitoring plan are used to address assumptions and uncertainties, verify the accuracy of the TMDLS and revise LAs if needed.

The assumptions and uncertainties associated with the TMDLs developed for the HC-WFBC drainage primarily lie with the flow estimates used to develop flow duration curves. Flow estimates are derived from gaged flow data collected at USGS Station 09253400 on Battle Creek near Encampment, WY. While this data is considered to adequately represent the flow regime in the HC-WFBC drainage, it is dated and the period-of-record is discontinuous. Gaged flow data collected at several locations on both streams would be ideal, but at least one gaging station should be established on Haggarty Creek to develop more accurate flow estimates. A more accurate estimate of the amount of mine water entering Haggarty Creek should also be considered. Broshears et al. (1993) and Kimball (1997) employed a tracer-dilution and synoptic sampling method to measure metal loading from acid mine drainage waters in Colorado. Perhaps a similar method could be employed to obtain a more accurate estimate of the total metal loading from the FHM site. In addition to the stream and mine drainage waters, estimates of the amount of flow diverted from Haggarty Creek at the Belvidere Ditch are needed to develop accurate flow estimates for West Fork Battle Creek.

Assuming a mitigation/remediation plan is selected and implemented, the following monitoring recommendations are provided:

- Monthly water quality sampling at historically sampled locations on Haggarty Creek above and below the FHM (Stations HC4 and HC8), HC14 above the Belvidere Ditch, the FHM effluent at the Osceola Tunnel FHM portal and at WFBC1 on West Fork Battle Creek. Instantaneous flow measurements should be collected all stations at the same time water samples are collected. Emphasis should be placed on acquiring water chemistry data during the winter months and critical metal loading periods (i.e., prior to the peak runoff period from late-May to early-June at the FHM site). Filtered and unfiltered metal samples should be collected both above and below the FHM site to validate the loading estimates used to derive the LDCs at HC8. Copper load

estimates used to develop the LDCs are based mostly on mass-balance estimates from the Cu load measured in the mine effluent and flow estimates generated for Haggarty Creek.

- Periodic seasonal sampling for Cd and Ag should be conducted upstream of HC14 to determine if the source of these metals can be identified. (*Because the documented standard exceedances for Cd and Ag are at or near analytical detection limits, and considering that no exceedances have been identified upstream of HC14, it is possible that measurement and/or sampling error is involved.*) Adherence to established QA/QC protocols for sampling and handling of all water samples ("clean hands" procedures) is paramount when sampling for metals in the Haggarty Creek and West Fork Battle Creek.
- Monthly flow measurements at HC14 and WFBC1 and at the Belvidere Ditch to develop accurate flow estimates for the drainage.
- Yearly bioassessment surveys at stations HC8, HC14 and WFBC1 after initial implementation of the mitigation/remediation plan, and every three years thereafter, to assess the response of the aquatic biota and to evaluate aquatic life use support. In order to perform trend analyses and evaluate aquatic life use support using the WDEQ/WQD biological indicator models, the same bioassessment survey protocols should be followed.
- Periodic fish population surveys conducted at locations on Haggarty Creek and West Fork Battle Creek to assess coldwater fish use support.

6.0 PUBLIC PARTICIPATION

Two public meetings were held to present results of this study. The first meeting was held on August 11th, 2011 in Saratoga, WY and the second meeting was held September 8th, 2011 in Baggs, WY. The document was made available for a 30-day public comment period, starting August 15th, 2011 and ending September 13th, 2011. Hard copies and electronic copies were made available for public review. The meetings and public comment period were advertised on the WDEQ/WQD website, as well as in local and regional newspapers to solicit stakeholder comment and input. WDEQ also solicited an informal review from EPA prior to official submittal. Public comments received through these activities were evaluated, and if warranted, used to revise the final document. One comment was received during the public comment period from the Town of Baggs, which requested that the municipality be notified of any future activity in the Little Snake River watershed that could potentially affect their municipal drinking water. The WDEQ recognizes the importance of the Little Snake River as a municipal drinking water source to Baggs and Dixon, and will keep stakeholders updated on any major activities and progress associated with the TMDL process.

7.0 REMEDIATION ALTERNATIVES

Potential water quality improvement and remediation strategies have been evaluated in the recent past to address the Cu contamination in Haggarty Creek and at the FHM site. Adrian Brown Consultants, Inc. and Knight Piésold, contractors who completed investigative work at the Ferris-Haggarty Mine (FHM) site from 1993 to 2000 for the WDEQ/Abandoned Mine Land Division (AML), evaluated several remediation alternatives to reduce Cu levels in the FHM effluent. The advantages/disadvantages, cost/benefit, technical feasibility, and practicality of each of remediation strategy proposed are considered in the evaluations. Other relevant discussion topics include the environmental, economic, social and aesthetic impacts associated with the remediation alternatives.

Excerpts of the remediation discussions contained in the investigative reports prepared for AML are summarized in **Appendix D**. Additional information about the remedial concepts and technologies evaluated are presented in reports prepared by Adrian Brown (1994) and Knight Piésold (1998, 1999, 2000). The reader should note that the cost estimates provided in the excerpts are dated and do not reflect current economic conditions. Furthermore, WDEQ/WQD does not favor, endorse or advocate one remediation strategy over another. This information is provided only to introduce the remediation alternatives previously considered to mitigate Cu contamination at the FHM site.

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APPENDIX

Appendix A.

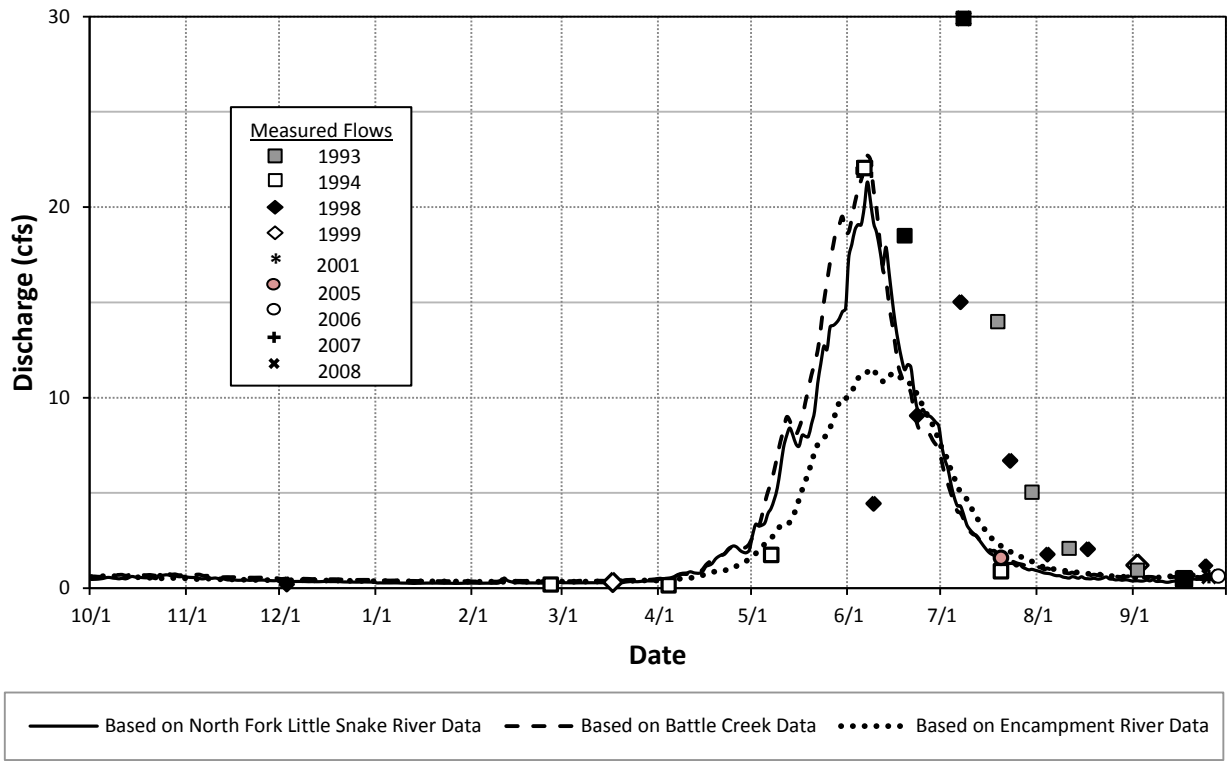
Flows at ungaged stations on Haggarty Creek (HC) and West Fork Battle Creek (WFBC) are estimated from measured (gaged) flow data collected at USGS Station 09253400, Battle Creek (BC) near Encampment, Wyoming (period-of-record 1956-63; 1985-88). The predicted flow data generated for ungaged stations in the Haggarty Creek-West Fork Battle Creek (HC-WFBC) drainage are derived from simple drainage area ratio adjustments applied to the BC gaged data. Hydrographs developed from the predicted data are designed to represent the site-specific flow regimes in HC immediately above the Ferris-Haggarty Mine (FHM) at station HC4, below the mine at station HC8 and above Belvidere Ditch at station HC14. The hydrograph prepared for the USGS water quality monitoring station on WFBC at Battle Creek Campground (WFBC1) is based on flow estimates derived for HC below the Belvidere Ditch and from separate estimates generated for Lost Creek. All stations are shown in **Figure 8.**

Several gaging stations occur in the same hydrophysiographic region within which the HC-WFBC drainage lies. Only a few, however, have characteristics similar to those found in Haggarty Creek and West Fork Battle Creek. Three representative gaging stations are listed in **Table 2**. None of the sites are subject to flow regulation and each has nine or more years of flow record. Based on an evaluation of their basin and hydrologic characteristics, the gaged data collected on BC near Encampment is considered to best represent the flow regime in the HC-WFBC drainage for the following reasons:

1) Basin Characteristics - Basin characteristics in the HC-WFBC drainage greatly influence peak runoff behavior. Streams with small drainage areas and steeper channel slopes typically have flows that respond rapidly to precipitation and snowmelt runoff events. Prevailing climate conditions prior to snowmelt in the spring can also have a considerable influence on runoff behavior. Because the BC and HC-WFBC drainages are adjacent to one another (**Figure 2**), it is assumed that their climate and vegetation conditions, geology, soils, drainage density, and mean basin elevations and slopes (**Table 2**) are very similar. In addition, both drainages have the same southwest facing orientation which can have a considerable influence on peak flows.
2) Hydrologic Characteristics - Peak flow runoff characteristics of smaller watersheds tend to differ from those with larger watersheds, typically peaking more rapidly following precipitation and snowmelt events and exhibiting greater flows per unit drainage area (**Table 2**). Based on instantaneous flow measurements made in HC, its peak flow behavior appears to closely resemble the peak flow signature of BC with respect to magnitude and duration. **Figure A-1**

shows the estimated hydrographs generated for HC4 from gaged flow data collected at the three USGS gaging stations listed in **Table 2**. Apparent in the figure is the similarity in the flow signatures of hydrographs generated from the BC and North Fork Little Snake River (NFLSR) data. With respect to flow magnitude and timing, the hydrograph generated from the Encampment River data is dissimilar to the BC and NFLSR hydrographs. These dissimilarities are most likely due to differences in precipitation, drainage basin size and basin characteristics. The Encampment River drains north into the North Platte River east of the Continental Divide. Consequently, its flow behavior is influenced by different orographic and physiographic factors than flows observed in streams west of the Continental Divide.

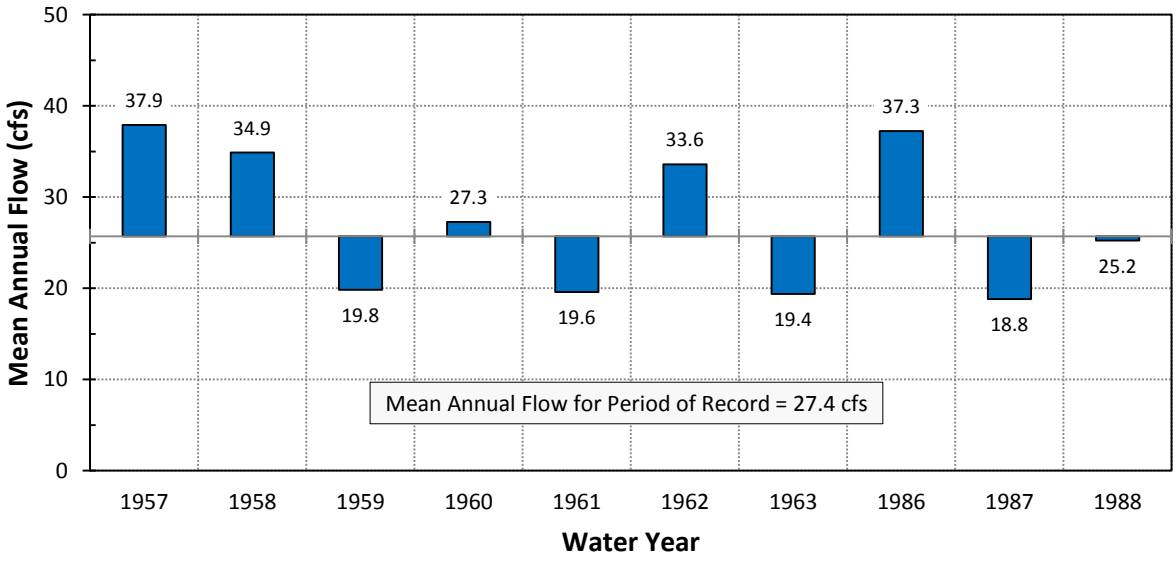
Figure A-1. Estimated hydrographs for station HC4 on Haggarty Creek below the FHM. Hydrographs are generated from gaged flow data collected at USGS stations in the Sierra Madre, south-central Wyoming.



3) Flow Record – A minimum of ten years of gaged flow data is available for the BC station. While a reasonable hydrograph could be produced from the NFLSR station data, ice conditions during winter months greatly affected the flow estimates made at the station. Ice conditions had less of an influence on winter flow estimates made at the BC station. While the period-of-record for the BC station is discontinuous and dated, it is considered to accurately represent the flow regime observed in the HC-WFBC drainage, encompassing years in which the region received

above and below normal precipitation (**Figure A-2**). While data compiled at other stations in the region provide a more long-term flow record, their basin and hydrologic characteristics are considered dissimilar enough to exclude them from consideration for generating flow data for the HC-WFBC drainage.

Figure A-2. Variation in mean annual flows at USGS Station 09253400, Battle Creek near Encampment, Wyoming relative to the overall mean annual flow for the period-of-record (1956-63; 1985-88).



The gaged data used to predict flows for ungaged stations on HC and WFBC are adjusted to account for differences in scale (drainage area), runoff timing and variability. Scale adjustments consist of calculating ungaged to gaged drainage area ratios and multiplying those ratios by the mean daily flow values measured at BC. Thus, the drainage area ratio of 1:10 calculated for HC4 (1.30 mi^2) and BC (13.0 mi^2) is used to scale-down the BC mean daily flow values by 90 percent to derive flow estimates at HC4.

After scale corrections are applied, the estimated flow data are used to produce hydrographs that depict mean daily flows. *(Note: Due to the large volume of data required to generate hydrographs and flow duration curves, these data are not provided in this document. Hydrologic data is available on request from WDEQ/WQD.)* Instantaneous flow measurements collected at the ungaged stations in past years (Appendix B) are plotted on the hydrograph to provide a means to gauge relative differences in estimated and measured flow values. From the plots, it can then be determined if the estimated data require further adjustments to account for differences in runoff timing and variability.

Since the estimated flow data are derived from gaging data collected at a lower elevation than the ungaged sites on HC, differences in runoff timing are expected. Because air temperatures at upper-elevation sites are cooler than those at lower elevations, peak flows generally occur later in the runoff season at higher elevations. This runoff behavior is observed at the high-elevation HC stations. For example, some of the peak flow measurements made at HC4 in mid-June to mid-July are greater than the predicted mean daily flow values (**Figure A-1**). These discrepancies are partly attributed to cool weather conditions in some years which can delay snowmelt runoff, but most are attributed to the temperature differences between high-elevation and low elevation sites. To create this runoff lag response for the high-elevation sites on HC, the estimated mean daily flow values are advanced in time by 15 days from the start of the water year (October 1). Because WFBC1 is at a lower elevation, no temporal adjustments are required.

In addition to scale and temporal adjustments, a period-specific standard deviation is added to each estimated mean daily flow value to account for the variability observed over six distinct flow periods. These adjustments are made based on observed differences between the estimated and measured flow values associated with each station. While predicted low flow values generally agree well with measured values at all stations, differences between high flow values are more apparent. Some differences are due to the limited amount of historical data used to estimate discharge and the error associated with measuring streamflow in mountain streams with cobble-boulder beds, but much is attributed to the inherent variability of flows in high-elevation, snow-melt dominated streams. For stations on HC and WFBC, flow period standard deviations are calculated from the estimated mean daily values that fall within the following dates:

	Flow Period					
Station	**Baseflow**	**Leading**	**Rising**	**Peak**	**Receding**	**Low Flow**
HC4 and HC8	12/1 - 4/30	5/1 - 5/14	5/15 - 5/31	6/1 - 7/15	7/16 - 7/31	8/1 - 11/30
HC14 and WFBC1	12/1 - 4/15	4/16 - 4/30	5/1 - 5/15	5/16 - 6/30	7/1 - 7/15	7/16 - 11/30

An argument could be made that the corrections applied to account for flow variability are overly conservative, but considering the aforementioned factors that can contribute to streamflow measurement error, the final estimates are considered to provide a reasonably accurate representation of actual flow conditions at each stream station.

Hydrographs generated for stations HC8 (below the FHM) and HC14 (above the Belvidere Ditch) are presented in **Figures A-3 and A-4**. The hydrograph for HC8 is produced from the summation of estimated mean daily flow data generated for HC4 and the mine discharge data collected at FHM1. The hydrograph developed for FHM1 (**Figure A-5**) is based on flow measurements and indirect estimates made at the Osceola Tunnel portal by several investigators from 1993 to 2008 (**Appendix B**). Much of the data originates from the mine site investigation conducted by Knight Piésold during various periods from 1996 through 1999. The same adjustment process used to account for the variability in the flow estimates made for stations on HC is applied to the FHM discharge data. The added adjustments in flow are also intended to account for mine waste waters that cannot be measured directly (subsurface flow and shallow surface seepage). Flow period standard deviations for the mine discharge data are calculated from values that fall within the following dates:

Flow Period					
Baseflow	**Leading**	**Rising**	**Peak**	**Receding**	**Low Flow**
1/16 - 4/30	5/1 - 5/19	5/20 - 5/31	6/1 - 7/20	7/21 - 8/15	8/16 - 1/15

Figure A-3. Predicted mean daily flow for station HC8, Haggarty Creek below the Ferris-Haggarty Mine.

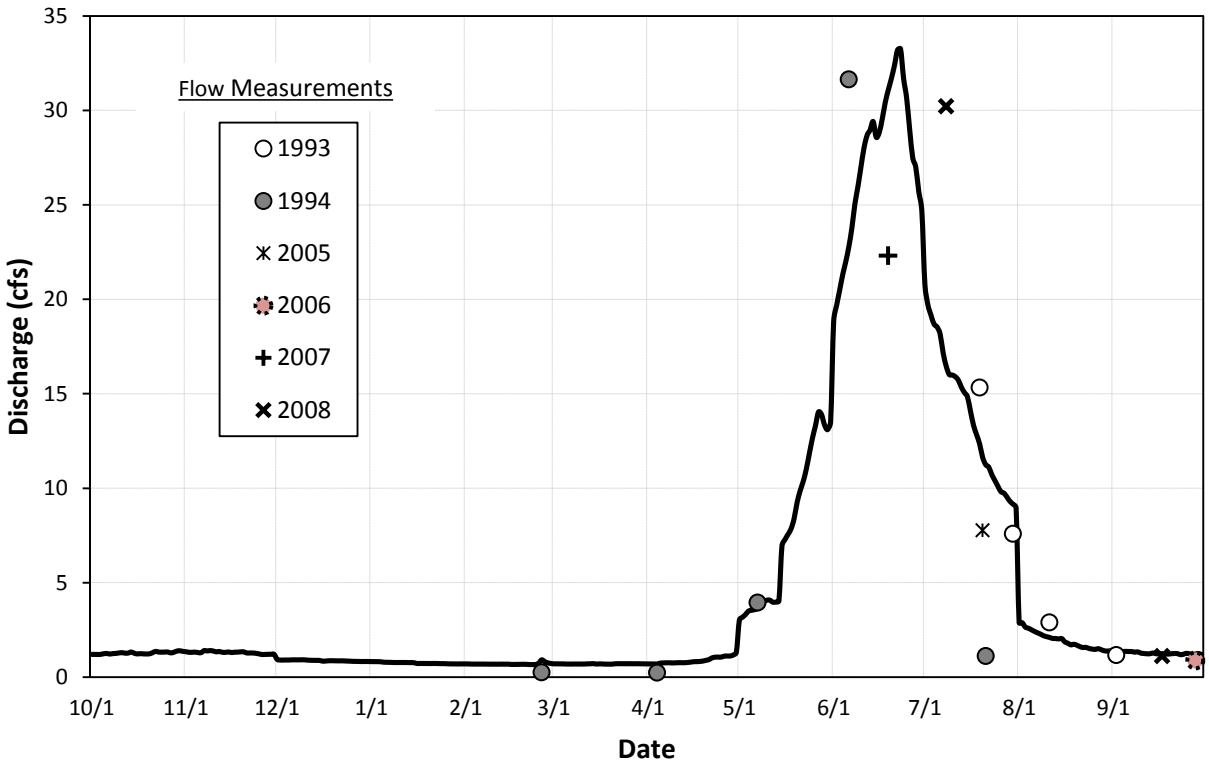


Figure A-4. Predicted mean daily flow for station HC14, Haggarty Creek above the Belvidere Ditch (USGS Station 09253455).

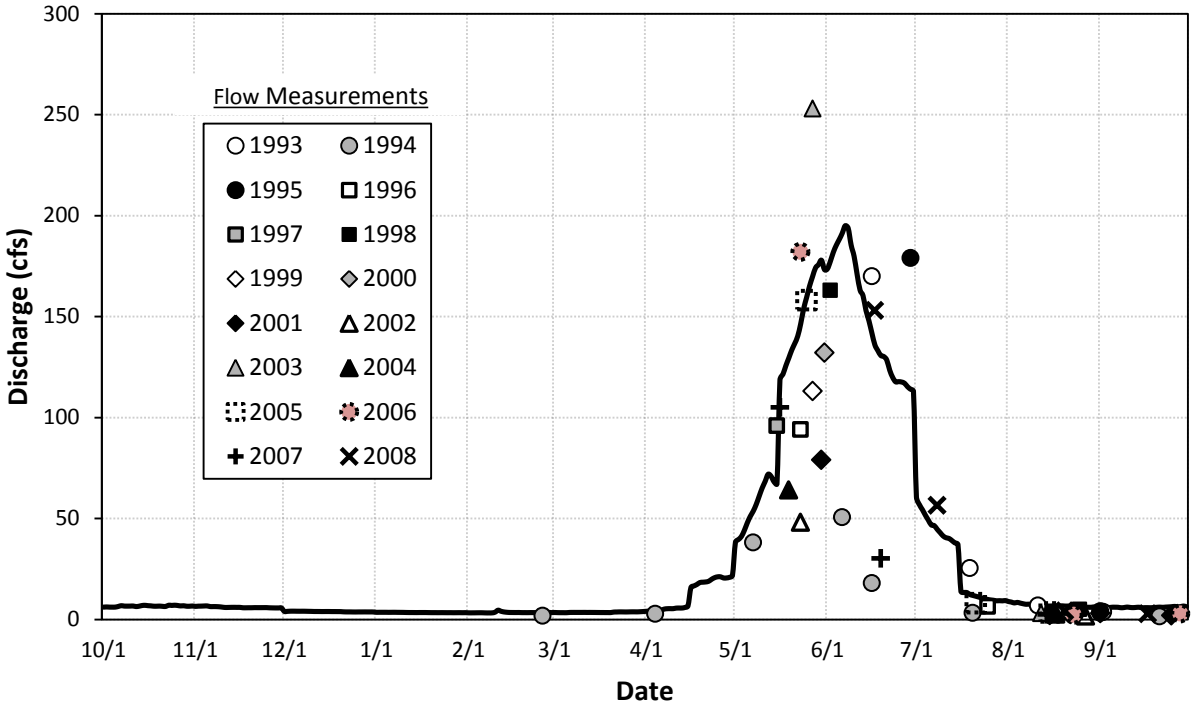
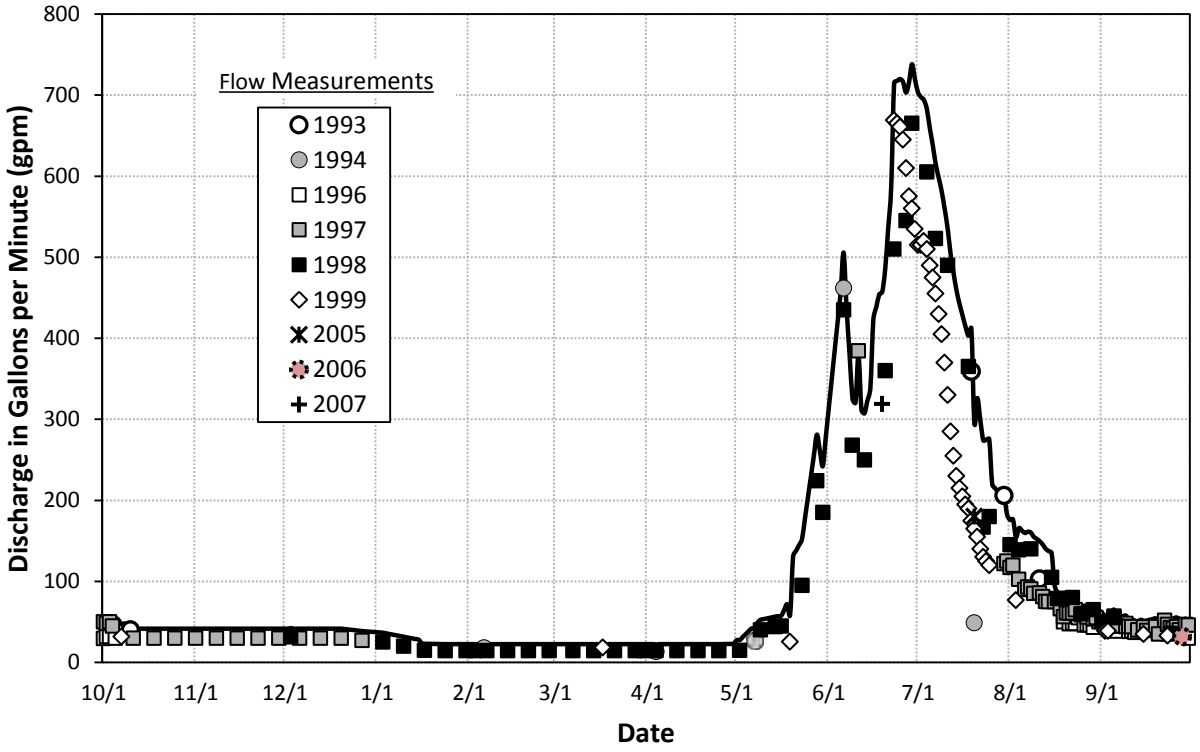


Figure A-5. Predicted mean daily flow for station FHM1, Ferris-Haggarty Mine discharge.



The hydrograph for station WFBC1 is derived from a combination of three different flow estimates:

1) HC below Belvidere Ditch- Streamflow remaining in HC below the Belvidere Ditch is derived from data generated for HC14, less the amount of flow diverted through the ditch. The proportion of flow diverted from HC is estimated from flow measurements made above and below the ditch by Adrian Brown (1994) during various flow periods in 1993 and 1994 (long-term, continuous flow data are unavailable for the ditch diversion). Flows for HC below the ditch are derived by reducing the mean daily values generated for HC14 by the percentage of flow withdrawn from HC during the following flow periods:

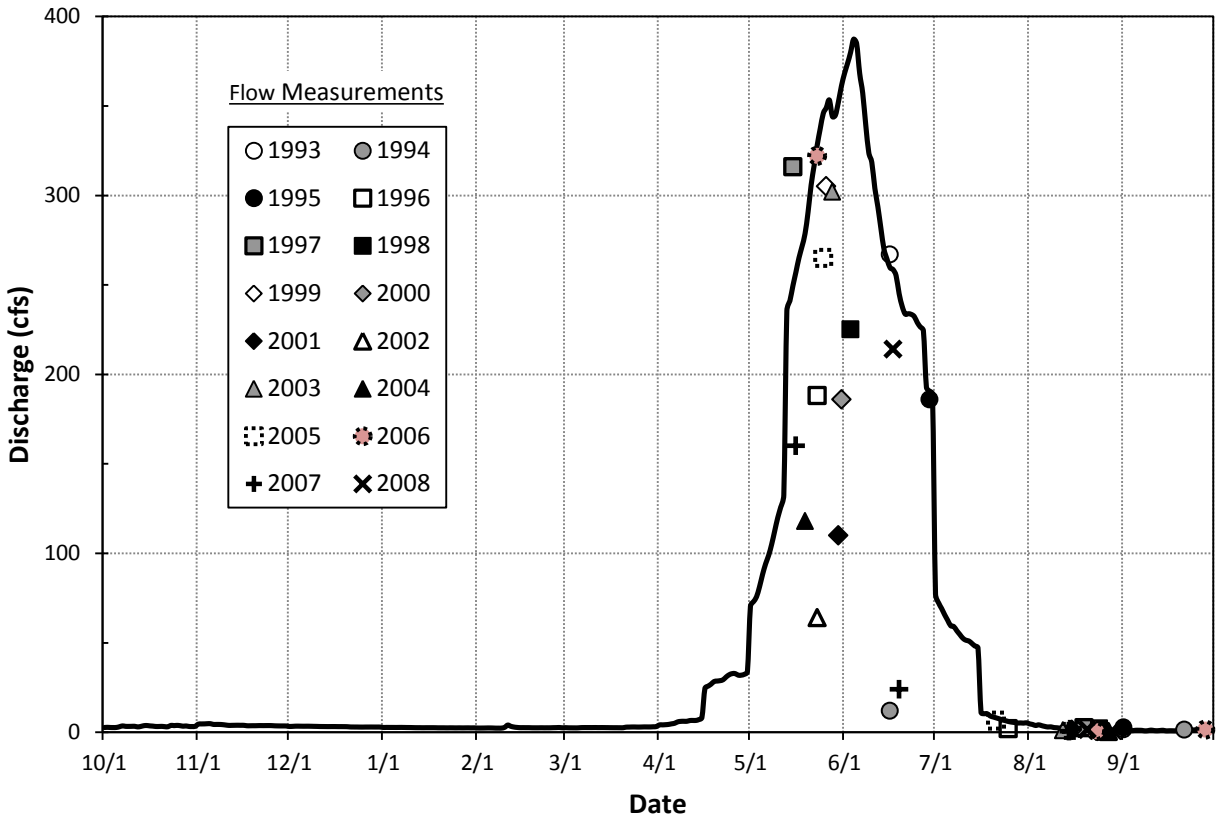
	Flow Period					
	Baseflow (10/1 - 3/31)	**Leading** (4/1 - 4/30)	**Rising** (5/1 - 5/15)	**Peak** (5/16 - 6/30)	**Receding** (7/1 - 8/15)	**Low Flow** (8/16 – 9/30)
Percentage (%) of flow diverted from HC into Belvidere Ditch	**75**	**50**	**25**	**40**	**75**	**75**

2) From HC below Belvidere Ditch to Lost Creek confluence- Flows estimated for this reach are also based on BC gage data through application of the same scale and temporal adjustments described previously for upstream stations. Only period-specific standard deviation values are added to mean daily flow values that fall within the period from April 16 to July 15 to better reflect the peak runoff behavior observed at WFBC1.
3) Lost Creek- The same procedure used to generate flow data for HC below the Belvidere ditch is used to estimate flows in Lost Creek.

Below the Haggarty Creek-Lost Creek confluence, only a handful of small tributaries (1st order) enter WFBC. These drainages and the seeps and springs that occur between the confluence and WFBC1 are assumed to contribute a negligible amount to the total flow in WFBC. Therefore, the combined flow from the three estimates described above is assumed to sufficiently represent the flows observed at WFBC1. The hydrograph produced for WFBC1 and the instantaneous flow measurements made at the station from 1993 to 2008 are displayed in **Figure A-6**.

Data used to produce flow duration curves at each ungaged station are also derived from gaged data collected at the BC station. Since flow duration curves are typically developed from mean daily flow values compiled from several years of record at a gaging station, a complete flow record had to be generated to produce curves for the ungaged stations in the HC-WFBC drainage.

Figure A-6. Predicted mean daily flow for station WFBC1, West Fork Battle Creek at Battle Creek Campground (USGS Station 09253465).



After estimated mean daily flow data are generated for an ungaged station, this data set is used with the BC mean daily flow values to calculate flow ratio factors which are used to proportionally scale the individual daily values collected at the BC station for the entire ten-year period-of-record to reflect flow rates at the ungaged station. The ratios are calculated by dividing each of the adjusted mean daily values for the water year (365 days) by their corresponding gaged mean daily values calculated from the BC flow record. Thus, an artificial data set is generated for each ungaged station from which flow duration curves can be developed.

Appendix B. Water quality data collected at stations in the HC-WFBC drainage (1993-2008), Carbon County, WY.

					Physical Parameters					
					Discharge[a]					
Station	**Station ID**	**Date**	**Time**	**Source**	**gpm**	**ft^3/s**	**Water Temp (°C)**	**pH**	**Specific Conductance (µS/cm @ 25°C)**	**Hardness (mg/L as $CaCO_3$)**
HC- West Fork	HC1	9/27/2004	1635	DEQ			6.6	8.26	33.4	17.5
HC- West Fork		7/20/2005	1245	DEQ			10.0	7.14	33.2	13.2
HC- East Fork	HC2	9/27/2004	1630	DEQ			6.0	8.20	32.6	13.7
HC- East Fork		7/20/2005	1255	DEQ			8.8	7.18	27.2	11.2
HC- RUDEFEHA (SR35)	HC3	9/27/2004	1650	DEQ			6.6	7.92	35.8	15.1
HC- RUDEFEHA (SR35)		7/20/2005	1305	DEQ	2621	5.84		7.34	29.3	12.3
HC- RUDEFEHA (SR35)		9/28/2006	1015	DEQ	337	0.75	2.9	6.56	52.3	55.2
HC- RUDEFEHA (SR35)		6/19/2007	1140	DEQ	6957	15.5	6.3	7.89	20.4	7.6
HC- RUDEFEHA (SR35)		7/8/2008	1100	DEQ	9609	21.4	6.1	8.28	21.2	10
HC- RUDEFEHA (SR35)		9/17/2008	1340	DEQ	301	0.67	8.7	7.54	35.1	16
HC- Above FHM	HC4	7/19/1993		ABC	6279	13.99		7.1		3
HC- Above FHM		7/30/1993		ABC	2262	5.04		6.9		
HC- Above FHM		8/11/1993		ABC	938	2.09	8	7.1		12
HC- Above FHM		9/2/1993		ABC	426	0.95	5	6.2		13
HC- Above FHM		2/26/1994		ABC	85	0.19	2	5.2		17
HC- Above FHM		4/4/1994		ABC	67	0.15	1	6.5		19
HC- Above FHM		5/7/1994		ABC	785	1.75	3	7.02		13
HC- Above FHM		6/6/1994		ABC	9897	22.05	5	6.9		3
HC- Above FHM		7/20/1994		ABC	399	0.89	5	6.94		14
HC- Above FHM		9/27/2004	1720	DEQ			6.4	7.91	36.3	15.2
HC- Above FHM		7/20/2005	1425	DEQ			11.1	7.46	26.3	10.9
HC- Above FHM		9/28/2006	1105	DEQ	287	0.64	5.4	7.27	46.5	17.2
HC- Above FHM		6/19/2007	1230	DEQ	8303	18.5	7.6	7.70	20.4	7.5
HC- Above FHM		7/8/2008	1145	DEQ	13402	29.9	7.7	8.36	20.0	
HC- Above FHM		9/17/2008	1425	DEQ	211	0.47	9.4	7.38	33.7	16
FHM Discharge	**FHM1**	**7/19/1993**		**ABC**	**359**	**0.80**	**4**	**6.10**		**6**

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
FHM Discharge		7/19/1993		ABC						
FHM Discharge		7/30/1993		ABC	206	0.46		6.02		
FHM Discharge		8/11/1993		ABC	103	0.23	4	6.30		24
FHM Discharge (Duplicate)		8/11/1993		ABC						24
FHM Discharge		9/2/1993		ABC	45	0.10	5	6.80		35
FHM Discharge (Duplicate)		9/2/1993		ABC						35
FHM Discharge		9/2/1993		ABC						
FHM Discharge		10/10/1993		ABC	40	0.09				
FHM Discharge		2/26/1994		ABC	18	0.04	1	5.40		52.2
FHM Discharge (Duplicate)		2/26/1994		ABC						52.4
FHM Discharge		2/26/1994		ABC						
FHM Discharge		4/4/1994		ABC	13.5	0.03	5	7.00		60
FHM Discharge (Duplicate)		4/4/1994		ABC						59
FHM Discharge		4/4/1994		ABC						
FHM Discharge		5/7/1994		ABC	27	0.06	4	6.67		36
FHM Discharge		5/7/1994		ABC						
FHM Discharge		6/6/1994		ABC	462	1.03	3	5.77		14
FHM Discharge (Duplicate)		6/6/1994		ABC						14
FHM Discharge		6/6/1994		ABC						
FHM Discharge		7/21/1994		ABC	49	0.11	4	6.75		31
FHM Discharge (Duplicate)		7/21/1994		ABC						31
FHM Discharge		7/21/1994		ABC						
FHM Discharge		8/26/1996		KP	46	0.10	4	7.12	90	
FHM Discharge		9/3/1996		KP	42	0.09	3.5	7.31	85	
FHM Discharge		9/6/1996		KP	38.5	0.09	4	7.33	95	
FHM Discharge		9/25/1996		KP	43	0.10		6.50	102.0	

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
FHM Discharge		10/2/1996		KP	32	0.07	3.5	7.26	76	
FHM Discharge		3/19/1997		KP	16.5	0.04		7.48	107.0	
FHM Discharge		4/30/1997		KP	15	0.03				
FHM Discharge		6/11/1997		KP	384.4	0.86				
FHM Discharge		7/15/1997		KP				6.20	44.3	
FHM Discharge		7/16/1997		KP				5.62	45.5	
FHM Discharge		7/22/1997		KP				6.44	50.9	
FHM Discharge		7/24/1997		KP				6.42	53.7	
FHM Discharge		7/31/1997		KP	125	0.28		6.52	61.5	
FHM Discharge		8/8/1997		KP	90.67	0.20		5.91	70.2	
FHM Discharge		8/14/1997		KP	74.8	0.17		5.61	72.8	
FHM Discharge		8/22/1997		KP	61.2	0.14		5.52	82.1	
FHM Discharge		8/29/1997		KP	53.5	0.12				
FHM Discharge		9/3/1997		KP	50.3	0.11				
FHM Discharge		9/12/1997		KP	40	0.09				
FHM Discharge		9/19/1997		KP	44.3	0.10				
FHM Discharge		9/26/1997		KP	44.1	0.10				
FHM Discharge		10/3/1997		KP	49.8	0.11				
FHM Discharge		12/16/1997		KP	30	0.07		7.18		
FHM Discharge[c]		12/17/1997		KP	30	0.07				
FHM Discharge		2/3/1998		KP	14.5	0.03				
FHM Discharge		2/4/1998		KP	16.3	0.04				
FHM Discharge		3/4/1998		KP	14.5	0.03				
FHM Discharge		3/11/1998		KP	14.5	0.03				
FHM Discharge		3/18/1998		KP	16.5	0.04				
FHM Discharge		3/25/1998		KP	14.5	0.03				

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
FHM Discharge		3/31/1998		KP	14.5	0.03				
FHM Discharge		4/1/1998		KP	14	0.03		6.03		
FHM Discharge		4/8/1998		KP	14.5	0.03		6.68		
FHM Discharge		4/15/1998		KP	14.5	0.03		6.01		
FHM Discharge		4/22/1998		KP	14.5	0.03		6.21		
FHM Discharge		4/29/1998		KP	15	0.03		6.38		
FHM Discharge		5/6/1998		KP	29.3	0.07		6.04		
FHM Discharge		5/13/1998		KP	43.2	0.10		5.87		
FHM Discharge		5/14/1998		KP	44	0.10		5.75		
FHM Discharge		5/18/1998		KP	59.3	0.13		6.03		
FHM Discharge		5/25/1998		KP	146.6	0.33		5.54		
FHM Discharge		5/28/1998		KP	224	0.50		5.32		
FHM Discharge		5/28/1998		KP	224	0.50		5.08		
FHM Discharge		6/1/1998		KP	256.4	0.57		6.63		
FHM Discharge		6/8/1998		KP	323.7	0.72		6.61		
FHM Discharge		6/9/1998		KP	268	0.60		6.69		
FHM Discharge		6/9/1998		KP	268	0.60		6.71		
FHM Discharge		6/15/1998		KP	281.4	0.63		6.4		
FHM Discharge		6/22/1998		KP	460	1.02		6.37		
FHM Discharge		6/23/1998		KP	510	1.14		6.17		
FHM Discharge		6/23/1998		KP	510	1.14		6.14		
FHM Discharge		6/29/1998		KP	665	1.48		6.18		
FHM Discharge		7/6/1998		KP	550.3	1.23		6.29		
FHM Discharge		7/7/1998		KP	523	1.17		6.28		
FHM Discharge		7/7/1998		KP	523	1.17		6.35		
FHM Discharge		7/13/1998		KP	454.3	1.01		5.97		

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
FHM Discharge		7/20/1998		KP	285.8	0.64		6.16		
FHM Discharge		7/23/1998		KP	167	0.37		6.19		
FHM Discharge		7/23/1998		KP	167	0.37		6.18		
FHM Discharge		7/27/1998		KP	170	0.38				
FHM Discharge		8/3/1998		KP	141	0.31				
FHM Discharge		8/4/1998		KP	139	0.31		6.98		
FHM Discharge		8/4/1998		KP	139	0.31		6.95		
FHM Discharge		8/10/1998		KP	130	0.29				
FHM Discharge		8/17/1998		KP	79	0.18		6.75		
FHM Discharge		8/17/1998		KP						
FHM Discharge		8/18/1998		KP	79	0.18		6.76		
FHM Discharge		8/24/1998		KP	66.7	0.15				
FHM Discharge		8/25/1998		KP	60	0.13				
FHM Discharge		8/31/1998		KP	55	0.12				
FHM Discharge		9/1/1998		KP	50	0.11		7.18		
FHM Discharge		9/1/1998		KP	50	0.11		7.22		
FHM Discharge		9/7/1998		KP	45.8	0.10				
FHM Discharge		9/14/1998		KP	40	0.09				
FHM Discharge		9/21/1998		KP	37.3	0.08				
FHM Discharge		9/24/1998		KP	35.9	0.08		7.38		
FHM Discharge		9/24/1998		KP				7.27		
FHM Discharge		12/3/1998		KP	31.4	0.07				
FHM Discharge		3/17/1999		KP	18.5	0.04		7.51		
FHM Discharge		5/19/1999		KP	25.6	0.06		7.2		
FHM Discharge		6/23/1999		KP	669	1.49		6.15		
FHM Discharge		6/23/1999		KP						

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
FHM Discharge		**6/30/1999**		**KP**	**535**	**1.19**				
FHM Discharge		**7/7/1999**		**KP**	**455**	**1.01**				
FHM Discharge		**8/4/1999**		**KP**	**76**	**0.17**				
FHM Discharge		**8/11/1999**		**KP**	**67**	**0.15**				
FHM Discharge		**9/2/1999**		**KP**	**39**	**0.09**		**7.25**		
FHM Discharge		**10/6/1999**		**KP**	**32**	**0.07**		**7.26**		
FHM Discharge		**9/27/2004**	**1735**	**DEQ**			**5.1**	**7.31**	**101.4**	**45.7**
FHM Discharge		**7/20/2005**	**1435**	**DEQ**	**180**	**0.40**	**4.4**	**6.48**	**52.9**	**17.7**
FHM Discharge		**9/28/2006**	**1120**	**DEQ**	**32**	**0.07**	**4.6**	**6.52**	**96.7**	**45.6**
FHM Discharge		**6/19/2007**	**1342**	**DEQ**	**319**	**0.71**	**5.3**	**6.74**	**50.0**	**11.8**
FHM Discharge		**7/8/2008**	**1215**	**DEQ**			**7.5**	**7.43**	**50.0**	**15**
FHM Discharge		**9/17/2008**	**1438**	**DEQ**	**12.6**	**0.03**	**6.9**	**6.91**	**96.6**	**43**
HC- Below FHM (SRI3)	HC8	7/19/1993		ABC	6876	15.32		6.80		3
HC- Below FHM (SRI3)		7/30/1993		ABC	3398	7.57		6.90		
HC- Below FHM (SRI3)		8/11/1993		ABC	1297	2.89	10	7.30		13
HC- Below FHM (SRI3)		9/2/1993		ABC	516	1.15	9	7.45		16
HC- Below FHM (SRI3)		2/26/1994		ABC	108	0.24	1	4.90		21
HC- Below FHM (SRI3)		4/4/1994		ABC	99	0.22	1	6.90		23
HC- Below FHM (SRI3)		5/7/1994		ABC	1768	3.94	3	6.84		13
HC- Below FHM (SRI3)		5/7/1994		ABC						13
HC- Below FHM (SRI3)		6/6/1994	1300	ABC	13411	29.88	5	6.98		2
HC- Below FHM (SRI3)		6/6/1994	1500	ABC	14982	33.38				
HC- Below FHM (SRI3)		7/21/1994		ABC	494	1.10	7	6.68		14
HC- Below FHM (SRI3)		9/27/2004	1830	DEQ			6.1	7.60	41.9	17.6
HC- Below FHM (SRI3)		7/20/2005	1525	DEQ	3487	7.77	12.0	6.83	29.9	11.0
HC- Below FHM (SRI3)		9/28/2006	1205	DEQ	390	0.87	4.7	7.30	42.6	19.5

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
HC- Below FHM (SRI3)		6/19/2007	1555	DEQ	10009	22.3	10.4	7.54	22.1	7.7
HC- Below FHM (SRI3)		7/8/2008	1240	DEQ	13559	30.2	8.6	8.05	19.0	10
HC- Below FHM (SRI3)		9/17/2008	1520	DEQ	498	1.11	10.5	7.34	40.7	18
HC- Above Deep Rock Creek	HC9	9/28/2006	1335	DEQ	386	0.86	5.3	7.58	44.9	19.0
HC- Above Deep Rock Creek (Duplicate)		9/28/2006	1335	DEQ						19.2
HC- Above Deep Rock Creek		6/19/2007	1630	DEQ	10144	22.6	10.1	7.55	22.6	7.2
Deep Rock Creek	DRC1	9/28/2004	915	DEQ			3.6	8.16	37.4	14.8
Deep Rock Creek		7/20/2005	1625	DEQ			11.8	7.41	27.6	11.4
Deep Rock Creek		9/28/2006		DEQ	278	0.62				
HC- Below Deep Rock Creek	HC10	9/28/2004	925	DEQ			3.6	7.88	40	
HC- Below Deep Rock Creek		7/20/2005	1635	DEQ	5498	12.3	12.0	7.44	28.6	
HC- Below Deep Rock Creek		9/28/2006	1340	DEQ	664	1.48	5.8	7.24	40.4	17.9
HC- Below Deep Rock Creek		6/19/2007	1640	DEQ	12253	27.3	9.8	7.42	22.9	8.1
HC- Below Deep Rock Creek		7/8/2008	1355	DEQ	18963	42.3	10.2	8.30	22.2	10
Vole Creek	VC1	9/28/2004	940	DEQ			3.9	8.23	39.1	17.4
Vole Creek		7/20/2005	1700	DEQ			11.4	7.31	24.6	12.9
Vole Creek		9/28/2006		DEQ	144	0.32				
HC- Below Vole Creek	HC11	9/28/2004	955	DEQ			3.8	8.00	40.8	
HC- Below Vole Creek		7/20/2005	1710	DEQ	5229	11.7	11.9	7.40	24.1	
HC- Below Vole Creek		9/28/2006	1420	DEQ	808	1.80	5.8	7.47	43.1	18.2
Bachelor Creek	B1	9/28/2004	1050	DEQ			6.1	7.92	46.2	19.6
Bachelor Creek		7/21/2005	740	DEQ			8.1	6.99	33.6	14.1
Bachelor Creek		9/28/2006		DEQ	256	0.57				
HC- Below Bachelor Creek	HC12	9/28/2004	1100	DEQ			4.8	7.93	42.8	
HC- Below Bachelor Creek		7/21/2005	755	DEQ			7.5	7.11	28.9	
HC- Below Bachelor Creek		9/28/2006	1500	DEQ	1064	2.37	6.1	7.42	41.0	18.9

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
Bachelor Al Creek	BA1	9/28/2004	1125	DEQ			8.3	7.62	30.4	
Bachelor Al Creek		7/21/2005	810	DEQ			9.9	7.32	23.2	
Bachelor Al Creek		9/28/2006		DEQ	126	0.28				
Alisha Creek	AC1	9/28/2004	1145	DEQ			5.6	7.69	39.4	
Alisha Creek		7/21/2005	830	DEQ			7.6	7.03	33.1	
Alisha Creek (Duplicate)		7/20/2005	830	DEQ						
Alisha Creek		9/28/2006		DEQ	126	0.28				
HC @ USGS Station (SRI4)	HC13	6/16/1993	15:15	USGS	76301	170	4.0	7.3	21	8
HC @ USGS Station (SRI4)		7/20/1993		ABC	11423	25	11	7.50		3
HC @ USGS Station (SRI4)		8/12/1993		ABC	3092	6.9	8	7.00		14
HC @ USGS Station (SRI4)		9/1/1993	10:30	USGS	1436	3.2	8.5	8.2	40	16
HC @ USGS Station (SRI4)		9/1/1993		ABC	1661	3.7	7.5	6.20		17
HC @ USGS Station (SRI4)		2/26/1994		ABC	826	1.8	1	5.20		21.2
HC @ USGS Station (SRI4)		4/4/1994		ABC	1221	2.7	1	7.10		22
HC @ USGS Station (SRI4)		5/7/1994		ABC	17123	38	2	6.76		13
HC @ USGS Station (SRI4)		6/7/1994		ABC	22702	51	5	6.92		3
HC @ USGS Station (SRI4)		6/16/1994	16:50	USGS	8079	18	11.5	7.8	28	11
HC @ USGS Station (SRI4)		7/20/1994		ABC	1436	3.2	16	7.24		14
HC @ USGS Station (SRI4)		9/21/1994	16:25	USGS	628	1.4	7.5	7.8	46	19
HC @ USGS Station (SRI4)		6/29/1995	8:55	USGS	80341	179	7.5	6.6	26	8
HC @ USGS Station (SRI4)		9/1/1995	13:15	USGS	1795	4.0	3.0	7.2	40	14
HC @ USGS Station (SRI4)		5/23/1996	15:20	USGS	42190	94	10.0	6.7	29	10
HC @ USGS Station (SRI4)		7/25/1996	9:45	USGS	2873	6.4	3.0	7.5	35	14
HC @ USGS Station (SRI4)		5/15/1997	16:35	USGS	43088	96	9.0	6.6	27	10
HC @ USGS Station (SRI4)		8/19/1997	17:40	USGS	1616	3.6	1.5	7.8	41	16
HC @ USGS Station (SRI4)		6/2/1998	16:50	USGS	73159	163	12.5	7.6	21	9

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
HC @ USGS Station (SRI4)		8/25/1998	8:45	USGS	2199	4.9	4.0	7.7	40	18
HC @ USGS Station (SRI4)		5/27/1999	10:10	USGS	50718	113	8.0	7.2	25	10
HC @ USGS Station (SRI4)		9/1/1999	8:45	USGS	1346	3.0	2.0	7.7	42	18
HC @ USGS Station (SRI4)		5/31/2000	14:05	USGS	59246	132	9.0	7.4	20	8
HC @ USGS Station (SRI4)		8/22/2000	17:25	USGS	1122	2.5	7.0	7.6	43	18
HC @ USGS Station (SRI4)		5/30/2001	14:00	USGS	35458	79	11.0	7.6	23	9
HC @ USGS Station (SRI4)		8/15/2001	10:10	USGS	943	2.1	6.0	7.7	42	18
HC @ USGS Station (SRI4)		5/23/2002	8:45	USGS	21544	48	9.0		26	10
HC @ USGS Station (SRI4)		8/27/2002	9:00	USGS	763	1.7	1.0	8.1	46	19
HC @ USGS Station (SRI4)		5/27/2003	16:15	USGS	113554	253	7.5	7.6	21	8
HC @ USGS Station (SRI4)		8/12/2003	11:00	USGS	1391	3.1	2.0	7.8	40	16
HC @ USGS Station (SRI4)		5/19/2004	12:50	USGS	28725	64	11.0	7.2	24	10
HC @ USGS Station (SRI4)		8/17/2004	12:10	USGS	1122	2.5	5.0	7.8	42	18
HC @ USGS Station (SRI4)		9/28/2004	1205	DEQ			11.0	7.73	69.3	19.1
HC @ USGS Station (SRI4)		5/25/2005	9:50	USGS	70915	158	3.0	7.4	23	9
HC @ USGS Station (SRI4)		7/21/2005	915	DEQ	3591	8.0	8.9	7.30	30.4	13.3
HC @ USGS Station (SRI4)		8/15/2005	17:15	USGS	1526	3.4	12.5	7.9	40	16
HC @ USGS Station (SRI4)		5/23/2006	8:50	USGS	81687	182	2.5	8.0	21	9
HC @ USGS Station (SRI4)		8/23/2006	14:30	USGS	987	2.2	14.0	7.2	43	16
HC @ USGS Station (SRI4)		9/28/2006	1540	DEQ	1315	2.9	7.4	7.77	44.4	19.7
HC @ USGS Station (SRI4)		5/16/2007	13:30	USGS	47127	105	6.0	7.7	24	10
HC @ USGS Station (SRI4)		6/19/2007	1755	DEQ	13510	30	10.8	7.58	25.2	8.5
HC @ USGS Station- SRI4 (Duplicate)		6/19/2007	1755	DEQ						8.7
HC @ USGS Station (SRI4)		8/14/2007	14:50	USGS	1077	2.4	16.0	7.7	42	17
HC @ USGS Station (SRI4)		7/8/2008	1455	DEQ	25319	56	11.0	8.20	21.0	11
HC @ USGS Station (SRI4)		6/17/2008	10:30	USGS	68671	153	3.4	6.2	21	8

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
HC @ USGS Station (SRI4)		8/20/2008	9:40	USGS	1885	4.2	8.0	8.1	44	18
HC @ USGS Station (SRI4)		9/17/2008	1610	DEQ	1248	2.8	10.1	7.75	40.6	19
HC @ USGS Station- SRI4 (Duplicate)		9/17/2008	1610	DEQ						20
West Fork Battle Creek- Campground	WFBC1	6/16/1993	18:00	USGS	119838	267	6.5	7.5	27	11
West Fork Battle Creek- Campground		9/1/1993	15:45	USGS	718	1.6	13.5	8.0	155	64
West Fork Battle Creek- Campground		6/16/1994	12:00	USGS	5386	12	10.5	8.1	61	25
West Fork Battle Creek- Campground		9/21/1994	12:30	USGS	628	1.4	9.0	8.0	256	110
West Fork Battle Creek- Campground		6/29/1995	10:30	USGS	83483	186	5.0	7.0	31	11
West Fork Battle Creek- Campground		9/1/1995	14:30	USGS	1167	2.6	17.0	7.8	120	48
West Fork Battle Creek- Campground		5/23/1996	17:35	USGS	84380	188	4.5	7.0		18
West Fork Battle Creek- Campground		7/25/1996	12:00	USGS	898	2.0	16.0	8.3	156	61
West Fork Battle Creek- Campground		5/15/1997	18:40	USGS	141831	316	5.0	6.8	43	18
West Fork Battle Creek- Campground		8/19/1997	16:35	USGS	1077	2.4	17.5	8.1	147	56
West Fork Battle Creek- Campground		6/3/1998	9:40	USGS	100987	225	4.0	7.7	29	12
West Fork Battle Creek- Campground		8/24/1998	17:00	USGS	987	2.2	18.0	7.9	149	64
West Fork Battle Creek- Campground		5/26/1999	15:15	USGS	136894	305	5.0	7.6	46	20
West Fork Battle Creek- Campground		8/31/1999	12:00	USGS	583	1.3	14.0	8.0	175	69
West Fork Battle Creek- Campground		5/31/2000	11:20	USGS	83483	186	7.5	7.6	27	11
West Fork Battle Creek- Campground		8/22/2000	15:00	USGS	292	0.65	16.0	8.2	215	85
West Fork Battle Creek- Campground		5/30/2001	10:00	USGS	49371	110	7.0	7.2	30	12
West Fork Battle Creek- Campground		8/15/2001	13:10	USGS	539	1.2	17.5	7.9	189	79
West Fork Battle Creek- Campground		5/23/2002	11:15	USGS	28725	64	3.5		32	12
West Fork Battle Creek- Campground		8/27/2002	11:30	USGS	148	0.33	15.5	7.6	297	120
West Fork Battle Creek- Campground		5/28/2003	9:20	USGS	135547	302	4.0	7.7	28	11
West Fork Battle Creek- Campground		8/12/2003	12:30	USGS	449	1.0	19.0	8.1	184	80
West Fork Battle Creek- Campground		5/19/2004	15:20	USGS	52962	118	7.0	7.7	32	13

Appendix B, Cont.

					Physical Parameters					
					Discharge[a]					
Station	Station ID	Date	Time	Source	gpm	ft^3/s	Water Temp (°C)	pH	Specific Conductance (µS/cm @ 25°C)	Hardness (mg/L as $CaCO_3$)
West Fork Battle Creek- Campground		8/17/2004	10:10	USGS	162	0.36	13.5	8.1	259	100
West Fork Battle Creek- Campground		9/28/2004	1350	DEQ			11.9	7.87	199.4	79.5
West Fork Battle Creek- Campground		5/25/2005	13:10	USGS		265	8.0	7.9	31	13
West Fork Battle Creek- Campground		7/21/2005	1025	DEQ	2881	6.42	14.8	7.57	69.2	30.4
West Fork Battle Creek- Campground		8/15/2005	15:45	USGS		1.2	19.0	8.3	168	63
West Fork Battle Creek- Campground		5/23/2006	12:40	USGS		322	4.5	7.9	27	12
West Fork Battle Creek- Campground		8/23/2006	11:40	USGS		0.44	17.0	7.2	252	100
West Fork Battle Creek- Campground		9/28/2006	1610	DEQ	660	1.47	11.3	7.55	144.0	62.5
West Fork Battle Creek- Campground		5/16/2007	10:20	USGS		160	5.0	7.9	29	12
West Fork Battle Creek- Campground		6/19/2007	1830	DEQ	10772	24.0	13.7	7.52	40.6	15.2
West Fork Battle Creek- Campground		8/14/2007	13:20	USGS		0.57	19.8	8.2	239	95
West Fork Battle Creek- Campground		6/17/2008	8:50	USGS		214	3.9	6.4	26	11
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ	25345	56.5	14.1	8.77	33.0	16
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ						16
West Fork Battle Creek- Campground		8/20/2008	8:15	USGS		1.4	11.0	8.5	160	65
West Fork Battle Creek- Campground		9/17/2008	1655	DEQ	561	1.25	14.5	8.03	180.7	79
Battle Creek- Above FS Road 807 (SRI9)	BC1	9/28/2006	1640	DEQ	6809	15.2	11.6	7.54	96.1	43.0
Battle Creek- Above FS Road 807 (SRI9)		6/19/2007	1905	DEQ	47576	106	14.1	7.57	43.3	17.1
Battle Creek- Above FS Road 807 (SRI9)		7/8/2008	1745	DEQ	72818	162	15.2	7.35	39.0	19
Battle Creek- Above FS Road 807 (SRI9)		9/17/2008	1725	DEQ	3604	8.03	14.6	7.69	89.7	43
Lost Creek- Campground (SRI8)	LC1	9/28/2004	1915	DEQ			8.0	7.83	43.4	18.6
Lost Creek- Campground (SRI8)		7/21/2005	950	DEQ			11.1	7.39	36.3	15.6

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**SO_4**
HC- West Fork	HC1	9/27/2004	1635	DEQ							5.4		1	
HC- West Fork		7/20/2005	1245	DEQ							4.1		0.7	
HC- East Fork	HC2	9/27/2004	1630	DEQ							4.1		0.9	
HC- East Fork		7/20/2005	1255	DEQ							3.4		0.7	
HC- RUDEFEHA (SR35)	HC3	9/27/2004	1650	DEQ							4.6		0.9	
HC- RUDEFEHA (SR35)		7/20/2005	1305	DEQ							3.8		0.7	
HC- RUDEFEHA (SR35)		9/28/2006	1015	DEQ							20.0		1.3	
HC- RUDEFEHA (SR35)		6/19/2007	1140	DEQ		0.6					2.5		-0.5	
HC- RUDEFEHA (SR35)		7/8/2008	1100	DEQ		0.4								
HC- RUDEFEHA (SR35)		9/17/2008	1340	DEQ		-2				34				
HC- Above FHM	HC4	7/19/1993		ABC	-5	-10	-20	-20	-10			-1		-2
HC- Above FHM		7/30/1993		ABC										
HC- Above FHM		8/11/1993		ABC						16				4.1
HC- Above FHM		9/2/1993		ABC		-1				16		2		3.8
HC- Above FHM		2/26/1994		ABC		-1	-20							2
HC- Above FHM		4/4/1994		ABC		-1	-20							2
HC- Above FHM		5/7/1994		ABC		-1	90							1
HC- Above FHM		6/6/1994		ABC		-1	-20							1
HC- Above FHM		7/20/1994		ABC		-1	-20							2
HC- Above FHM		9/27/2004	1720	DEQ							4.5		0.9	
HC- Above FHM		7/20/2005	1425	DEQ							3.3		0.7	
HC- Above FHM		9/28/2006	1105	DEQ						16	5.2		1.0	
HC- Above FHM		6/19/2007	1230	DEQ		1.9				12	2.4		-0.5	
HC- Above FHM		7/8/2008	1145	DEQ						10	1.7			
HC- Above FHM		9/17/2008	1425	DEQ		-2								
FHM Discharge	**FHM1**	**7/19/1993**		**ABC**		**3920**				**10**		**-1**		**16**

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
FHM Discharge		7/19/1993		ABC		4000*								
FHM Discharge		7/30/1993		ABC		4100*								
FHM Discharge		8/11/1993		ABC		4400*				20		0.1		16.5
FHM Discharge (Duplicate)		8/11/1993		ABC						20		0.1		16.5
FHM Discharge		9/2/1993		ABC		4700				28		2		19
FHM Discharge (Duplicate)		9/2/1993		ABC		4400				26		2		18.9
FHM Discharge		9/2/1993		ABC		4950*								
FHM Discharge		10/10/1993		ABC		3400								
FHM Discharge		2/26/1994		ABC		2600	400			44				15
FHM Discharge (Duplicate)		2/26/1994		ABC		2800	130			44				15
FHM Discharge		2/26/1994		ABC		2820*								
FHM Discharge		4/4/1994		ABC		2420	70							15
FHM Discharge (Duplicate)		4/4/1994		ABC		2140	60							15
FHM Discharge		4/4/1994		ABC		2730*								
FHM Discharge		5/7/1994		ABC		8800	200							26
FHM Discharge		5/7/1994		ABC		9280*								
FHM Discharge		6/6/1994		ABC		6500	30							20
FHM Discharge (Duplicate)		6/6/1994		ABC		6500	160							21
FHM Discharge		6/6/1994		ABC		6560*								
FHM Discharge		7/21/1994		ABC		5130	480			20				20
FHM Discharge (Duplicate)		7/21/1994		ABC		5140	80			25				20
FHM Discharge		7/21/1994		ABC		5150*								
FHM Discharge		8/26/1996		KP		4560*								
FHM Discharge		9/3/1996		KP		4980*								
FHM Discharge		9/6/1996		KP		3740*								
FHM Discharge		9/25/1996		KP		3730				34				26

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
FHM Discharge		10/2/1996		KP		4310*								21
FHM Discharge		3/19/1997		KP		1590								21
FHM Discharge		4/30/1997		KP		1970				42				19
FHM Discharge		6/11/1997		KP		6450				6				21
FHM Discharge		7/15/1997		KP		2850*								
FHM Discharge		7/16/1997		KP		2940*								
FHM Discharge		7/22/1997		KP		3260*								
FHM Discharge		7/24/1997		KP		3310*								
FHM Discharge		7/31/1997		KP		3350*								
FHM Discharge		8/8/1997		KP		3160*								
FHM Discharge		8/14/1997		KP		3750*								21
FHM Discharge		8/22/1997		KP		3670*								
FHM Discharge		8/29/1997		KP		3570*								
FHM Discharge		9/3/1997		KP		3620*								
FHM Discharge		9/12/1997		KP		3250*								
FHM Discharge		9/19/1997		KP		3960*								
FHM Discharge		9/26/1997		KP		3860*								
FHM Discharge		10/3/1997		KP		5380*								
FHM Discharge		12/16/1997		KP		4090								20
FHM Discharge[c]		12/17/1997		KP		3610								
FHM Discharge		2/3/1998		KP		2930								
FHM Discharge		2/4/1998		KP		4080								
FHM Discharge		3/4/1998		KP		6190								
FHM Discharge		3/11/1998		KP		3670								
FHM Discharge		3/18/1998		KP		5450								
FHM Discharge		3/25/1998		KP		4710								

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
FHM Discharge		3/31/1998		KP		3360								
FHM Discharge		4/1/1998		KP		2490*								
FHM Discharge		4/8/1998		KP		2790*								
FHM Discharge		4/15/1998		KP		2620*								
FHM Discharge		4/22/1998		KP		2860*								
FHM Discharge		4/29/1998		KP		3060*								
FHM Discharge		5/6/1998		KP		9720*								
FHM Discharge		5/13/1998		KP		9810*								
FHM Discharge		5/14/1998		KP		9660*								
FHM Discharge		5/18/1998		KP		10800*								
FHM Discharge		5/25/1998		KP		11520*								
FHM Discharge		5/28/1998		KP		11820*								
FHM Discharge		5/28/1998		KP		11870*								
FHM Discharge		6/1/1998		KP		9600*				14.8				
FHM Discharge		6/8/1998		KP		7740*				11				
FHM Discharge		6/9/1998		KP		6480*				11				
FHM Discharge		6/9/1998		KP		9135*				9.6				
FHM Discharge		6/15/1998		KP		10620*								
FHM Discharge		6/22/1998		KP		8310*								
FHM Discharge		6/23/1998		KP		5160*								
FHM Discharge		6/23/1998		KP		5400*								
FHM Discharge		6/29/1998		KP		6420*								20
FHM Discharge		7/6/1998		KP		4680*								17
FHM Discharge		7/7/1998		KP		3940*								
FHM Discharge		7/7/1998		KP		3900*								16
FHM Discharge		7/13/1998		KP		8600*				6.8				17

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
FHM Discharge		7/20/1998		KP		3980*				6.7				16
FHM Discharge		7/23/1998		KP		3060*				6.6				15
FHM Discharge		7/23/1998		KP		3080*								
FHM Discharge		7/27/1998		KP		16500								
FHM Discharge		8/3/1998		KP		5690								
FHM Discharge		8/4/1998		KP		3500*				6.8				18
FHM Discharge		8/4/1998		KP		3430*				7				17
FHM Discharge		8/10/1998		KP		7940								
FHM Discharge		8/17/1998		KP		3240*				4.8				19
FHM Discharge		8/17/1998		KP		6800								
FHM Discharge		8/18/1998		KP		3280				4.7				18
FHM Discharge		8/24/1998		KP		4470								
FHM Discharge		8/25/1998		KP		3190								
FHM Discharge		8/31/1998		KP		3450*								
FHM Discharge		9/1/1998		KP		2540								
FHM Discharge		9/1/1998		KP		2520								
FHM Discharge		9/7/1998		KP		3120*								
FHM Discharge		9/14/1998		KP		3340*								
FHM Discharge		9/21/1998		KP		3420*								
FHM Discharge		9/24/1998		KP		2730								
FHM Discharge		9/24/1998		KP		2760								
FHM Discharge		12/3/1998		KP		3470								
FHM Discharge		3/17/1999		KP		2990								
FHM Discharge		5/19/1999		KP		4520								
FHM Discharge		6/23/1999		KP		6660								
FHM Discharge		6/23/1999		KP		9100								

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
FHM Discharge		**6/30/1999**		**KP**		**5170**								
FHM Discharge		**7/7/1999**		**KP**		**4330**								
FHM Discharge		**8/4/1999**		**KP**		**18500**								
FHM Discharge		**8/11/1999**		**KP**		**10300**								
FHM Discharge		**9/2/1999**		**KP**		**4490**								
FHM Discharge		**10/6/1999**		**KP**		**3250**								
FHM Discharge		**9/27/2004**	**1735**	**DEQ**							**12.8**		**3.4**	
FHM Discharge		**7/20/2005**	**1435**	**DEQ**							**5.0**		**1.3**	
FHM Discharge		**9/28/2006**	**1120**	**DEQ**						**30**	**13.1**		**3.1**	
FHM Discharge		**6/19/2007**	**1342**	**DEQ**		**4550**				**10**	**3.4**		**0.8**	
FHM Discharge		**7/8/2008**	**1215**	**DEQ**		**4110**								
FHM Discharge		**9/17/2008**	**1438**	**DEQ**		**2530**								
HC- Below FHM (SRI3)	HC8	7/19/1993		ABC	-5	200	50	-20	-10	12		-1	-1.0	6
HC- Below FHM (SRI3)		7/30/1993		ABC										
HC- Below FHM (SRI3)		8/11/1993		ABC						18		0.1	0.8	4.9
HC- Below FHM (SRI3)		9/2/1993		ABC		210				22		2	1	5.1
HC- Below FHM (SRI3)		2/26/1994		ABC		180	-20			20			1.4	3
HC- Below FHM (SRI3)		4/4/1994		ABC		127	-20							3
HC- Below FHM (SRI3)		5/7/1994		ABC		122	60							2
HC- Below FHM (SRI3)		5/7/1994		ABC		100	40							2
HC- Below FHM (SRI3)		6/6/1994	1300	ABC		210	-20							2
HC- Below FHM (SRI3)		6/6/1994	1500	ABC										
HC- Below FHM (SRI3)		7/21/1994		ABC		320	-20			15				3
HC- Below FHM (SRI3)		9/27/2004	1830	DEQ							5.2		1.1	
HC- Below FHM (SRI3)		7/20/2005	1525	DEQ							3.4		0.6	
HC- Below FHM (SRI3)		9/28/2006	1205	DEQ						17	5.9		1.2	

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
HC- Below FHM (SRI3)		6/19/2007	1555	DEQ		222				10	2.5		-0.5	
HC- Below FHM (SRI3)		7/8/2008	1240	DEQ		193								
HC- Below FHM (SRI3)		9/17/2008	1520	DEQ		359								
HC- Above Deep Rock Creek	HC9	9/28/2006	1335	DEQ							5.7		1.2	
HC- Above Deep Rock Creek (Duplicate)		9/28/2006	1335	DEQ							5.8		1.2	
HC- Above Deep Rock Creek		6/19/2007	1630	DEQ		192					2.3		-0.5	
Deep Rock Creek	DRC1	9/28/2004	915	DEQ							4.3		1	
Deep Rock Creek		7/20/2005	1625	DEQ							3.6		0.6	
Deep Rock Creek		9/28/2006		DEQ										
HC- Below Deep Rock Creek	HC10	9/28/2004	925	DEQ										
HC- Below Deep Rock Creek		7/20/2005	1635	DEQ										
HC- Below Deep Rock Creek		9/28/2006	1340	DEQ							5.4		1.1	
HC- Below Deep Rock Creek		6/19/2007	1640	DEQ		156					2.6		-0.5	
HC- Below Deep Rock Creek		7/8/2008	1355	DEQ		97.1								
Vole Creek	VC1	9/28/2004	940	DEQ							4.8		1.3	
Vole Creek		7/20/2005	1700	DEQ							3.7		0.9	
Vole Creek		9/28/2006		DEQ										
HC- Below Vole Creek	HC11	9/28/2004	955	DEQ										
HC- Below Vole Creek		7/20/2005	1710	DEQ										
HC- Below Vole Creek		9/28/2006	1420	DEQ							5.4		1.1	
Bachelor Creek	B1	9/28/2004	1050	DEQ							5.4		1.5	
Bachelor Creek		7/21/2005	740	DEQ							4.1		1.0	
Bachelor Creek		9/28/2006		DEQ										
HC- Below Bachelor Creek	HC12	9/28/2004	1100	DEQ										
HC- Below Bachelor Creek		7/21/2005	755	DEQ										
HC- Below Bachelor Creek		9/28/2006	1500	DEQ							5.6		1.2	

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**SO_4**
Bachelor Al Creek	BA1	9/28/2004	1125	DEQ										
Bachelor Al Creek		7/21/2005	810	DEQ										
Bachelor Al Creek		9/28/2006		DEQ										
Alisha Creek	AC1	9/28/2004	1145	DEQ										
Alisha Creek		7/21/2005	830	DEQ										
Alisha Creek (Duplicate)		7/20/2005	830	DEQ										
Alisha Creek		9/28/2006		DEQ										
HC @ USGS Station (SRI4)	HC13	6/16/1993	15:15	USGS						8				
HC @ USGS Station (SRI4)		7/20/1993		ABC		60				12				2
HC @ USGS Station (SRI4)		8/12/1993		ABC						18				4.3
HC @ USGS Station (SRI4)		9/1/1993	10:30	USGS						17				
HC @ USGS Station (SRI4)		9/1/1993		ABC		24				18				4
HC @ USGS Station (SRI4)		2/26/1994		ABC		15	40			20				1
HC @ USGS Station (SRI4)		4/4/1994		ABC		20	90							1
HC @ USGS Station (SRI4)		5/7/1994		ABC		27	37							1
HC @ USGS Station (SRI4)		6/7/1994		ABC		100	-20							1
HC @ USGS Station (SRI4)		6/16/1994	16:50	USGS						12				
HC @ USGS Station (SRI4)		7/20/1994		ABC		27	40			15				2
HC @ USGS Station (SRI4)		9/21/1994	16:25	USGS						22				
HC @ USGS Station (SRI4)		6/29/1995	8:55	USGS										
HC @ USGS Station (SRI4)		9/1/1995	13:15	USGS										
HC @ USGS Station (SRI4)		5/23/1996	15:20	USGS										
HC @ USGS Station (SRI4)		7/25/1996	9:45	USGS										
HC @ USGS Station (SRI4)		5/15/1997	16:35	USGS										
HC @ USGS Station (SRI4)		8/19/1997	17:40	USGS										
HC @ USGS Station (SRI4)		6/2/1998	16:50	USGS										

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**SO_4**
HC @ USGS Station (SRI4)		8/25/1998	8:45	USGS										
HC @ USGS Station (SRI4)		5/27/1999	10:10	USGS										
HC @ USGS Station (SRI4)		9/1/1999	8:45	USGS										
HC @ USGS Station (SRI4)		5/31/2000	14:05	USGS										
HC @ USGS Station (SRI4)		8/22/2000	17:25	USGS										
HC @ USGS Station (SRI4)		5/30/2001	14:00	USGS										
HC @ USGS Station (SRI4)		8/15/2001	10:10	USGS										
HC @ USGS Station (SRI4)		5/23/2002	8:45	USGS										
HC @ USGS Station (SRI4)		8/27/2002	9:00	USGS										
HC @ USGS Station (SRI4)		5/27/2003	16:15	USGS										
HC @ USGS Station (SRI4)		8/12/2003	11:00	USGS										
HC @ USGS Station (SRI4)		5/19/2004	12:50	USGS										
HC @ USGS Station (SRI4)		8/17/2004	12:10	USGS										
HC @ USGS Station (SRI4)		9/28/2004	1205	DEQ							5.5		1.3	
HC @ USGS Station (SRI4)		5/25/2005	9:50	USGS										
HC @ USGS Station (SRI4)		7/21/2005	915	DEQ							4.1		0.8	
HC @ USGS Station (SRI4)		8/15/2005	17:15	USGS										
HC @ USGS Station (SRI4)		5/23/2006	8:50	USGS										
HC @ USGS Station (SRI4)		8/23/2006	14:30	USGS										
HC @ USGS Station (SRI4)		9/28/2006	1540	DEQ							5.8		1.3	
HC @ USGS Station (SRI4)		5/16/2007	13:30	USGS										
HC @ USGS Station (SRI4)		6/19/2007	1755	DEQ		81.7					2.6		-0.5	
HC @ USGS Station- SRI4 (Duplicate)		6/19/2007	1755	DEQ		79.9					2.7		-0.5	
HC @ USGS Station (SRI4)		8/14/2007	14:50	USGS										
HC @ USGS Station (SRI4)		7/8/2008	1455	DEQ		70.2								
HC @ USGS Station (SRI4)		6/17/2008	10:30	USGS										

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**SO_4**
HC @ USGS Station (SRI4)		8/20/2008	9:40	USGS										
HC @ USGS Station (SRI4)		9/17/2008	1610	DEQ		22								
HC @ USGS Station- SRI4 (Duplicate)		9/17/2008	1610	DEQ		22								
West Fork Battle Creek- Campground	WFBC1	6/16/1993	18:00	USGS										
West Fork Battle Creek- Campground		9/1/1993	15:45	USGS										
West Fork Battle Creek- Campground		6/16/1994	12:00	USGS										
West Fork Battle Creek- Campground		9/21/1994	12:30	USGS										
West Fork Battle Creek- Campground		6/29/1995	10:30	USGS										
West Fork Battle Creek- Campground		9/1/1995	14:30	USGS										
West Fork Battle Creek- Campground		5/23/1996	17:35	USGS										
West Fork Battle Creek- Campground		7/25/1996	12:00	USGS										
West Fork Battle Creek- Campground		5/15/1997	18:40	USGS										
West Fork Battle Creek- Campground		8/19/1997	16:35	USGS										
West Fork Battle Creek- Campground		6/3/1998	9:40	USGS										
West Fork Battle Creek- Campground		8/24/1998	17:00	USGS										
West Fork Battle Creek- Campground		5/26/1999	15:15	USGS										
West Fork Battle Creek- Campground		8/31/1999	12:00	USGS										
West Fork Battle Creek- Campground		5/31/2000	11:20	USGS										
West Fork Battle Creek- Campground		8/22/2000	15:00	USGS										
West Fork Battle Creek- Campground		5/30/2001	10:00	USGS						13				
West Fork Battle Creek- Campground		8/15/2001	13:10	USGS						56				
West Fork Battle Creek- Campground		5/23/2002	11:15	USGS						13				
West Fork Battle Creek- Campground		8/27/2002	11:30	USGS						75				
West Fork Battle Creek- Campground		5/28/2003	9:20	USGS						11				
West Fork Battle Creek- Campground		8/12/2003	12:30	USGS						53				
West Fork Battle Creek- Campground		5/19/2004	15:20	USGS						15				

Appendix B, Cont.

					Total Concentrations									
					Metals (µg/L)					Major Ions (mg/L)				
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	SO_4
West Fork Battle Creek- Campground		8/17/2004	10:10	USGS						66				
West Fork Battle Creek- Campground		9/28/2004	1350	DEQ							24.8		4.3	
West Fork Battle Creek- Campground		5/25/2005	13:10	USGS						13				
West Fork Battle Creek- Campground		7/21/2005	1025	DEQ							9.5		1.6	
West Fork Battle Creek- Campground		8/15/2005	15:45	USGS						50				
West Fork Battle Creek- Campground		5/23/2006	12:40	USGS						12				
West Fork Battle Creek- Campground		8/23/2006	11:40	USGS						69				
West Fork Battle Creek- Campground		9/28/2006	1610	DEQ							19.6		3.3	
West Fork Battle Creek- Campground		5/16/2007	10:20	USGS						14				
West Fork Battle Creek- Campground		6/19/2007	1830	DEQ		34.7					4.8		0.8	
West Fork Battle Creek- Campground		8/14/2007	13:20	USGS						64				
West Fork Battle Creek- Campground		6/17/2008	8:50	USGS						14				
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ		38.9								
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ		38.9								
West Fork Battle Creek- Campground		8/20/2008	8:15	USGS						51				
West Fork Battle Creek- Campground		9/17/2008	1655	DEQ		8								
Battle Creek- Above FS Road 807 (SRI9)	BC1	9/28/2006	1640	DEQ							13.0		2.6	
Battle Creek- Above FS Road 807 (SRI9)		6/19/2007	1905	DEQ		7.5					5.3		0.9	
Battle Creek- Above FS Road 807 (SRI9)		7/8/2008	1745	DEQ		15.0								
Battle Creek- Above FS Road 807 (SRI9)		9/17/2008	1725	DEQ		-2								
Lost Creek- Campground (SRI8)	LC1	9/28/2004	1915	DEQ							5.5		1.2	
Lost Creek- Campground (SRI8)		7/21/2005	950	DEQ							4.8		0.9	

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Ag**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**K**	**Na**	**SO_4**	**Sulfide**	**Carbon (Organic)**
HC- West Fork	HC1	9/27/2004	1635	DEQ	-0.5	0.4			-0.1										
HC- West Fork		7/20/2005	1245	DEQ	-0.5	0.5			-0.1										
HC- East Fork	HC2	9/27/2004	1630	DEQ	-0.5	0.5			-0.1										
HC- East Fork		7/20/2005	1255	DEQ	-0.5	0.4			-0.1										
HC- RUDEFEHA (SR35)	HC3	9/27/2004	1650	DEQ	-0.5	0.3		-0.1											
HC- RUDEFEHA (SR35)		7/20/2005	1305	DEQ	-0.5	1.0		-0.1											
HC- RUDEFEHA (SR35)		9/28/2006	1015	DEQ	-1	-1			-1										
HC- RUDEFEHA (SR35)		6/19/2007	1140	DEQ	-0.1	0.4		-0.5	-0.1										
HC- RUDEFEHA (SR35)		7/8/2008	1100	DEQ	-0.1	0.4			-0.1	2.0	10	3.1	-0.4	0.54	0.38	0.8	3.3	-0.5	0.96
HC- RUDEFEHA (SR35)		9/17/2008	1340	DEQ	-0.1	0.2					34	5.0	-1	0.90	0.52	0.9	4	-1	0.48
HC- Above FHM	HC4	7/19/1993		ABC	-5	-10	-20	-20			10	3.0		-1		-1			
HC- Above FHM		7/30/1993		ABC															
HC- Above FHM		8/11/1993		ABC		-1						3.6	-0.1	0.7		0.9			
HC- Above FHM		9/2/1993		ABC	-0.1	-1	-20	-20		-10		4.3		0.6		1.7			-1
HC- Above FHM		2/26/1994		ABC		19	-20					5		1					
HC- Above FHM		4/4/1994		ABC		-1	-20					5.6		1.1					
HC- Above FHM		5/7/1994		ABC		-1	-20					3.9		0.8					
HC- Above FHM		6/6/1994		ABC		-1	-20					2.8		-1					
HC- Above FHM		7/20/1994		ABC		-1	-20					4		-1					
HC- Above FHM		9/27/2004	1720	DEQ	-0.5	1.4		-0.1											
HC- Above FHM		7/20/2005	1425	DEQ	-0.5	2.0		-0.1											
HC- Above FHM		9/28/2006	1105	DEQ	-1	2		-1											
HC- Above FHM		6/19/2007	1230	DEQ	-0.1	1.5		-0.5	-0.1										
HC- Above FHM		7/8/2008	1145	DEQ	-0.1	1.6			-0.1	2.1	8	2.9	-0.4	0.54	0.38	1.2	3.3	-0.5	1.01
HC- Above FHM		9/17/2008	1425	DEQ	-0.1	1.4					16	5.0	-1	0.93	0.49	1.0	3	-1	0.54
FHM Discharge	**FHM1**	**7/19/1993**		**ABC**	**-0.5**	**3590**		**-20**		**20**		**4**		**-1**		**1**			
FHM Discharge		**7/19/1993**		**ABC**															
FHM Discharge		**7/30/1993**		**ABC**															
FHM Discharge		**8/11/1993**		**ABC**		**3500**						**6.8**		**1.7**		**1.8**			
FHM Discharge (Duplicate)		**8/11/1993**		**ABC**		**3700**						**6.8**		**1.7**		**1.7**			
FHM Discharge		**9/2/1993**		**ABC**	**0.2**	**3200**	**-20**	**-20**		**40**		**9.8**		**2.5**		**2.4**			**-1**
FHM Discharge (Duplicate)		**9/2/1993**		**ABC**	**0.2**	**2500**	**-20**	**-20**		**40**		**9.8**		**2.5**		**2.3**			**-1**
FHM Discharge		**9/2/1993**		**ABC**															
FHM Discharge		**10/10/1993**		**ABC**		**1300**													
FHM Discharge		**2/26/1994**		**ABC**		**1700**	**-20**					**14.8**		**3.7**					

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
FHM Discharge (Duplicate)		2/26/1994		ABC		1900	-20					14.9		3.7					
FHM Discharge		2/26/1994		ABC															
FHM Discharge		4/4/1994		ABC		1550	-20					17.1		4.2					
FHM Discharge (Duplicate)		4/4/1994		ABC		1680	-20					16.9		4.2					
FHM Discharge		4/4/1994		ABC															
FHM Discharge		5/7/1994		ABC		4800	-20					9.9		2.8					
FHM Discharge		5/7/1994		ABC															
FHM Discharge		6/6/1994		ABC		5500	-20					3.9		1					
FHM Discharge (Duplicate)		6/6/1994		ABC		6100	-20					4		1					
FHM Discharge		6/6/1994		ABC															
FHM Discharge		7/21/1994		ABC		4200	20					9		2					
FHM Discharge (Duplicate)		7/21/1994		ABC		4000	-20					9		2					
FHM Discharge		7/21/1994		ABC															
FHM Discharge		8/26/1996		KP															
FHM Discharge		9/3/1996		KP															
FHM Discharge		9/6/1996		KP															
FHM Discharge		9/25/1996		KP		1280	30												
FHM Discharge		10/2/1996		KP															
FHM Discharge		3/19/1997		KP															
FHM Discharge		4/30/1997		KP		850	20												
FHM Discharge		6/11/1997		KP		5900	30												
FHM Discharge		7/15/1997		KP															
FHM Discharge		7/16/1997		KP															
FHM Discharge		7/22/1997		KP															
FHM Discharge		7/24/1997		KP															
FHM Discharge		7/31/1997		KP															
FHM Discharge		8/8/1997		KP															
FHM Discharge		8/14/1997		KP															
FHM Discharge		8/22/1997		KP															
FHM Discharge		8/29/1997		KP															
FHM Discharge		9/3/1997		KP															
FHM Discharge		9/12/1997		KP															
FHM Discharge		9/19/1997		KP															
FHM Discharge		9/26/1997		KP															
FHM Discharge		10/3/1997		KP															

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
FHM Discharge		7/23/1998		KP															
FHM Discharge		7/23/1998		KP															
FHM Discharge		7/27/1998		KP															
FHM Discharge		8/3/1998		KP															
FHM Discharge		8/4/1998		KP															
FHM Discharge		8/4/1998		KP															
FHM Discharge		8/10/1998		KP															
FHM Discharge		8/17/1998		KP															
FHM Discharge		8/17/1998		KP															
FHM Discharge		8/18/1998		KP															
FHM Discharge		8/24/1998		KP															
FHM Discharge		8/25/1998		KP															
FHM Discharge		8/31/1998		KP															
FHM Discharge		9/1/1998		KP															
FHM Discharge		9/1/1998		KP															
FHM Discharge		9/7/1998		KP															
FHM Discharge		9/14/1998		KP															
FHM Discharge		9/21/1998		KP															
FHM Discharge		9/24/1998		KP															
FHM Discharge		9/24/1998		KP															
FHM Discharge		12/3/1998		KP															
FHM Discharge		3/17/1999		KP															
FHM Discharge		5/19/1999		KP															
FHM Discharge		6/23/1999		KP															
FHM Discharge		6/23/1999		KP															
FHM Discharge		6/30/1999		KP															
FHM Discharge		7/7/1999		KP															
FHM Discharge		8/4/1999		KP															
FHM Discharge		8/11/1999		KP															
FHM Discharge		9/2/1999		KP															
FHM Discharge		10/6/1999		KP															
FHM Discharge		9/27/2004	1735	DEQ	-0.5	1900		-0.1	-0.1										
FHM Discharge		7/20/2005	1435	DEQ	-0.5	3010		-0.1	-0.1										
FHM Discharge		9/28/2006	1120	DEQ	-1	3260			-1										
FHM Discharge		6/19/2007	1342	DEQ	0.2	3990		-0.5	-0.1										

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
FHM Discharge		**7/8/2008**	**1215**	**DEQ**	**0.1**	**3880**			**-0.1**	**10.5**	**9**	**4.3**	**-0.4**	**1.04**	**0.53**	**1.5**	**15.5**	**-0.5**	**0.91**
FHM Discharge		**9/17/2008**	**1438**	**DEQ**	**0.2**	**2530**					**27**	**12.3**	**-1**	**2.94**	**0.96**	**2.5**	**25**	**-1**	**0.41**
HC- Below FHM (SRI3)	HC8	7/19/1993		ABC	-5	160	-20	-20		-10		3		-1		-1			
HC- Below FHM (SRI3)		7/30/1993		ABC															
HC- Below FHM (SRI3)		8/11/1993		ABC		160						3.7		0.8		1			
HC- Below FHM (SRI3)		9/2/1993		ABC	-0.1	130	-20	-20		-10		4.7		1		1.3			-1
HC- Below FHM (SRI3)		2/26/1994		ABC		156	-20					6.1		1.4					
HC- Below FHM (SRI3)		4/4/1994		ABC		114	-20					6.9		1.5					
HC- Below FHM (SRI3)		5/7/1994		ABC		85	-20					3.8		0.8					5
HC- Below FHM (SRI3)		5/7/1994		ABC		80	-20					3.9		0.8					
HC- Below FHM (SRI3)		6/6/1994	1300	ABC		210	-20					2.6		-1					2
HC- Below FHM (SRI3)		6/6/1994	1500	ABC															
HC- Below FHM (SRI3)		7/21/1994		ABC		210	20					4		1					
HC- Below FHM (SRI3)		9/27/2004	1830	DEQ		139		-0.1											
HC- Below FHM (SRI3)		7/20/2005	1525	DEQ	-0.5	162		-0.1											
HC- Below FHM (SRI3)		9/28/2006	1205	DEQ	-1	364		-1											
HC- Below FHM (SRI3)		6/19/2007	1555	DEQ	-0.1	202		-0.5	-0.1										
HC- Below FHM (SRI3)		7/8/2008	1240	DEQ	-0.1	186			-0.1	2.7	10	2.9	-0.4	0.54	0.39	1.1	4.2	-0.5	1.25
HC- Below FHM (SRI3)		9/17/2008	1520	DEQ	-0.1	172					16	5.4	-1	1.08	0.53	1.1	6	-1	0.55
HC- Above Deep Rock Creek	HC9	9/28/2006	1335	DEQ	-1	100		-1											
HC- Above Deep Rock Creek (Duplicate)		9/28/2006	1335	DEQ	-1	103		2											
HC- Above Deep Rock Creek		6/19/2007	1630	DEQ	-0.1	175		-0.5	-0.1										
Deep Rock Creek	DRC1	9/28/2004	915	DEQ	-0.5	0.5			-0.1										
Deep Rock Creek		7/20/2005	1625	DEQ	-0.5	0.6			-0.1										
Deep Rock Creek		9/28/2006		DEQ															
HC- Below Deep Rock Creek	HC10	9/28/2004	925	DEQ	-0.5	63.6			-0.1										
HC- Below Deep Rock Creek		7/20/2005	1635	DEQ	-0.5	91.4			-0.1										
HC- Below Deep Rock Creek		9/28/2006	1340	DEQ	-1	64		-1											
HC- Below Deep Rock Creek		6/19/2007	1640	DEQ	-0.1	132		-0.5	-0.1										
HC- Below Deep Rock Creek		7/8/2008	1355	DEQ	-0.1	97.6			-0.1	2.6	10	3.1	-0.4	0.57	0.42	1.1	3.3	-0.5	0.87
Vole Creek	VC1	9/28/2004	940	DEQ	-0.5	0.5			ND										
Vole Creek		7/20/2005	1700	DEQ	-0.5	0.5			-0.1										
Vole Creek		9/28/2006		DEQ															
HC- Below Vole Creek	HC11	9/28/2004	955	DEQ	-0.5	50.7		-0.1											
HC- Below Vole Creek		7/20/2005	1710	DEQ	-0.5	78.1		-0.1											

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	**Station ID**	**Date**	**Time**	**Source**	**Cd**	**Cu**	**Fe**	**Pb**	**Ag**	**Zn**	**Alkalinity (as $CaCO_3$)**	**Ca**	**Cl**	**Mg**	**K**	**Na**	**SO_4**	**Sulfide**	**Carbon (Organic)**
HC- Below Vole Creek		9/28/2006	1420	DEQ	-1	50		-1											
Bachelor Creek	B1	9/28/2004	1050	DEQ	-0.5	0.4			-0.1										
Bachelor Creek		7/21/2005	740	DEQ	-0.5	0.3			-0.1										
Bachelor Creek		9/28/2006		DEQ															
HC- Below Bachelor Creek	HC12	9/28/2004	1100	DEQ	-0.5	31.4		-0.1											
HC- Below Bachelor Creek		7/21/2005	755	DEQ	-0.5	65.3		-0.1											
HC- Below Bachelor Creek		9/28/2006	1500	DEQ	-1	39		-1											
Bachelor Al Creek	BA1	9/28/2004	1125	DEQ	-0.5	0.6			-0.1										
Bachelor Al Creek		7/21/2005	810	DEQ	-0.5	0.5			-0.1										
Bachelor Al Creek		9/28/2006		DEQ															
Alisha Creek	AC1	9/28/2004	1145	DEQ	-0.5	0.4			-0.1										
Alisha Creek		7/21/2005	830	DEQ	-0.5	0.5			-0.1										
Alisha Creek (Duplicate)		7/20/2005	830	DEQ	-0.5	0.5			-0.1										
Alisha Creek		9/28/2006		DEQ															
HC @ USGS Station (SRI4)	HC13	6/16/1993	15:15	USGS	-1	**47**		-1	-1										
HC @ USGS Station (SRI4)		7/20/1993		ABC	-5	**50**	-20	-20		-10		3		-1		-1			
HC @ USGS Station (SRI4)		8/12/1993		ABC		**48**						4.3		0.9		1.1			
HC @ USGS Station (SRI4)		9/1/1993	10:30	USGS	**1**	**22**		-1	-1										
HC @ USGS Station (SRI4)		9/1/1993		ABC	0.1	**20**	-20	-20		20		5		1.1		1.6			1
HC @ USGS Station (SRI4)		2/26/1994		ABC		**15**	-20					6.2		1.4					
HC @ USGS Station (SRI4)		4/4/1994		ABC		**17**	30					6.5		1.4					
HC @ USGS Station (SRI4)		5/7/1994		ABC		**20**	70					3.6		0.9					4
HC @ USGS Station (SRI4)		6/7/1994		ABC		**85**	-20					2.9		-1					
HC @ USGS Station (SRI4)		6/16/1994	16:50	USGS	-1	**58**		-1	-1										
HC @ USGS Station (SRI4)		7/20/1994		ABC		**24**	-20					4		1					
HC @ USGS Station (SRI4)		9/21/1994	16:25	USGS	**1**	**14**		-1	-1										
HC @ USGS Station (SRI4)		6/29/1995	8:55	USGS	-1	**49**		-1	**6**										
HC @ USGS Station (SRI4)		9/1/1995	13:15	USGS	-1	**19**		-1	**1**										
HC @ USGS Station (SRI4)		5/23/1996	15:20	USGS	-1	**32**		-1	-1										
HC @ USGS Station (SRI4)		7/25/1996	9:45	USGS	-1	**25**		-1	**1**										
HC @ USGS Station (SRI4)		5/15/1997	16:35	USGS	-1	**14.8**		-1	-1										
HC @ USGS Station (SRI4)		8/19/1997	17:40	USGS	-1	**15.6**		-1	**1**										
HC @ USGS Station (SRI4)		6/2/1998	16:50	USGS	-8	**40.2**		-1	-4										
HC @ USGS Station (SRI4)		8/25/1998	8:45	USGS	-8	**17.5**		-1	-4										
HC @ USGS Station (SRI4)		5/27/1999	10:10	USGS	-1	**26.5**		-1	-1										

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
HC @ USGS Station (SRI4)		9/1/1999	8:45	USGS	-1	**18**		-1	-1										
HC @ USGS Station (SRI4)		5/31/2000	14:05	USGS	-1	**60.7**		-1	-1										
HC @ USGS Station (SRI4)		8/22/2000	17:25	USGS	-1	**14.1**		-1	-1										
HC @ USGS Station (SRI4)		5/30/2001	14:00	USGS	0.05	**66**		0.33	-1										
HC @ USGS Station (SRI4)		8/15/2001	10:10	USGS	-0.04	**19.1**		-0.08	-1										
HC @ USGS Station (SRI4)		5/23/2002	8:45	USGS	E0.03	**26.5**		E.06	-1										
HC @ USGS Station (SRI4)		8/27/2002	9:00	USGS	-0.04	**15.1**		-0.08	-1										
HC @ USGS Station (SRI4)		5/27/2003	16:15	USGS	-0.04	**35.9**		E0.04	-0.2										
HC @ USGS Station (SRI4)		8/12/2003	11:00	USGS	-0.04	**20.8**		-0.08	-0.2										
HC @ USGS Station (SRI4)		5/19/2004	12:50	USGS	E0.02	**27.4**		-0.08	-0.2										
HC @ USGS Station (SRI4)		8/17/2004	12:10	USGS	-0.04	**18.5**		0.1	-0.2										
HC @ USGS Station (SRI4)		9/28/2004	1205	DEQ	-0.5	**22.8**			-0.1										
HC @ USGS Station (SRI4)		5/25/2005	9:50	USGS	-0.04	**52.7**		0.23	-0.2										
HC @ USGS Station (SRI4)		7/21/2005	915	DEQ	-0.5	**43.8**			-0.1										
HC @ USGS Station (SRI4)		8/15/2005	17:15	USGS	E0.04	**20.6**		0.11	-0.2										
HC @ USGS Station (SRI4)		5/23/2006	8:50	USGS	-0.04	**48.3**		-0.08	-0.2										
HC @ USGS Station (SRI4)		8/23/2006	14:30	USGS	-0.04	**17.5**		-0.08	-0.2										
HC @ USGS Station (SRI4)		9/28/2006	1540	DEQ	-1	**29**		1											
HC @ USGS Station (SRI4)		5/16/2007	13:30	USGS	-0.04	**49.5**		E0.09	-0.1										
HC @ USGS Station (SRI4)		6/19/2007	1755	DEQ	-0.1	**74.7**		-0.5	-0.1										
HC @ USGS Station- SRI4 (Duplicate)		6/19/2007	1755	DEQ	-0.1	**75.2**		-0.5	-0.1										
HC @ USGS Station (SRI4)		8/14/2007	14:50	USGS	**0.09**	**19.4**		E0.07	-0.1										
HC @ USGS Station (SRI4)		7/8/2008	1455	DEQ	-0.1	**63.9**			-0.1	2.7	10	3.3	-0.4	0.67	0.38	1.1	3.4	-0.5	0.99
HC @ USGS Station (SRI4)		6/17/2008	10:30	USGS	-0.04	**42.4**		E0.05	-0.1										
HC @ USGS Station (SRI4)		8/20/2008	9:40	USGS	-0.04	**19.5**		-0.08	-0.1										
HC @ USGS Station (SRI4)		9/17/2008	1610	DEQ	-0.1	**20.2**					21	5.5	-1	1.15	0.48	1.4	5	-1	0.92
HC @ USGS Station- SRI4 (Duplicate)		9/17/2008	1610	DEQ	-0.1	**20.8**					18	5.9	-1	1.24	0.48	1.4	5	-1	0.90
West Fork Battle Creek- Campground	WFBC1	6/16/1993	18:00	USGS	-1	**28**	84	2	-1	110									
West Fork Battle Creek- Campground		9/1/1993	15:45	USGS	-1	7	15	-1	-1	-10									
West Fork Battle Creek- Campground		6/16/1994	12:00	USGS	**1**	**17**	33	-1	**2**	40									
West Fork Battle Creek- Campground		9/21/1994	12:30	USGS	-1	4	15	-1	-1	-10									
West Fork Battle Creek- Campground		6/29/1995	10:30	USGS	-1	**32**	37	-1	**3**	50									
West Fork Battle Creek- Campground		9/1/1995	14:30	USGS	-1	**8**	11	-1	-1	10									
West Fork Battle Creek- Campground		5/23/1996	17:35	USGS	-1	**15**	63	-1	-1	240									
West Fork Battle Creek- Campground		7/25/1996	12:00	USGS	-1	**8**	6	-1	-1										

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
West Fork Battle Creek- Campground		5/15/1997	18:40	USGS	-1	**8.1**	65	-1	-1	100									
West Fork Battle Creek- Campground		8/19/1997	16:35	USGS	-1	**7.5**	-3	-1	-1	10									
West Fork Battle Creek- Campground		6/3/1998	9:40	USGS	-8	**21.7**	30	-1	-4	40									
West Fork Battle Creek- Campground		8/24/1998	17:00	USGS	-8	**7.2**	-10	-1	-4	-10									
West Fork Battle Creek- Campground		5/26/1999	15:15	USGS	-1	**9.3**	179	-1	-1	288									
West Fork Battle Creek- Campground		8/31/1999	12:00	USGS	-1	6.1	E5	-1	-1	5									
West Fork Battle Creek- Campground		5/31/2000	11:20	USGS	-1	**36.0**	22	-1	-1	-44.3									
West Fork Battle Creek- Campground		8/22/2000	15:00	USGS	-1	4.9	-10	-1	-1	4.4									
West Fork Battle Creek- Campground		5/30/2001	10:00	USGS	0.13	**33.1**	25	0.12	-1	31.7									
West Fork Battle Creek- Campground		8/15/2001	13:10	USGS	-0.04	6.1	E8	-0.08	-1	5.2									
West Fork Battle Creek- Campground		5/23/2002	11:15	USGS	0.06	**12.2**	21	0.37	-1	24.2									
West Fork Battle Creek- Campground		8/27/2002	11:30	USGS	E0.03	2.9	15	-0.08	-1	2.6									
West Fork Battle Creek- Campground		5/28/2003	9:20	USGS	-0.04	**19.4**	26	-0.08	-0.2	36.7									
West Fork Battle Creek- Campground		8/12/2003	12:30	USGS	-0.04	6.7	9	-0.08	-0.2	4.8									
West Fork Battle Creek- Campground		5/19/2004	15:20	USGS	E0.02	**13.8**	21	E0.05	-0.2	23.6									
West Fork Battle Creek- Campground		8/17/2004	10:10	USGS	0.06	4.9	E4	-0.08	-0.2	4.1									
West Fork Battle Creek- Campground		9/28/2004	1350	DEQ	-0.5	5.9			-0.1										
West Fork Battle Creek- Campground		5/25/2005	13:10	USGS	-0.04	**24.0**	34	-0.08	-0.2	33.5									
West Fork Battle Creek- Campground		7/21/2005	1025	DEQ	-0.5	**15.4**			-0.1										
West Fork Battle Creek- Campground		8/15/2005	15:45	USGS	-0.04	**6.6**	E6	0.26	-0.2	6.1									
West Fork Battle Creek- Campground		5/23/2006	12:40	USGS	-0.04	**26.1**	38	0.10	-0.2	51.8									
West Fork Battle Creek- Campground		8/23/2006	11:40	USGS	-0.04	4.4	12	-0.08	-0.2	3.9									
West Fork Battle Creek- Campground		9/28/2006	1610	DEQ	-1	**9**			-1										
West Fork Battle Creek- Campground		5/16/2007	10:20	USGS	-0.04	**25.8**	42	-0.12	-0.1	50.2									
West Fork Battle Creek- Campground		6/19/2007	1830	DEQ	-0.1	**31.2**		-0.5	-0.1										
West Fork Battle Creek- Campground		8/14/2007	13:20	USGS	E0.02	6.3	9	-0.12	-0.1	6.5									
West Fork Battle Creek- Campground		6/17/2008	8:50	USGS	-0.04	**23.1**	81	E0.06	-0.1	90.4									
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ	-0.1	**34.4**			-0.1	2.0	14	4.9	-0.4	0.92	0.38	1.3	4.6	-0.5	1.04
West Fork Battle Creek- Campground		7/8/2008	1555	DEQ	-0.1	**34.3**			-0.1	1.6	13	5.1	-0.4	0.92	0.38	1.4	4.8	-0.5	1.01
West Fork Battle Creek- Campground		8/20/2008	8:15	USGS	-0.04	**6.5**	*7	-0.08	-0.1	4.9									
West Fork Battle Creek- Campground		9/17/2008	1655	DEQ	-0.1	**7.3**					51	24.7	3	4.18	0.71	6.4	33	-1	1.40
Battle Creek- Above FS Road 807 (SRI9)	BC1	9/28/2006	1640	DEQ	-1	2		-1											
Battle Creek- Above FS Road 807 (SRI9)		6/19/2007	1905	DEQ	-0.1	6.7		-0.5	-0.1										
Battle Creek- Above FS Road 807 (SRI9)		7/8/2008	1745	DEQ	-0.1	12.1			-0.1	1.7	16	5.7	-0.4	1.05	0.37	1.6	4.5	-0.5	1.11
Battle Creek- Above FS Road 807 (SRI9)		9/17/2008	1725	DEQ	-0.1	1.1					39	13.2	-1	2.51	0.52	2.4	9	-1	1.28

Appendix B, Cont.

					Dissolved Concentrations														
					Metals (µg/L)						Major Ions (mg/L)							Non-Metals (mg/L)	
Station	Station ID	Date	Time	Source	Cd	Cu	Fe	Pb	Ag	Zn	Alkalinity (as $CaCO_3$)	Ca	Cl	Mg	K	Na	SO_4	Sulfide	Carbon (Organic)
Lost Creek- Campground (SRI8)	LC1	9/28/2004	1915	DEQ	-0.5	0.4			-0.1										
Lost Creek- Campground (SRI8)		7/21/2005	950	DEQ	-0.5	0.4			-0.1										

* Cu measured with Hach colorimeter test kit

[a] Discharge values for the FHM effluent include instantaneous, mean daily and mean weekly estimates.

[b] ND - Not detected at reporting limit.

E- Estimated value

Appendix C. WSII and WY RIVPACS scores and corresponding narrative aquatic life use assignments for sites on Haggarty Creek, West Fork Battle Creek and Lost Creek, Carbon, County, WY (1996-2008). F = Full-Support, I = Indeterminate, P/N = Partial/Non-Support.

	HC3	HC8			HC14			WFBC1			LC1			
Southern Rockies WSII Metrics	9/25/2001	8/21/1996	9/26/2001	9/17/2008	8/21/1996	9/26/2001	9/17/2008	8/22/1996	9/27/2001	9/16/2008	8/22/1996	9/27/2001	9/25/2002	9/17/2003
Number of Ephemeroptera taxa	7	3	1	1	1	2	2	4	3	4	6	6	7	7
Number of Trichoptera taxa	8	2	1	1	3	4	6	9	10	6	9	11	11	10
Number of Plecoptera taxa	10	1	0	1	1	0	2	4	4	4	6	8	5	7
% Non-insects	8.96	12.50	55.56	23.08	0.67	0.17	2.29	14.43	3.96	18.32	5.37	4.49	4.15	1.22
% Trichoptera (less Hydropsychidae) (% within community)	9.43	18.75	11.11	2.56	3.36	6.86	10.89	4.08	85.87	30.80	53.17	34.44	20.38	13.44
Number of Scraper taxa	6	2	0	0	0	2	2	6	3	2	3	4	6	5
Biological Condition Index (CTQa)	56.9	54.5	96.0	94.4	72.0	66.1	79.4	65.8	57.3	58.8	53	61.33	61.3	60.4
Number of Semi-voltine taxa (less semivoltine Coleoptera)	0	0	0	0	1	1	2	2	1	4	4	2	2	2
WSII Score	**62.8**	**36.7**	**7.1**	**13.6**	**28.7**	**35.2**	**40.3**	**53.2**	**61.4**	**57.6**	**75.0**	**72.7**	**68.7**	**67.7**
WSII Narrative Assignment	**I**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**I**	**I**	**I**	**F**	**F**	**F**	**I**
WY RIVPACS Score	**0.69**	**0.40**	**0.13**	**0.35**	**0.20**	**0.30**	**0.4**	**0.80**	**0.50**	**0.75**			**0.98**	**1.03**
WY RIVPACS Narrative Assignment	**I**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**I**	**P/N**	**I**	**F**	**F**	**F**	**F**
Aquatic Life Use-Support (Combined WSII and WY RIVPACS Narrative Assignments)	**I**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**P/N**	**I**	**I**	**I**	**F**	**F**	**F**	**F**

Appendix D. Potential remediation alternatives proposed by Adrian Brown Consultants, Inc. (Adrian Brown 1994).

6.0 REMEDIAL ASSESSMENT

6.1 REMEDIAL CONCEPT

6.1.1 Potential remedial strategies

Potential remediation strategies for the Osceola Tunnel mine effluent were initially considered under four categories:

- No action
- Source control
- Pathway control
- Effluent control

All remediation plans need to consider a no action alternative. Evaluation of a no action alternative provides a means in which to compare any gains or benefits provided in implementation of any one of the other identified alternatives. Emplacement of source control(s) would prevent the water/orebody interaction such that water would not become contaminated. Pathway control(s) would prevent contaminated water from entering the stream, at least directly. Effluent control would utilize some type of treatment technology to remediate contaminated water prior to entering the surface water system.

6.1.2 Remedial technologies considered

Remedial technologies/approaches which appear to have applicability in the Ferris-Haggarty setting are as follows:

Source Controls

1. Removal of the source
   a) Mine all material containing leachable copper

2. Eliminate the source of water leaching the copper
   a) Install upgradient surface water flow diversions
   b) Seal streambed with grout/clay/HDPE liners
   c) Seal all upgradient surface/mine connections
   d) Seal land surface above mine workings
   e) Revegetation above old mine workings

3. Remove oxidation availability to orebody
   a) Seal exposed orebody by flooding mine or area(s) of mine
   b) Seal exposed orebody by plugging mine or area(s) of mine
   c) Seal surface above mine workings to exclude air

4. Control solubility of copper
   a) Prevent the formation of copper colloids or complexes
   b) Remove the copper material(s) from solution at source

Pathway Controls

1. Internal mine flow controls
   a) Seal portal
   b) Seal other portions of mine to control flow path[5]
   c) Segregate clean water from copper laden leachate in mine

2. External mine flow controls
   a) Reroute mine discharge across contour above Haggarty Creek
   b) Pipe mine discharge to Belvidere Ditch for disposal
   c) Pipe mine discharge to Lost Creek/West Fork Battle Creek

Effluent Controls

1. Organic/biological treatments
   a) Wetlands treatment
   b) Organic flow-through system
   c) Activated sludge system
   d) Rotating biological contactor
   e) Trickling filter

2. Chemical/geochemical treatment
   a) Simple reduction/oxidation
   b) Ion exchange
   c) Precipitation at alkaline pH in settling ponds
   d) Electrolytic precipitation
   e) Reverse osmosis

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[5] *Although the pathway control alternatives of sealing portions of the mine and/or segregating clean water within the mine may be possible, there is an insufficient amount of information available at this time to determine the feasibility or cost of such alternatives. The information required to make this determination will require opening the portal. Further evaluation of these alternatives should, therefore, be considered if any reconstruction of the Osceola Tunnel is performed.*

6.1.3 System considerations

Flow control

Where possible, each remediation system has been evaluated both with and without flow control. The discharge from the Osceola Tunnel varies greatly over the year, ranging from 40 to 400 gpm in a normal year with even greater flows possible in an extreme year. The issue of flow variability impacts the assessment of remedial alternatives in that the capital cost of most of the remedies will increase if flow control is not provided. In general, the absence of flow control has the following cost impacts:

- no availability to locate equipment within the secured portal, thereby requiring the installation of heated buildings without exception;
- the absence of a plug or dam in the portal discharge will either require the installation of feed pumps and associated power generating equipment to transfer the water through the treatment equipment or, alternatively, will require the treatment system be located down slope such that there would be sufficient head differential between the discharge collection point and the treatment system to provide a hydrodynamic driving force. This second option represents an increased capital and operating cost in that freeze protected, pressure rated piping will be required to transfer the water.
- equipment will be larger in size such that it can accommodate a greater maximum flow;
- instrument control systems will be more complex.

Failure to provide flow control will also increase the risk of failure in that:

- the systems will be, in general, more complex; and,
- there will be no way to turn the discharge off should equipment begin to malfunction or need cleaning, etc.

Further, many of the remedial elements presented above are difficult to operate at this location in the winter due to the elevation, temperature, snow depth, difficulty of maintaining access, and lack of power. In the spring, it is difficult to operate due to high stream flows, soft ground, and unreliable weather conditions. Accordingly, remedial operating costs can be dramatically reduced by operating during the summer and fall, rather than year-round. In the absence of flow control, however, these increased operating costs must be included.

In order to achieve flow control, a considerable storage of water is required. This storage can be achieved by the following means:

1. Mine storage. Based on the amount of material which was removed from the mine during operation (estimated at about 200,000 tons of ore), and the current remaining mine voids (estimated at the equivalent of 400,000 tons of total production) it would appear that the mine has a storage volume in the order of 30 million gallons. This is sufficient volume to contain between 6 months and one year's flow from the mine portal. The drainage drift provides an outlet at elevation 9501 feet, with the next outlet being a drift at elevation 9846 feet. Plugging of the drainage adit provides the opportunity for flow from the mine to be controlled, with surge flow being reduced to an average flow of around 100 gpm annually, or 200 gpm if the discharge were to be limited to six months of the year.

2. Reservoir storage. If a reservoir were to be built, it would have to have an active storage of about the same as the mine, that is about 30 million gallons (or about 100 acre feet). This is a relatively large reservoir (for example it would require a cistern 500 feet on a side, and 20 feet deep), and would not be likely to be feasible at this site.

Based on the assessment of flow control mechanisms presented above, each remedial action that involves treatment or transport of the water is evaluated for the conditions of no flow control and flow control via storage in the mine voids.

Winter Operations

The "no flow control" evaluation of the various remedial actions requires the consideration of winter operations. This includes the assumptions that access will be maintained during the winter and facilities will be located either in heated buildings or underground.

Reliability

The reliability of the remediation is important to the selection of the preferred process. If the system fails such that dissolved copper is again released into Haggarty Creek, the result may be the elimination of the fishery and/or other aquatic organisms re-established in the stream. Accordingly, success of any remediation is impacted by the reliability of the solution. For this reason, passive remedial approaches are preferable to active in this environment, due to the difficulty of maintaining year-round access, and the difficulty of monitoring the performance of any remedy in the long term.

It is worthy of note, however, that the reliability of the system may not be so critical as to warrant costly secondary and/or tertiary backup systems. Based on evaluations

completed during this study, it appears that populations of Colorado River cutthroat trout may have survived nearly 100 years of creek contamination by using the side tributaries; it is therefore presumed that if the mainstem stream were temporarily contaminated, re-population could occur once the remedial system were re-established.

6.2 REMEDIATION ALTERNATIVES

The following sections present a preliminary discussion of various remediation alternatives. Each discussion includes a brief description of the basic technology involved, a preliminary cost estimate (±50%), advantages and disadvantages of each alternative, and a brief assessment of the reliability of the technology.

Design Development

A conceptual design of each remedial alternative was developed in order to establish a preliminary cost estimate. Each alternative had to consider several significant requirements:

- Any system shutdown, failure, overflow, or release is likely to exceed one of the industrial standards for copper (acute:0.30 mg/l; chronic:0.15 mg/l; see Section 4.1.1), and hence, create a potential compliance issue with the CWA.
- Any uncontrolled release of water to the creek will have a potentially negative impact on part or all of the regained aquatic habitat.
- No matter what remediation system is selected, site access limitations must be a significant design consideration both from the standpoint of difficulties associated with getting to the site as well as difficulties associated with protecting the equipment at the site from theft/vandalism.
- Remediation designs must also consider the impact of the system or ancillary construction on the general safety of the site from a public access perspective.

Cost Estimate Preparation

Using the preliminary designs, cost estimates were prepared. A more detailed analysis will be required to confirm the viability of any selected alternative before a

construction design and estimate can be prepared. The cost analysis for each remedial option was estimated using the following parameters:

- Operating life of twenty years.
- Net present value in 1994 dollars.
- Discount rate of 5 percent.

In regard to the cost impact of no flow control versus flow control, Williams[6] demonstrated the equipment size and cost correlated fairly well to the logarithmic relationship known as the "six-tenths factor." The relationship, in equation form, is:

$$C_n = f(r^{0.6}C_D + C_I)$$

where C_n is the new equipment cost, f is a lumped sum cost index, r is the ratio of new equipment capacity to old equipment capacity, C_D is the total direct cost, and C_I is the total indirect cost.

For the purposes of comparing installations of dissimilar size equipment which would have the same construction date and location, such as is the case in comparing the impact of increased equipment size due to no flow control, f is equal to one. The cost estimates presented in the following discussions were originally developed assuming flow control would be provided and used an equipment size required to accommodate 300 gpm. To develop the cost estimate for a "no flow control" scenario, a new equipment capacity of 500 gpm is required. With this, the equipment ratio factor for the six-tenths equation would be:

$$r^{0.6} = (500/300)^{0.6} = 1.36 \text{ or } 136\%$$

Therefore, the cost of equipment for alternatives without flow control will be 136% of the capital cost of equipment designed to operate with flow control. The indirect cost does not change appreciably in that engineering costs, etc. are not affected, within reason, by equipment size; i.e. it cost the same to design a 500 gpm reactor as it does a 300 gpm reactor.

Reliability/Risk of Failure Analysis

Two aspects of reliability are addressed in the Reliability/Risk of Failure discussions. The first consideration involves the reliability of the technology from a technical applicability and most likely mode of failure perspective. In regard to this consideration of the reliability, the following questions are addressed:

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[6] *Chemical Engineering*, **54**(12), p. 124, 1947.

1. What is the likelihood the remediation alternative will be technically able to perform in the conditions associated with the Ferris-Haggarty/Osceola mine site application?

2. Given the alternative is technically able to perform under the conditions of the Ferris Haggarty mine, how likely is it that the treatment process will consistently attain the required discharge level of copper?

3. What is the most likely mode of failure for the alternative?

The second aspect of the reliability discussion centers on the impacts or risks associated with a treatment system failure.

Technology Development

Although the analysis of remedial alternatives began with an evaluation of individual strategies, the final products of the design process are a compilation of one or more strategies. This is, for the most part, out of necessity. For instance, typically all of the treatment scenarios either required or benefitted significantly by some form of flow control. Without flow control, the treatment system would have to accommodate both maximum peak flow during the spring thaw as well as nominal flow rates through other periods of the year.

Based on the project team's assessment, the most functional and cost effective form of flow control applicable at the Ferris-Haggarty/Osceola Tunnel site is obtained by plugging the portal. The portal plug alternative is, therefore, presented as an alternative in and of itself as well as being included as a flow control mechanism for several of the other treatment options. Similarly, some technologies were determined to have a viable chance of obtaining the remediation goals only in combination with other technology. An example of this is the wetlands/reroute discharge option. This technology will only reasonably obtain the remediation goals if used in conjunction with a more aggressive primary treatment step.

As identified in Section 2.1, the preferred options, by project design are those minimizing:

- Complexity
- Cost
- Extent of disturbance
- Impact on mineral interests
- Maintenance
- Use of non-natural materials

Intuitively, favored options would consist of passive treatment systems, such as:

- Plug the portal;
- Seal/divert above the mine;
- In-mine flow segregation;
- Portal plugging with wetlands discharge; and,
- Portal plugging with simple effluent treatment.

Although active treatment technologies were initially considered infeasible due to perceived cost restrictions, a discussion of such alternative technologies have been included at the request of AML. The following relevant treatment technologies applicable to the portal discharge were reviewed:

- Chemical precipitation;
- Ion exchange;
- Reverse osmosis;
- Other combinations of treatment methods commonly used on heavy metal removal applications.

State of the art advancements have been considered in each technology evaluation provided. Different power sources, including solar energy, diesel generator, and hydropower were investigated. Due to site limitations and heavy power demands for some alternatives, solar energy is not considered feasible. For the most part, it was determined the most economical power supply would involve the use of hydrodynamic energy to transport the water and batteries, charged by the generator as needed, to run most if not all of the instrumentation.

Twelve strategies, reviewed in some detail, are presented below:

- No Action
- Plugging the Portal
- Rerouting/Wetland Treatment
- Reduction/Oxidation
- Ion Exchange (IX)
- Chemical Precipitation
- Chemical Precipitation with IX
- Ion Exchange with Electrolytic Recovery
- Reverse Osmosis
- Pipeline to Belvidere Ditch
- Pipeline to Lost Creek/Battle Creek
- Alternative Treatment Siting

associated with an easier access to the facility, especially once SH70 upgrades are completed.

Estimated Costs

An example cost of the least expensive treatment option is included in the summary table, Table 6-17.

6.3 SUMMARY OF REMEDIAL APPROACHES

The cost estimates for the remediation alternatives discussed above are summarized in Table 6-17.

Table 6-17 - Cost Estimate - Summary of Alternatives

CONTROL STRATEGY	CAPITAL[2] COST	ANNUAL OPERATING COST	NPV OP + CAP COST
No Action	$ 0	$ 0	$ 0
Plug Portal	$ 200,000	$ 1,000	$ 212,000
Wetlands	$ 350,000	$ 5,000	$ 412,000
Reduction/Oxidation	$ 467,000	$ 13,000	$ 629,000
Redox + Wetlands	$ 617,000	$ 18,000	$ 841,000
Ion Exchange	$1,499,000	$ 91,000	$2,633,000
Chem Precip (lime)	$ 266,000	$ 78,000	$1,238,000
Chem Precip (NaOH)	$1,325,000	$ 116,000	$2,771,000
Chem Precip+IX (lime)	$1,808,000	$ 116,000	$3,254,000
Chem Precip+IX (NaOH)	$2,592,000	$ 138,000	$4,312,000
IX + Recovery	$1,640,000	$ 58,000	$2,363,000
Reverse Osmosis	$1,437,000	$ 236,000	$4,378,000
Belvidere Ditch Pipe	$1,164,000	$ 2,000	$1,189,000
Battle Creek Pipe	$1,354,000	$ 2,000	$1,379,000
Treatment at SH-70[1]	$2,703,100	$ 103,000	$3,987,000

[1] Assumes the least expensive form of treatment (IX) and 10% reduction in capital and operating costs.
[2] Costs do not include road upgrade.

The remedial approaches fall into five categories:

1. No action. This is a maintenance of the current situation. No cost is incurred, and the main stem of Haggarty Creek remains barren of fish.

2. Plug portal. This strategy involves using the mine as a reservoir, to distribute the flow which enters the mine. Ideally, the discharge will pass through the rockmass surrounding the mine and reappear as seeps across the hillside. This technology is expected to cost about $200,000, and will require little

maintenance. It is not known whether this strategy will fully protect the stream, although it is expected to reduce the flow and mass flux of copper to Haggarty Creek.

3. Wetlands treatment. This strategy involves copper removal using passive wetlands technology, with flow control achieved by portal plugging. Total cost is about $400,000. It is expected that this technology will require some maintenance.

4. Pipe flow past Haggarty Creek. This group of strategies involves piping the flow from the portal past the sensitive portion of the stream, discharging the effluent at a location where it will not impact fisheries. This treatment is a passive system, and is expected to cost about $1 million.

5. Treatment of flow. This strategy involves conventional treatment of the flow from the Osceola Tunnel, using a range of feasible methods. These remedies cost between $1 million and $4 million.

Generally speaking, the simpler alternatives will likely provide the better overall performance while minimizing the risk. Additionally, a phased approach to remediating Haggarty Creek beginning with the simplest method is likely to provide the most satisfactory results. Based on considerations of cost, practicality, and potential for remediating Haggarty Creek, a reasonable approach to remediation of the creek is as follows:

1. Plug the portal and implement a quarterly monitoring program for a period of one year to assess the impact of the plug on creek quality and the surrounding habitat.

2. Depending upon the results of the first year's monitoring, one of three actions may be taken:

   - If the desired water quality in Haggarty Creek has been obtained, implement an annual monitoring program for both water quality and aquatic biota for a period of three years. If after three years the water quality in Haggarty Creek continues to meet the recommended concentrations, the restoration of the fishery in Haggarty Creek should be considered accomplished.

   - If the data indicates that water quality is improving, continue the monitoring for an additional period of time.

   - If there is no evidence of improved water quality, construct a wetlands system and divert flow at a controlled rate. Continue the quarterly

monitoring program for an additional year after the construction of the wetlands is complete.

An alternative solution that may be within a reasonable economic consideration is to pipe the discharge directly to Belvidere Ditch or Lost Creek/West Fork Battle Creek. This approach assures the attainment of the remediation goal provided the continuous operation and integrity of the pipeline can be maintained.

Ultimately, WDEQ/AML and the State of Wyoming must conclude which alternative best protects the concerns of the citizens of Wyoming. This decision-making process will require an assessment of both the quantifiable costs and benefits (Section 4) as well as the less quantifiable considerations associated with environmental, aesthetic, historical and mineral resource impacts.

Appendix D (Cont.) Potential remediation alternatives proposed by Knight Piésold, LLC.

In 1996, AML contracted with Knight Piésold, LLC to perform in-mine investigations at the Ferris-Haggarty Mine (FHM) to identify and characterize sources of water and copper (Cu) contamination and develop mitigation options. Their pre-design report (Knight Piésold 1999) presents an evaluation of potential alternatives based on site characterizations conducted over the past several years.

The FHM was re-opened in 1996 and rehabilitation of the Osceola Tunnel was initiated in 1997. The work included partial removal of a caved zone which allowed access to evaluate various mine drainage waters. The hydrologic and chemical aspects of various water sources within the tunnel were monitored during the 1997 and 1998 hydrologic cycles. The site characterization showed that the mine drainage is comprised of two distinct water sources; a relatively 'clean' (low Cu concentration) water source that enters the first 1000 feet of tunnel, and a contaminated (high Cu concentration) source originating from a caved zone about 1,400 feet from the portal.

Given the opportunity to separate relatively clean from contaminated water, three potential water sources were identified for possible treatment. These sources included treating the total Osceola

Tunnel discharge, treating only sources of contaminated water and treating a mixture of some of the relatively clean and all of the contaminated water.

Four basic treatment alternatives were evaluated for remediating the FHM effluent:

- No Action
- Source Control
- Active Treatment
- Passive Treatment

Economic Considerations

Detailed economic analyses were conducted by Knight Piésold on five active treatment options, including polymeric precipitation, chemical precipitation, cation exchange, reverse osmosis and electrodialysis. The economics of the no action alternative was not evaluated because it did not meet project goals, and none of the source control alternatives were considered practical enough to merit the analysis of their economics.

Based on the economic analyses of the active and passive treatment alternatives, passive treatment was considered to offer a technically feasible approach to mitigate the Cu contamination at a reasonable cost. The cost of passive treatment compared favorably with that of active treatment options, but would not require any energy inputs. Minimal maintenance would be required and the system could be left unattended for extended periods.

The construction cost of the passive treatment system was estimated at $1.51 million (1999 dollars), including underground water diversion and reinforcement of the underground mine roof with steel sets in the first 600 feet of the tunnel. The passive treatment system operational costs were estimated to range from $14,000 to $24,000 per annum, including scheduled major repair work (organic substrate replacement) every 30 to 50 years. The costs of diverting the mine water to the treatment facility and installing steel sets (common to all alternatives) were estimated at $282,000.

Technical Considerations

Active treatment technologies face a number of significant obstacles in addressing water contamination at the FHM (Knight Piésold 1999). While the benefit of all active treatment processes includes the flexibility in treating variable flows, they have two major draw backs. These are the high energy

requirement and the monitoring and maintenance of generators, pumps and mixers at the relatively remote and inaccessible (during eight months of the year) FHM site.

Because of the site's remote location AML encouraged the evaluation of passive treatment techniques. Reasons for recommending this approach are described in the reports prepared by Knight Piésold (1998, 1999, 2000) and submitted to the WDEQ AML program. Knight Piésold conducted laboratory, bench-scale and pilot-scale passive treatment experiments during the course of their investigations. Results of those tests proved promising.

Knight Piésold's conceptual-level design of the passive treatment system consisted of treating only the contaminated water source. From this location, the contaminated flows would be conveyed by a discharge pipe to the passive treatment facility. Relatively clean water originating within the first 1,000 feet of tunnel would not be treated (identified as the 'untreated' portion of the mine discharge), allowing for a smaller system design. The facility, consisting of four anaerobic cells and an aerobic cell, would be designed to accommodate a maximum flow rate of about 490 gpm. The primary anaerobic cell would treat flow year-round at a rate of about 25 gpm. Three larger cells would process water during spring runoff at a maximum rate of 155 gpm each. The purpose of the aerobic cell is to aerate and 'polish' the treated water prior to discharging into Haggarty Creek.

During peak flow conditions, the average maximum flow rate at the Osceola Tunnel portal was estimated at about 650 gpm. Because the design capacity of the passive treatment system is 490 gpm, about 200 gpm (during peak flow conditions) of mine discharge would not be treated. This relatively clean water would be diverted from the portal into Haggarty Creek, immediately upstream of the treated discharge point. Since the duration of the peak flow period is short-lived, the contention was that flows at the portal would rapidly diminish as water infiltration into the mine workings decreased with the receding snowpack at the surface.

A treated concentration of 0.15 mg/L total Cu with an in-stream target concentration of 0.007 mg/L (7 µg/L) were identified as the water quality targets to be achieved for the mine effluent and Haggarty Creek below the FHM, respectively. The targets were based on whole effluent toxicity test results (Adrian Brown 1994, Knight Piésold 1999) which consist of exposing a small population of test organisms *(Ceriodaphnia dubia)* to various concentrations of mine discharge water to determine what

concentration is required for half the population to survive exposure for 48 hours. That concentration is commonly referred to as the "lethal-concentration- 50 percent", or LC_{50}. When wet test results are used for regulatory compliance the LC_{50} value is the typical performance criterion.

The following excerpts, paraphrased from the Knight Piésold pre-design report (1999), provide an overview of the principle concepts of the passive treatment process and conceptual layout of the system. The Knight Piésold report provides a more detailed discussion, including cost/benefit analyses, conceptual treatment design layout, performance monitoring, proposed construction schedule and projected costs.

Passive Treatment Concept

Description

Passive water treatment includes processes that utilize common geochemical reactions typically assisted by microbes or plants to improve water quality. These processes do not require the steady addition of reagents, power and/or the short-term periodic exchange of process media.

Passive treatment systems include aerobic (oxygen-rich) systems and anaerobic (oxygen-deficient) systems. Aerobic systems are "powered" by sunlight via photosynthesis. Sulfate-reducing-bacteria (SRB) hosted in organic matter "power" anaerobic systems.

The treatment process occurs in the substrate (a recipe of native hay, alfalfa, cattle manure, aged sawdust, limestone and gypsum) of the anaerobic cells where bacteria convert sulfate (SO_4) in the mine water to sulfide (S^{-2}) using the organic matter as a nutrient source. The sulfide combines with the dissolved Cu in the mine water to form a solid, copper sulfide (CuS). The copper sulfide (a common mineral) is in turn "filtered out" by the substrate. Another feature of the bacterial reaction is the formation of bicarbonate (the active ingredient in most antacid tablets like Tums™). This bacterial action, plus limestone in the substrate, can raise the pH of the mine water, which can get as low as 3.5, up to a level of 7.0, which is neutral.

The anaerobic cell effluent is typically low in dissolved oxygen and has elevated concentrations of unreacted sulfide ion and may have minute amounts of colloidal-size copper sulfide. This water is passed through the aerobic cell populated by wetland-type plants. Here, sulfide oxidizing bacteria convert the

sulfide back to sulfate, the plants infuse the water with dissolved oxygen and various physical, chemical and biological mechanisms (e.g., adsorption, settling, metal uptake by roots and leaves, and filtration) act to immobilize the colloidal copper sulfide in the aerobic cell biomass.

For slightly acidic, metal-laden waters (pH greater than 5.5) without excessive dissolved iron concentrations, hydroxide precipitation catalyzed by bacteria may be utilized as the dominant metal removal mechanism. For very acidic waters (pH less than 5.5), sulfide precipitation assisted by SRB thriving in anaerobic zones of the wetland substrate has been demonstrated to be the most significant metal removal mechanism.

The SRB appear to function best above pH 5.0 and are known to produce two byproducts from their life cycle: hydrogen sulfide gas (H_2S) and bicarbonate (HCO_3). The hydrogen sulfide gas, bubbling up through the wetland substrate or occurring as the dissolved sulfide ion (S^{-2}), precipitates metals as sulfides, essentially reversing the reactions that occurred to produce the contaminated water. The bicarbonate raises the pH of the solution.

The key conditions for SRB health are a pH of 5.0 (maintained by the SRB itself through the bicarbonate reaction), the presence of a source of sulfate (typically from the contaminated water), and organic matter (CH_2O, from the substrate).

<u>Pros</u>

- *The chemistry of contaminated waters at Ferris-Haggarty lends itself to passive treatment using anaerobic and/or aerobic processes.*
- *Bench-scale and pilot-scale tests conducted at Ferris-Haggarty have resulted in Cu level reductions to below the 0.15 mg/L target concentration.*
- *Large volumes of sludge would not be generated. Therefore, sludge disposal may be delayed for decades. Resource recovery to offset costs may also be feasible.*
- *The system would not require energy to operate and would operate using gravity flow.*
- *The system would require minimal maintenance.*

<u>Cons</u>

- *Land requirements for a passive treatment system would be greater than the other*

alternatives.

- *Treating large variations in Cu loading and flow would be more difficult than for some active systems; the "modular drain-down" approach, discussed in Section 4.7, to handling flow is new and has not been tested in the pilot scale system.*
- *The system would release hydrogen sulfide gas. Proper venting would be required.*

Overall Assessment/Feasibility

Bench-scale and pilot-scale experiments have shown that passive treatment is a technologically feasible treatment method of contaminated waters at Ferris-Haggarty. In addition, passive treatment is cost-effective because it requires no energy, operates by gravity flow and has minimal, if any, sludge removal.