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Estimated Loads of Suspended Sediment and Selected Trace Elements Transported through the Milltown Reservoir Project Area Before and After the Breaching of Milltown Dam in the Upper Clark Fork Basin, Montana, Water Year 2008

Scientific Investigations Report 2009–5095

U.S. Department of the Interior
U.S. Geological Survey

Front cover. View of the Clark Fork flowing past the remnants of Milltown Dam, which was breached on March 28, 2008 (courtesy of U.S. Environmental Protection Agency, August 2008).

Back cover. Large photograph: View looking downstream to the confluence of the Blackfoot River (left) and Clark Fork Bypass. The area to the right of the Bypass is where bottom sediment of the former Milltown Reservoir has been excavated (courtesy of U.S. Environmental Protection Agency, August 2008).

Small photograph: Aerial view of the Clark Fork flowing past the remnants of Milltown Dam (courtesy of Gary Matson, April 2008).

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors, Datum, Abbreviated Units, and Acronyms

Multiply	By	To obtain
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic yard (yd^3)	0.7647	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
gallon (gal)	3.785	liter (L)
inch (in.)	25.4	millimeter (mm)
inch (in.)	25,400	micrometer (µm)
mile (mi)	1.609	kilometer (km)
ounce (oz)	28,350	milligram (mg)
ounce (oz)	28,350,000	microgram (µg)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
square mile (mi^2)	2.590	square kilometer (km^2)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per year (ton/yr)	0.9072	metric ton per year

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2008 is the period from October 1, 2007, through September 30, 2008.

Abbreviated units and symbol used in this report:

acre-ft	acre-feet
ft	feet
ft^3/s	cubic feet per second
µg/L	micrograms per liter
mg/L	milligrams per liter
mi	miles
mi^2	square miles
mm	millimeter
ton/d	tons/day
µm	micrometer
yd^3	cubic yards
<	less than

Acronyms used in this report:

ASQ	arsenic discharge
CDQ	cadmium discharge
CUQ	copper discharge
FEQ	iron discharge
LOG	logarithm (base 10)
LOWESS	locally weighted scatter plot smoothing
LRL	laboratory reporting level
MNQ	manganese discharge
NPL	National Priorities List
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
OLS	ordinary least squares
PBQ	lead discharge
p-value	significance level
Q	streamflow
R^2	coefficient of determination
RBCF	retransformation-bias-correction factor
RSD	relative standard deviation
SE	standard error of estimate
SEDQ	suspended-sediment discharge

USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
ZNQ	zinc discharge

Estimated Loads of Suspended Sediment and Selected Trace Elements Transported through the Milltown Reservoir Project Area Before and After the Breaching of Milltown Dam in the Upper Clark Fork Basin, Montana, Water Year 2008

By John H. Lambing and Steven K. Sando

Abstract

This report presents estimated daily and cumulative loads of suspended sediment and selected trace elements transported during water year 2008 at three streamflow-gaging stations that bracket the Milltown Reservoir project area in the upper Clark Fork basin of western Montana. Milltown Reservoir is a National Priorities List Superfund site where sediments enriched in trace elements from historical mining and ore processing have been deposited since the construction of Milltown Dam in 1907. Milltown Dam was breached on March 28, 2008, as part of Superfund remedial activities to remove the dam and contaminated sediment that had accumulated in Milltown Reservoir. The estimated loads transported through the project area during the periods before and after the breaching of Milltown Dam, and for the entire water year 2008, were used to quantify the net gain or loss (mass balance) of suspended sediment and trace elements within the project area during the transition from a reservoir environment to a free-flowing river. This study was done in cooperation with the U.S. Environmental Protection Agency.

Streamflow during water year 2008 compared to long-term streamflow, as represented by the record for Clark Fork above Missoula (water years 1930-2008), generally was below normal (long-term median) from about October 2007 through April 2008. Sustained runoff started in mid-April, which increased flows to near normal by mid-May. After mid-May, flows sharply increased to above normal, reaching a maximum daily mean streamflow of 16,800 cubic feet per second (ft^3/s) on May 21, which essentially equaled the long-term 10th-exceedance percentile for that date. Flows substantially above normal were sustained through June, then decreased through the summer and reached near-normal by August. Annual mean streamflow during water year 2008 (3,040 ft^3/s) was 105 percent of the long-term mean annual streamflow (2,900 ft^3/s). The annual peak flow (17,500 ft^3/s) occurred on May 21 and was 112 percent of the long-term mean annual peak flow (15,600 ft^3/s). About 81 percent of the annual flow volume was discharged during the post-breach period.

Daily loads of suspended sediment were estimated directly by using high-frequency sampling of the daily sediment monitoring. Daily loads of unfiltered-recoverable arsenic, cadmium, copper, iron, lead, manganese, and zinc were estimated by using regression equations relating trace-element discharge to either streamflow or suspended-sediment discharge. Regression equations for estimating trace-element discharge in water year 2008 were developed from instantaneous streamflow and concentration data for periodic water-quality samples collected during all or part of water years 2004–08. The equations were applied to records of daily mean streamflow or daily suspended-sediment loads to produce estimated daily trace-element loads.

Variations in daily suspended-sediment and trace-element loads generally coincided with variations in streamflow. Relatively small to moderately large daily net losses from the project area were common during the pre-breach period when low-flow conditions were prevalent. Outflow loads from the project area sharply increased immediately after the breaching of Milltown Dam and during the rising limb and peak flow of the annual hydrograph. Net losses of suspended sediment and trace elements from the project area decreased as streamflow decreased during the summer, eventually becoming small or reaching an approximate net balance between inflow and outflow.

Estimated daily loads of suspended sediment and trace elements for all three stations were summed to determine cumulative inflow and outflow loads for the pre-breach and post-breach periods, as well as for the entire water year 2008. Overall, the mass balance between the combined inflow loads from two upstream source areas (upper Clark Fork and Blackfoot River basins) and the outflow loads at Clark Fork above Missoula indicates net losses of suspended sediment and trace elements from the project area during all periods in water year 2008.

Of the 510,000 tons of suspended-sediment outflow load transported past Clark Fork above Missoula in water year 2008, only 119,000 tons were contributed from the two upstream source areas; thus, 391,000 tons of the outflow load were derived from eroded sediment within the project area. The suspended-sediment load contributed from the project area represented about 77 percent of the outflow load, with the upper Clark Fork basin contributing about 11 percent and the Blackfoot River basin contributing about 12 percent. Most of the large annual net loss of suspended sediment (-391,000 tons) from the project area occurred during the post-breach period (-375,000 tons), which was more than 22 times greater than the load contributed during the pre-breach period; the net loss during the post-breach period represented about 96 percent of the annual net loss for the entire water year 2008.

The large annual net loss of suspended sediment from the project area in water year 2008 resulted in large annual net losses for every trace element. Net losses of trace elements from the project area were about 7 to 20 times greater during the post-breach period compared to the pre-breach period. The largest annual net losses of trace elements from the project area, in percent of the outflow load transported past Clark Fork above Missoula, occurred for cadmium, copper, lead, and zinc—about 82 percent for cadmium (-0.938 tons), 84 percent for copper (-157 tons), 78 percent for lead (-22.5 tons), and 84 percent for zinc (-245 tons). The large annual net losses of trace elements in water year 2008 indicate that much of the outflow trace-element load transported past Clark Fork above Missoula was derived from eroded sediment within the Milltown Reservoir project area, rather than from inflow loads transported from upstream source areas.

Introduction

Milltown Reservoir was located on the Clark Fork at the confluence of the Clark Fork and Blackfoot River in western Montana (fig. 1). The reservoir was formed by the construction of Milltown Dam in 1907. Historical large-scale mining and ore processing in the upper Clark Fork basin produced large quantities of tailings enriched with trace elements such as arsenic, cadmium, copper, lead, and zinc. Tailings have been eroded and transported downstream along the Clark Fork, contaminating the approximately 6.6 yd^3 of sediment that had accumulated in Milltown Reservoir (U.S. Environmental Protection Agency, 2004). Potential toxicity from the elevated trace-element concentrations in water and bed sediment led to the designation of Milltown Reservoir and upstream reaches of the Clark Fork as an extended National Priorities List (NPL) Superfund site in 1983 (U.S. Environmental Protection Agency, 2004).

As part of remediation planning associated with the Superfund process, the U.S. Environmental Protection Agency (USEPA) issued a record of decision in December 2004 that included removal of Milltown Dam as one of the remedial activities (U.S. Environmental Protection Agency, 2004). Descriptions of activities associated with the removal of Milltown Dam are provided in a series of updates by USEPA (*http://www.epa.gov/region8/superfund/mt/milltown/updates.html*). On March 28, 2008, Milltown Dam was breached as part of the process to remove the dam and excavate a large portion of the contaminated sediment. The term "Milltown Reservoir project area" (hereinafter referred to as "project area") is used to encompass the periods before and after the dam breach when the environment changed from a reservoir to a free-flowing river. The project area (fig. 1) collectively includes the former location of the reservoir, plus river reaches of indefinite length upstream from the Clark Fork and Blackfoot River arms of the reservoir where increased erosion could occur as the result of the rivers adjusting to the steeper channel gradient caused by the breaching of Milltown Dam.

To accommodate various construction activities and the excavation of a portion of the reservoir bottom sediments prior to dam removal, the initial phase (Stage 1) of a permanent drawdown of the reservoir to a lower pool level began on June 1, 2006 (U.S. Environmental Protection Agency, written commun., July 2006); thus, in water year 2008, Milltown Reservoir was shallow during the entire period before the breaching of Milltown Dam. The Stage 1 drawdown lowered the average summer pool by about 10–12 ft. Two subsequent phases of drawdown (Stages 2 and 3) were designed to lower the reservoir pool an additional 17 ft (for a total drawdown of about 29 ft) to allow access for removal of the powerhouse and spillway (U.S. Environmental Protection Agency, written commun., September 2007). The Stage 2 drawdown occurred on March 28, 2008, when the powerhouse coffer dam was breached, thereby lowering the water-surface elevation by 15 ft at the former forebay foundation (U.S. Environmental Protection Agency, written commun., January 2009). The Stage 3 drawdown will occur when the spillway coffer dam is breached, thereby lowering the water-surface elevation the final 2 ft to the estimated pre-dam elevation at the former spillway (U.S. Environmental Protection Agency, written commun., January 2009).

Because of the large quantity of contaminated sediment that was deposited in Milltown Reservoir, there was concern regarding an increased potential for scour of bottom sediments and associated trace elements from the shallow reservoir after the start of the permanent drawdown, especially during high streamflow. To address this concern, the USEPA initiated a program of intensive sampling by the U.S. Geological Survey (USGS) that began in water year 2006 to supplement the routine sampling of the long-term monitoring program (Dodge and others, 2008). The supplemental sampling was conducted during the April–June periods of water years 2006 and 2007 to target the rising limb and peak flow of the annual hydrograph, as well as selected periods of reservoir drawdown. The sampling provided additional information on variations in water quality and constituent transport through Milltown Reservoir. The supplemental sampling continued in

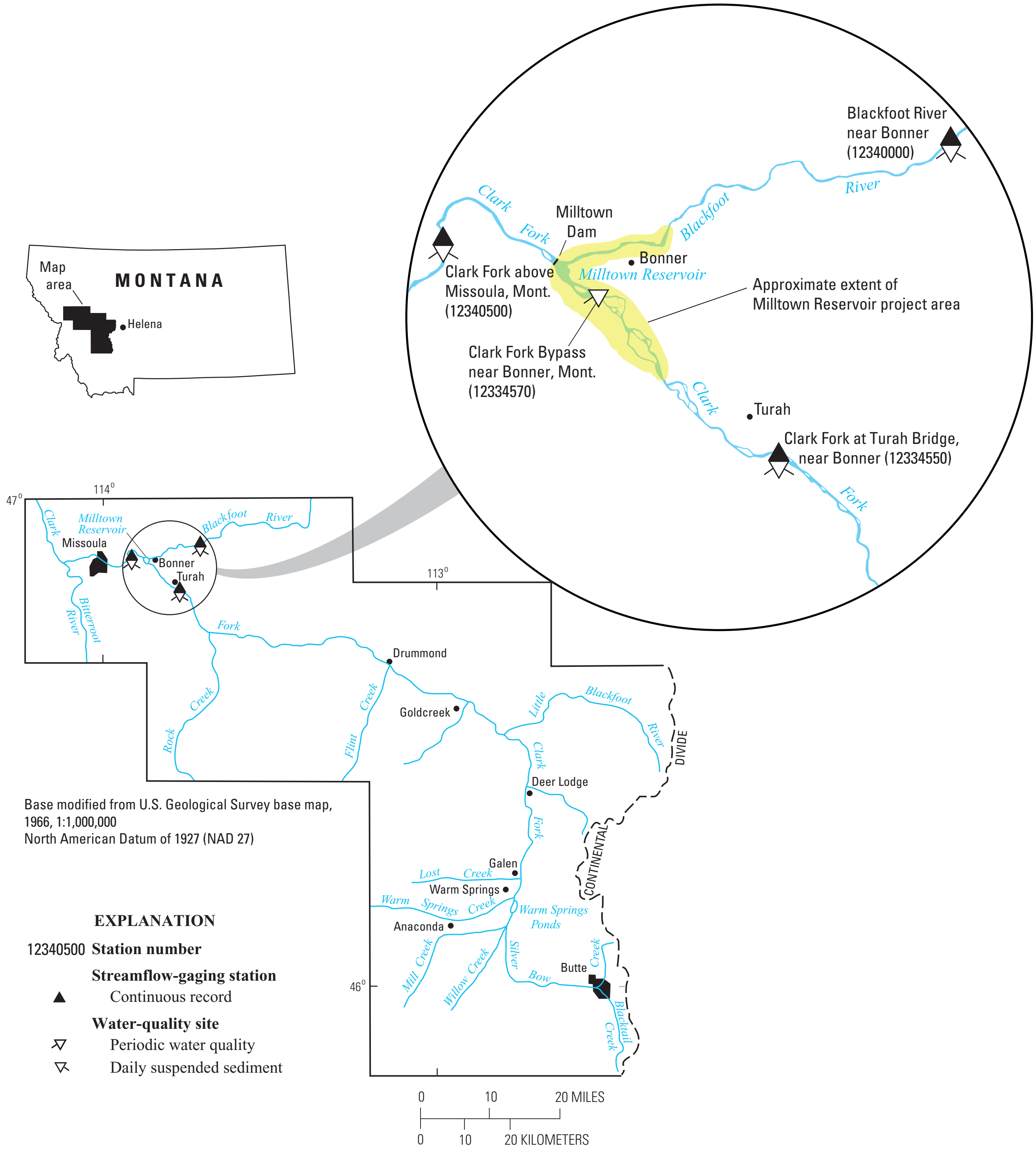


Figure 1. Location of study area.

water year 2008 during March–July to characterize suspended-sediment and trace-element transport during the final stages of the permanent reservoir drawdown and for several months after the breaching of Milltown Dam.

The USGS, in cooperation with the USEPA, estimated daily suspended-sediment and trace-element loads transported at three streamflow-gaging stations that bracket the Milltown Reservoir project area (two sites upstream and one site downstream from the project area). Loads were estimated by using periodic water-quality, daily streamflow, and daily suspended-sediment data. Cumulative loads for various periods were determined by summing estimated daily loads for each site; the difference between the cumulative inflow and outflow loads were used to quantify the net gain or loss (mass balance) of suspended sediment and selected trace elements within the project area during the periods before and after the breaching of Milltown Dam, as well as for the entire water year 2008 (October 1, 2007, through September 30, 2008).

Purpose and Scope

The purpose of this report is to present estimated daily and cumulative loads of suspended sediment and selected trace elements (unfiltered-recoverable arsenic, cadmium, copper, iron, lead, manganese, and zinc) transported during water year 2008 at three streamflow-gaging stations that bracket the Milltown Reservoir project area (fig. 1). The cumulative estimated loads were used to quantify the mass balance of suspended sediment and trace elements within the project area for the individual periods before (October 1, 2007–March 27, 2008) and after (March 28, 2008–September 30, 2008) the breaching of Milltown Dam, as well as for all of water year 2008. The methods used to estimate loads and the characteristics of daily and cumulative loads transported through the project area are described; bed load was not sampled or estimated for this study.

The USGS has collected periodic water-quality samples and daily suspended-sediment data at each of the three streamflow-gaging stations that bracket the Milltown Reservoir project area as part of Clark Fork monitoring programs (Dodge and others, 2008). In 2008, a supplemental sampling site for periodic water quality was established within the project area (fig. 1, Clark Fork Bypass near Bonner, station 12334570) to provide additional spatial resolution on transport characteristics in a reach of channel near the upper end of the former Milltown Reservoir. The Clark Fork Bypass near Bonner has no streamflow gage or daily sediment monitoring; thus, daily and cumulative loads are not presented for this site. The periodic water-quality, daily streamflow, and daily suspended-sediment data used to develop regression equations and estimate loads are accessible on the USGS National Water Information System (NWIS) Web site for Montana (*http://waterdata.usgs.gov/mt/nwis*). These data also are published in "Water Resources Data for the United States, Water Year 2008," which is accessible at *http://wdr.water.usgs.gov/wy2008/search.jsp*.

Description of the Study Area

Milltown Reservoir was a small impoundment of about 540 acres formed by Milltown Dam at the confluence of the Clark Fork and Blackfoot River (fig. 1). The Clark Fork basin upstream from Milltown Dam drains an area of about 6,000 mi^2. The former reservoir was at the downstream end of a contiguous complex of NPL Superfund sites extending from the headwaters of Silver Bow Creek near Butte to Milltown Dam near Missoula (U.S. Environmental Protection Agency, 2004). Before the breaching of Milltown Dam, Milltown Reservoir was considered a "run of the river" reservoir because streamflow leaving the reservoir was equal to the streamflow of the Clark Fork and Blackfoot River entering the reservoir (U.S. Environmental Protection Agency, written commun., 2003), where the retention time of water in the reservoir generally was not substantially different than a free-flowing system. After Milltown Dam was breached, the confluence of the Clark Fork and Blackfoot River transitioned from a reservoir environment to a free-flowing river.

Data for two streamflow-gaging stations upstream from the Milltown Reservoir project area (Clark Fork at Turah Bridge, near Bonner, station 12334550; and Blackfoot River near Bonner, station 12340000) represent the combined inflow of streamflow and constituent load to the project area; data for the streamflow-gaging station Clark Fork above Missoula (station 12340500) represent the outflow from the project area. For brevity, Clark Fork at Turah Bridge, near Bonner will be referred to as Clark Fork at Turah Bridge in this report. The supplemental sampling site within the project area (Clark Fork Bypass near Bonner, station 12334570) is located about 5 river mi downstream from Clark Fork at Turah Bridge (fig. 1). The supplemental sampling site is near the upstream end of a constructed bypass channel into which the Clark Fork was diverted on March 21, 2008, to allow the excavation of contaminated reservoir sediment for hauling to a repository (U.S. Environmental Protection Agency, written commun., 2008). Data from periodic water-quality samples collected on concurrent dates at Clark Fork Bypass near Bonner and Clark Fork at Turah Bridge provide a better understanding of the erosional processes occurring in the short intervening reach of channel near the upper end of the Clark Fork arm of the former reservoir as the river adjusts to the steeper channel gradient caused by the breaching of Milltown Dam.

Hydrologic Characteristics

Streamflow magnitude is a predominant factor affecting the transport of suspended sediment and sediment-associated constituents through a drainage basin. Streamflow magnitude can affect the sustained delivery of constituent loads from the basin, as well as the capacity to locally scour sediments within the project area. The hydraulic energy associated with high flows is especially important relative to the scour of bottom sediments in shallow water bodies, such as Milltown

Reservoir during the permanent drawdown. Increased hydraulic energy from high flows and the steeper channel gradient after the breaching of Milltown Dam are primary factors affecting erosion of remnant coffer dam materials, former reservoir bottom sediments, and channel streambed and banks.

Because streamflow can vary substantially from year to year, thereby affecting rates of constituent transport, comparison of streamflow during water year 2008 to a long-term period of record allows recent hydrologic conditions to be placed in a historical perspective. Clark Fork above Missoula has the longest period of continuous-streamflow record (79 years, water years 1930–2008) for comparison to streamflow during water year 2008 (*http://waterdata.usgs.gov/mt/nwis*). The variation in daily mean streamflow at Clark Fork above Missoula during water year 2008 is shown in figure 2, along with selected long-term streamflow characteristics for water years 1930–2008, to illustrate differences between recent and long-term hydrologic conditions.

The long-term streamflow characteristics for Clark Fork above Missoula (fig. 2) are represented by selected exceedance percentiles (10th, 50th, and 90th) of daily mean streamflow during the period of record. An exceedance percentile indicates the magnitude of daily mean streamflow that was exceeded the given percent of time on a specific day of the year during the long-term period of record. For example, the 10th-exceedance percentile of long-term daily mean streamflow represents a relatively high streamflow magnitude that was exceeded only 10 percent of the time on that specific day of the year (for example, on all of the October 1 dates, October 2 dates, and so on) during the period of record. Exceedance percentiles are determined for each day of the year to produce an annual hydrograph of long-term daily mean

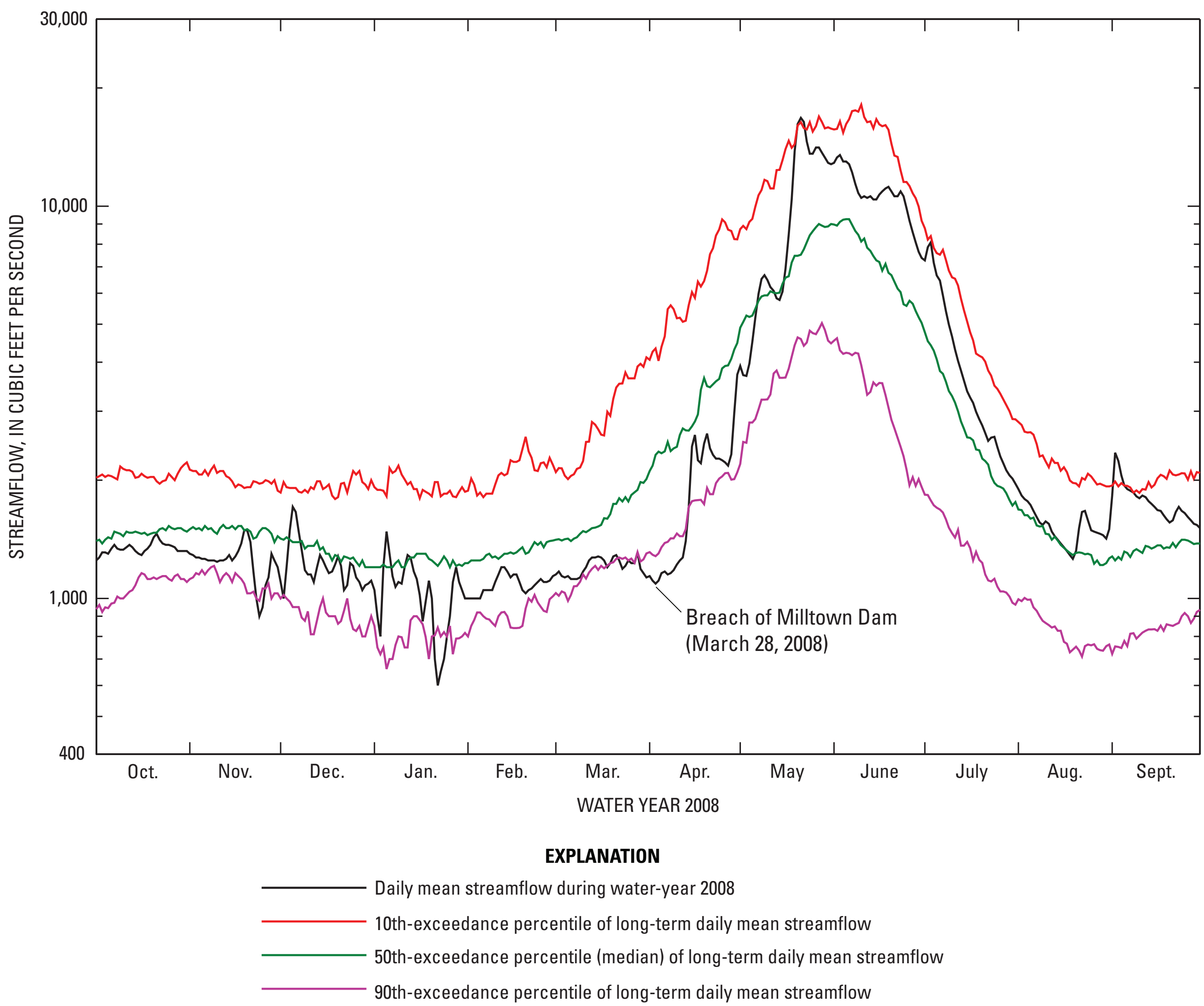


Figure 2. Daily mean streamflow during water year 2008 and selected exceedance percentiles of long-term (water years 1930–2008) daily mean streamflow for Clark Fork above Missoula, Mont.

streamflows representing a particular exceedance percentile. For brevity and relative comparison of streamflow during water year 2008 to long-term streamflow, “normal” in this report refers to the 50th-exceedance percentile, or long-term median.

Streamflow at Clark Fork above Missoula during water year 2008 (fig. 2) generally was below normal from about October 2007 through April 2008. Streamflow during late November to mid-April occasionally decreased to magnitudes near or below the 90th-exceedance percentile. Winter flows were erratic, possibly because of variations in the duration and intensity of freezing conditions, or runoff during periods of thawing. Sustained runoff started in mid-April, which increased flows to near normal by mid-May; after mid-May, flows sharply increased to above normal. The maximum daily mean streamflow in water year 2008 (16,800 ft^3/s) occurred on May 21 (*http://waterdata.usgs.gov/mt/nwis*) and was above normal, essentially equaling the long-term 10th-exceedance percentile for that date. Flows substantially above normal were sustained through June, with the departure from normal decreasing through the summer and eventually reaching near-normal flows by August. From late August through September, runoff increased flows to above normal, with several days slightly exceeding the 10th-exceedance percentile in early September. The timing of the rising limb, peak flow, and falling limb of the annual hydrograph for water year 2008 generally was similar to long-term patterns, unlike the shift towards an earlier occurrence of runoff and streamflow recession noted for water years 2006 and 2007 (Lambing and Sando, 2008).

Selected annual streamflow and peak-flow characteristics for Clark Fork above Missoula for water year 2008 (table 1) are compared to long-term characteristics for the period of continuous-streamflow records (water years 1930–2008) and peak-flow records (water years 1908, 1930–2008). Annual mean streamflow for water year 2008 (3,040 ft^3/s) was 105 percent of the long-term mean annual streamflow (2,900 ft^3/s). The annual peak flow during water year 2008 (17,500 ft^3/s) occurred on May 21 and was 112 percent of the long-term mean annual peak flow (15,600 ft^3/s), but only 36 percent of the long-term maximum annual peak flow (48,000 ft^3/s), which occurred in 1908.

Methods of Data Collection and Quality Assurance

Water-quality samples were collected periodically for analysis of suspended sediment and trace elements. Routine samples at the three streamflow-gaging stations (fig. 1) were collected at a frequency of 6–8 times per year during water year 2008 as part of the long-term Clark Fork monitoring program (Dodge and others, 2008). An additional 16 samples were collected at each of the three stations during March–July 2008 as part of a supplemental monitoring program for the lower Clark Fork basin to provide better resolution of the transport of sediment and trace elements from the project area associated with dam-removal activities. The combined sampling efforts for both programs resulted in a sampling frequency of 23–24 times per year at each streamflow-gaging station. The sampling site Clark Fork Bypass near Bonner is not part of the long-term monitoring program; thus it was sampled only 16 times during water year 2008 as part of the supplemental monitoring program.

Periodic water-quality samples were collected by the USGS throughout the entire stream depth at multiple locations across the stream by using depth- and width-integration methods described by Ward and Harr (1990), Edwards and Glysson (1999), and U.S. Geological Survey (variously dated). Sampling equipment consisted of depth-integrating suspended-sediment samplers (DH–81, D–74TM, and D–95), which were equipped with nylon nozzles and constructed of plastic or coated with a nonmetallic epoxy paint. Depth-integrating samplers are designed to sample the water column isokinetically, whereby velocity flow paths into the nozzle are not distorted and suspended particles enter the sample-collection bottle at the same concentration as in the

Table 1. Comparison of annual streamflow and peak-flow characteristics for water year 2008 with long-term annual streamflow (water years 1930–2008) and peak-flow (water years 1908, 1930–2008) characteristics for Clark Fork above Missoula, Mont.

[Abbreviations: ft^3/s, cubic feet per second]

Annual streamflow			Annual peak flow		
Water year 2008 annual mean streamflow (ft^3/s)	Percent of long-term mean annual streamflow (2,900 ft^3/s)	Percent of long-term maximum annual streamflow (5,070 ft^3/s; 1976)	Water year 2008 peak flow (ft^3/s)	Percent of long-term mean peak flow (15,600 ft^3/s)	Percent of long-term maximum peak flow (48,000 ft^3/s; 1908)
[1]3,040	105	60	17,500	112	36

[1]The exceedance percentile associated with an annual mean streamflow of 3,040 cubic feet per second is 41 percent. The exceedance percentile indicates the percent of the time that the annual mean streamflow for the given year was exceeded during the long-term period of continuous-streamflow records (water years 1930–2008). For example, an exceedance percentile of 41 percent represents a moderately high streamflow condition that was exceeded 41 percent of the time during the long-term period of record.

surrounding water. The combination of appropriate sampling methods and depth-integrating sampling equipment provides a vertically and laterally discharge-weighted composite sample of water and particulate matter that is representative of the entire flow passing through the cross-sectional area of the stream. Samples were processed onsite according to procedures described by Ward and Harr (1990), Horowitz and others (1994), and U.S. Geological Survey (variously dated). Quality-assurance procedures for processing water-quality samples are described by U.S. Geological Survey (variously dated) and Lambing (2006).

Measurements of pH, specific conductance, and water temperature were made onsite during all sampling visits. Instantaneous streamflow at the time of periodic water-quality sampling was determined either by direct measurement at the time of sampling or from stage readings applied to the stage-discharge rating table for the station (Rantz and others, 1982).

Daily mean streamflows at the three streamflow-gaging stations were determined by applying stage-discharge relations developed from periodic streamflow measurements to the continuous record of stage according to procedures described by Rantz and others (1982). All three sites were operated as daily-sediment stations during water year 2008. Suspended-sediment samples for the daily-sediment stations were collected at a high frequency (2–14 times per week) by local contract observers using depth-integration methods at a single location near midstream. The frequency of suspended-sediment sample collection by observers increased seasonally as flows increased or temporarily during short-duration periods of runoff. Quality-assurance procedures for generating daily records of streamflow and suspended-sediment data are described by White and others (1998). The quality of daily records (Rantz and others, 1982) were rated good to excellent, except for periods of ice cover, which were rated poor.

Periodic water-quality samples were analyzed for suspended-sediment concentration and percent of suspended sediment finer than 0.062-mm diameter (*http://waterdata.usgs.gov/mt/nwis*) by the USGS Montana Water Science Center Sediment Laboratory (hereinafter referred to as Montana Sediment Laboratory) in Helena, Mont., according to methods described by Guy (1969) and Dodge and Lambing (2006). Samples collected by observers for the daily sediment stations were analyzed only for suspended-sediment concentration. Quality-assurance procedures used by the Montana Sediment Laboratory are described by Dodge and Lambing (2006).

Periodic water-quality samples also were analyzed for filtered (0.45-µm pore size) and unfiltered-recoverable trace-element concentrations (*http://waterdata.usgs.gov/mt/nwis*) by the USGS National Water Quality Laboratory (NWQL) in Denver, Colo. Filtered concentrations formerly were referred to as dissolved; unfiltered-recoverable concentrations formerly were referred to as total recoverable. Unfiltered-recoverable concentrations represent the combined dissolved and particulate fractions of the trace element. Unfiltered samples were first digested with dilute hydrochloric acid before analysis to liberate the weakly bound trace elements from sediment particles (Hoffman and others, 1996). Filtered samples and the digested unfiltered samples then were analyzed by inductively coupled plasma-mass spectrometry (Garbarino and Struzeski, 1998). Quality-assurance procedures used by the NWQL are described by Friedman and Erdmann (1982), Jones (1987), Pritt and Raese (1995), and Maloney (2005).

Quality-assurance data for periodic water-quality samples were obtained by analysis of quality-control samples (blanks and replicates), which were submitted along with the environmental samples on every field trip. Analytical results for quality-control samples are used to evaluate the performance of sampling and analytical methods to ensure that results for environmental samples are accurate and unbiased. Quality-assurance data for the Clark Fork basin sampling program are reported in annual data reports for previous years; quality-assurance data for water year 2008 are available for inspection (Kent A. Dodge, U. S. Geological Survey, written commun., 2008).

Trace-element concentrations in blank samples collected during water year 2008 were almost always less than the laboratory reporting level (LRL). Values exceeding twice the LRL were noted during data reviews to evaluate the presence of a consistent trend that could indicate systematic contamination. Values exceeding twice the LRL were infrequent and occurred sporadically, which indicated that there were no consistent trends of contamination bias that might affect the data for environmental samples; therefore, no adjustments to trace-element concentrations were made during water year 2008 based on analytical results for blanks.

Precision of trace-element concentrations was determined by calculating a relative standard deviation (RSD) for analytical results of replicate samples. The RSDs for all the unfiltered-recoverable trace-elements used to estimate loads during water year 2008 were within the 20-percent data quality objective of acceptable precision for concentrations in replicate samples, with the exception of iron. The RSD for unfiltered-recoverable iron was 30 percent. The high RSD was caused by a single replicate sample pair; removing the results for the one pair of replicate samples resulted in a low RSD of 6 percent, thereby indicating that the poor precision for iron was an isolated occurrence rather than a systematic sampling or analytical problem.

Methods for Estimating Constituent Loads

The term “load” represents the mass (commonly expressed as tons or pounds) of a constituent transported past a sampling site during a specified period of time. Loads can be computed for various time increments, such as instantaneous, daily, monthly, seasonal, or annual. Instantaneous loads represent the mass transported at the time of sampling, whereas daily, monthly, seasonal, and annual loads represent the cumulative mass transported over a prolonged period. The term "discharge" represents the rate at which load is transported and incorporates both mass and time units (commonly expressed as tons per day or tons per year). The measured instantaneous discharge of a constituent is calculated as the product of sample concentration and instantaneous streamflow at the time of sampling. Instantaneous discharge also can be expressed as an equivalent daily discharge that represents the total load transported during a day (daily load) if the measured rate of instantaneous discharge was maintained for 24 hours. Daily loads can be added to determine the cumulative load for specific periods within a year or an annual load for the entire year.

Cumulative loads, such as seasonal or annual, generally are more informative than instantaneous loads measured at the time of sampling because they represent the total constituent mass transported over a prolonged period, and thereby incorporate the potentially large range of daily and seasonal variations. Cumulative loads also are useful for evaluating differences in constituent transport among sites to identify source areas contributing substantial inputs on a sustained basis over time. Differences in cumulative loads transported past various locations along a stream can result from differences in seasonal or annual flow volumes, physical basin characteristics, current and historical land-use activities, and localized conditions that affect constituent supply or susceptibility to erosion.

Estimation of cumulative loads typically requires either high-frequency sampling or applying statistical relations, such as regression equations, to a daily record of a measured or estimated explanatory variable to produce an estimated daily load. The daily loads estimated by such methods provide increased temporal resolution of variability within a year that can give added insight to the effects of streamflow variations, seasonal differences, or unique conditions associated with discrete events.

Regression equations used to estimate constituent discharges based on relations with explanatory variables were developed from instantaneous streamflow at the time of sampling and concentration data for periodic water-quality samples collected during all or part of water years 2004–08. Various forms of data transformation were examined to produce a linear distribution that could be fit adequately by an ordinary least squares (OLS) regression line (Helsel and Hirsch, 2002). Selection of the best data transformation was based on the ability to produce linear relations that were statistically significant at the 0.05 significance level (p-value < 0.05) and that had a uniform distribution of residuals around the regression line. Also, the coefficient of determination (R^2) and standard error of estimate (SE), in percent, which are measures of the scatter of data points around the regression line, were used in conjunction with statistical significance and uniformity of residual distribution to evaluate the various relations and select the best form of regression equation.

For trace-element concentrations that were censored (reported as less than the LRL), one-half of the LRL used during the data-collection period for regression analysis was substituted for purposes of plotting and analysis of statistical relations. For constituents that had multiple LRLs during the period, one-half of the median LRL during the period was substituted. The effect of the treatment of censored values on regression relations and load estimates was analyzed to evaluate the appropriateness of the selected method relative to study objectives. Presentation of the results of these detailed analyses is beyond the scope of this report, but a general discussion of the potential effects of censored values is provided below.

The effect of censored values on statistical analyses was minor, with the exception of cadmium and zinc for samples collected at Blackfoot River near Bonner. For Clark Fork at Turah Bridge and Clark Fork above Missoula, censored values accounted for no more than 2 percent of the concentrations for any trace element. For Blackfoot River near Bonner, censored values accounted for no more than 15 percent of the concentrations for arsenic, copper, iron, lead, and manganese; however, about 71 and 33 percent of the concentrations for cadmium and zinc, respectively, were censored. Consequently, the statistical relations and load estimates for all trace elements at Clark Fork at Turah Bridge and Clark Fork above Missoula are relatively unaffected by censored values; statistical relations and load estimates for arsenic, copper, iron, lead, and manganese at Blackfoot River near Bonner also are relatively unaffected by censored values.

Statistical relations and load estimates for cadmium and zinc at Blackfoot River near Bonner have a greater degree of uncertainty than for other sites or other trace elements. However, general conclusions are that the large percentage of censored values for cadmium and zinc for Blackfoot River near Bonner did not substantially bias the study results because: (1) censored values generally were associated with low to moderate streamflows and did not substantially affect estimates of daily loads during high-flow periods when the largest constituent transport occurs; and (2) variability of cadmium and zinc concentrations among samples generally was small, especially for samples collected during low to moderate streamflows. As a result, it was determined that concentrations for the censored values were reasonably represented by using one-half the median LRL. Thus, although the estimates of cadmium and zinc loads for Blackfoot River near Bonner potentially are subject to greater error, their presentation is warranted to provide an important indication of load contributions from the Blackfoot River basin relative to other source areas.

Suspended Sediment

Daily suspended-sediment loads for water year 2008 were estimated directly for each of the three streamflow-gaging stations bracketing the project area (fig. 1) by using high-frequency sampling of the daily sediment monitoring program. Suspended-sediment samples for daily sediment monitoring were collected by a contract observer 2–14 times per week, with sampling frequency increasing as streamflow increased. The concentration data from observer samples characterized daily temporal variations needed for developing continuous-concentration curves. Daily mean suspended-sediment concentrations were determined from the continuous-concentration curves according to methods described by Porterfield (1972). The daily mean suspended-sediment concentrations then were multiplied by the daily mean streamflows (and a units-conversion constant) to generate a record of daily suspended-sediment loads (*http://waterdata.usgs.gov/mt/nwis*).

Even though daily suspended-sediment loads were estimated directly by using high-frequency sampling, relations between suspended-sediment discharge and streamflow (sediment-transport relations) during water years 2004–08 were examined for all three streamflow-gaging stations to evaluate differences in sediment-transport characteristics between the periods before (pre-breach) and after (post-breach) Milltown Dam was breached on March 28, 2008. Separate relations were examined for the pre-breach period (October 1, 2003–March 27, 2008) and the post-breach period (March 28, 2008–September 30, 2008) for the two stations upstream from the project area (Clark Fork at Turah Bridge and Blackfoot River near Bonner). Water year 2004 was used as the starting point for the period of data analysis for the two stations upstream from the project area to incorporate the same dataset used to estimate loads for water years 2004–07 (Lambing and Sando, 2008) with the additional data for water year 2008. For Clark Fork above Missoula, the pre-breach period of data analysis was restricted to dates between the start of the permanent drawdown of Milltown Reservoir to the day before the dam breach (June 1, 2006–March 27, 2008). This restricted period was used because the sediment-transport relation for Clark Fork above Missoula changed substantially after the start of the permanent drawdown, whereas no substantial difference was noted in the relations for the periods before and after the permanent drawdown at the two upstream sites (Lambing and Sando, 2008).

Before developing the sediment-transport relations, the suspended-sediment concentration for each periodic water-quality sample was converted to an equivalent suspended-sediment discharge, in tons per day, according to the equation:

$$Q_{sed} = C_{sed}QK, \tag{1}$$

where

- Q_{sed} is suspended-sediment discharge, in tons per day;
- C_{sed} is suspended-sediment concentration, in milligrams per liter;
- Q is streamflow, in cubic feet per second; and
- K is a units-conversion constant (0.0027 for concentrations in milligrams per liter) to convert instantaneous suspended-sediment discharge to an equivalent daily suspended-sediment discharge.

After suspended-sediment concentrations were converted to suspended-sediment discharges, the relations between suspended-sediment discharge and streamflow for the two periods before and after March 28, 2008, were plotted to visually identify changes in sediment-transport characteristics. Because of the substantial increase in sediment transport at Clark Fork above Missoula subsequent to the breaching of Milltown Dam, sediment-transport relations for the post-breach period were further examined for all three stations to identify shifts within specific phases of the annual hydrograph. This analysis was done by segregating post-breach data into the rising limb and falling limb of the annual hydrograph to account for a potential loop effect of sediment supply where sediment discharge is greater for a given streamflow when the stream is rising than when it is falling (Colby, 1956).

Sediment-transport relations for the pre-breach and two post-breach periods are illustrated by scatter plots (fig. 3), which are fit with locally weighted scatter plot smoothing (LOWESS) lines (Cleveland and McGill, 1984; Cleveland, 1985) that show the central tendencies of the data distribution over the range of streamflows sampled. For the post-breach period, two smooth curves were plotted to illustrate patterns for the rising limb of the hydrograph from the day of the dam breach through the day of annual peak flow (March 28, 2008–May 21, 2008) and for the falling limb of the hydrograph from the day after the annual peak flow through the end of the water year (May 22, 2008–September 30, 2008). The smooth lines are not regression lines and do not imply statistically significant relations; instead, smooth lines are used as a visual indication of temporal differences in sediment-transport characteristics at each of the three stations. An upward shift in the relation indicates a larger load transported for a given streamflow; a downward shift indicates a smaller load transported for a given streamflow. Identifying differences in sediment-transport relations during different periods aided in determining whether or not the data distribution was relatively uniform over time, or if shifts occurred that were of sufficient magnitude to warrant separate regression equations for discrete time intervals.

The relations between suspended-sediment discharge and streamflow before and after the breaching of Milltown Dam indicate no substantial change between any of the periods for Clark Fork at Turah Bridge and Blackfoot River near Bonner during water years 2004–08 (fig. 3*A* and 3*B*). There was a small upward shift in the relations for several samples during the post-breach rising limb (March 28, 2008–May 21, 2008) at Blackfoot River near Bonner (fig. 3*B*), but it was not large or consistent enough to warrant a separate equation; therefore, the sediment-transport relations for the pre-breach period and both parts of the post-breach period at the two stations upstream from the project area can be considered equivalent for the entire data-analysis period of water years 2004–08. As a result, suspended-sediment transport during water year 2008 can be described by single regression equations for Clark Fork at Turah Bridge and Blackfoot River near Bonner (table 2).

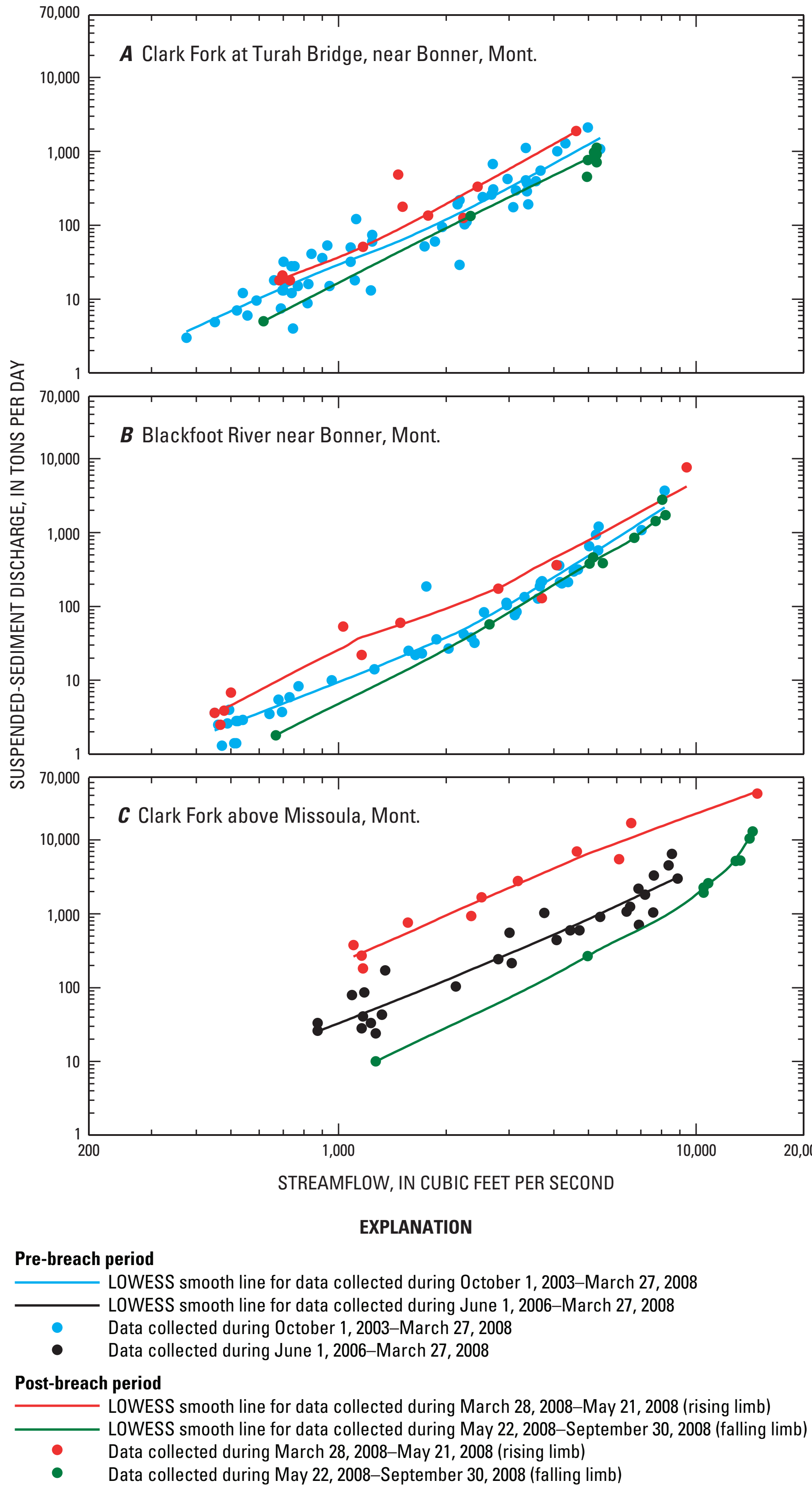


Figure 3. Relations between suspended-sediment discharge and streamflow before and after March 28, 2008 (breaching of Milltown Dam), water years 2004–08: *A*, Clark Fork at Turah Bridge, near Bonner, Mont.; *B*, Blackfoot River near Bonner, Mont.; and *C*, Clark Fork above Missoula, Mont.

In contrast to the two stations upstream from the project area, notable shifts in the sediment-transport relations were apparent for Clark Fork above Missoula (fig. 3*C*) after the breaching of Milltown Dam. The relation during the rising limb of the post-breach period (March 28, 2008–May 21, 2008) was substantially and consistently higher throughout the range of sampled flows than the relation for the pre-breach period (June 1, 2006–March 27, 2008) when Milltown Reservoir was drawn down. The upward shift in the post-breach sediment-transport relation for the rising limb was not sustained, however, as indicated by a large downward shift during the falling limb (May 22, 2008–September 30, 2008). The relation for the falling limb of the post-breach period diverges from the relation for the rising limb at the higher flows and drops to levels below the pre-breach period through the medium and low flows.

The upward shift in the sediment-transport relation for Clark Fork above Missoula during the rising limb of the post-breach period presumably resulted from localized inputs of sediment from within the project area, including erosion of coffer dam sediment, reservoir bottom sediment, and sediment from the streambed and banks near the upper end of the former reservoir as the river adjusted to the steeper channel gradient caused by the dam breach. The extent of the upward shift also likely was affected by the magnitude of the annual peak flow, which was relatively large in water year 2008 (112 percent of the long-term mean annual peak flow, table 1). The downward shift of the sediment-transport relation during the falling limb of the post-breach period probably represented a diminished sediment supply following the erosion and transport of large quantities of sediment from the project area during the rising limb. As a result of the shift in transport characteristics and large localized inputs of sediment from within the project area, it was determined that separate regression equations for the pre-breach period and the two post-breach periods (rising limb and falling limb) were needed to adequately describe the sediment-transport relations at Clark Fork above Missoula. The regression equations for estimating suspended-sediment discharge (table 2) are presented primarily for informational purposes because the high-frequency sampling for daily sediment monitoring, which allowed direct estimation of daily sediment loads, was used to quantify suspended-sediment transport during water year 2008 at all three streamflow-gaging stations (*http://waterdata.usgs.gov/mt/nwis*).

Regression equations for estimating suspended-sediment discharge for water year 2008 at all three streamflow-gaging stations, and the period of record used to develop the equations, are presented in table 2. As part of regression analysis, the data were transformed to various units and examined to determine which form produced the best linear distribution and fit of a regression line. Values for suspended-sediment discharge were transformed to base-10 logarithms (log) and streamflow values were transformed to either log units, square roots ($Q^{0.500}$), or cube roots ($Q^{0.333}$) to obtain the best linear distribution and least scatter. Where both suspended-sediment discharge and streamflow were transformed to log units, the equations are presented in exponential form. Single equations representing sediment-transport relations for the entire water year 2008 at Clark Fork at Turah Bridge and Blackfoot River near Bonner were developed from data collected during water years 2004–08. Three equations representing sediment-transport relations during different periods in water year 2008 at Clark Fork above Missoula were developed from data collected during water years 2006–08. The data for Clark Fork above Missoula were segregated into the pre-breach period (June 1, 2006–March 27, 2008), rising limb of the post-breach period (March 28, 2008–May 21, 2008) and falling limb of the post-breach period (May 22, 2008–September 30, 2008) before developing the regression equations.

All the regression equations for estimating suspended-sediment discharge for water year 2008 (table 2) are statistically significant (p-value < 0.001). The large R^2 values (ranging from 0.88 to 0.99) and small to moderate SE values (ranging from 23.8 to 65.9) indicate relatively good sediment-transport relations at all three stations. Retransformation-bias-correction factors (RBCF) were determined for each of the equations to account for the systematic bias that can occur when data are transformed to log units for purposes of removing curvature in the distribution, and then retransformed back to original arithmetic units to produce the final estimate (Koch and Smillie, 1986). To compensate for log-transformation bias, retransformed results can be multiplied by a non-parametric bias-correction factor (Duan, 1983); bias-correction factors ranged from 1.00 to 1.03.

The regression equations for estimating suspended-sediment discharge (table 2) describe the relations only for the range of streamflow that was sampled at each station during the period used to develop the equations; therefore, extrapolation to higher streamflows might be subject to substantial error. More importantly, the three equations for Clark Fork above Missoula represent distinctly different sediment-transport conditions during periods before and after the breaching of Milltown Dam and during the rising and falling limbs of the annual hydrograph. The potential for localized erosion of sediment from the project area is subject to change as the rivers continue to adjust to the steeper channel gradient, or as additional construction activities occur within the project area. As a result, the separate equations for estimating suspended-sediment discharge at Clark Fork above Missoula are applicable only to the specific dates indicated in table 2.

Trace Elements

Daily loads of unfiltered-recoverable trace elements for water year 2008 were estimated for each of the three streamflow-gaging stations bracketing the project area (fig. 1) by using regression relations developed from instantaneous streamflow at the time of sampling and concentration data for periodic water-quality samples collected during all or part of water years 2004–08. Data for the entire 5-year period were used to examine trace-element transport relations at

Table 2. Regression equations for estimating suspended-sediment discharge for Clark Fork at Turah Bridge, near Bonner, Mont., Blackfoot River near Bonner, Mont., and Clark Fork above Missoula, Mont., water year 2008.

[Abbreviations: N, number of values; R^2, coefficient of determination; p-value, significance level; SE, standard error of estimate, in percent; RBCF, retransformation-bias-correction factor; SEDQ, suspended-sediment discharge, in tons per day; Q, streamflow, in cubic feet per second; LOG, base 10 logarithm. Symbol: <, less than]

Station	Period of record used in developing equations	Equation[1]	N	R^2	p-value	SE	RBCF
Clark Fork at Turah Bridge, near Bonner, Mont. (12334550)	Oct. 1, 2003–Sept. 30, 2008	$SEDQ=0.0000118(Q)^{2.14}$	77	0.88	<0.001	65.9	1.03
Blackfoot River near Bonner, Mont. (12340000)	Oct. 1, 2003–Sept. 30, 2008	$LOG(SEDQ)=0.239(Q^{0.333})-1.40$	69	.95	<.001	53.6	1.03
Clark Fork above Missoula, Mont.[2] (12340500)	Pre-breach June 1, 2006–March 27, 2008	$LOG(SEDQ)=0.184(Q^{0.333})-0.262$	30	.92	<.001	54.3	1.02
Clark Fork above Missoula, Mont.[2] (12340500)	Post-breach rising limb March 28, 2008–May 21, 2008	$SEDQ=0.000193(Q)^{2.02}$	11	.96	<.001	38.8	1.01
Clark Fork above Missoula, Mont.[2] (12340500)	Post-breach falling limb May 22, 2008–Sept. 30, 2008	$LOG(SEDQ)=0.0348(Q^{0.500})-0.183$	9	.99	<.001	23.8	1.00

[1] Equations are provided primarily for informational purposes. Daily suspended-sediment discharges for water year 2008 were estimated directly by high-frequency sampling of the daily sediment monitoring program.

[2] Separate equations for Clark Fork above Missoula were developed using data from three periods: (1) pre-breach period from the start of the permanent draw-down of Milltown Reservoir on June 1, 2006, to the day prior to the breaching of Milltown Dam on March 28, 2008; and (2) post-breach rising limb period after the breaching of Milltown Dam to the peak flow of water-year 2008 on May 21, 2008; and (3) post-breach falling limb period after the peak flow of water year 2008 to September 30, 2008. Unlike the other two sites, there were substantial differences in sediment-transport characteristics for Clark Fork above Missoula associated with those periods (fig. 3). The shifts warranted development of the separate regression equations to more accurately describe the conditions.

Clark Fork at Turah Bridge and Blackfoot River near Bonner. However, data used to develop trace-element transport relations for Clark Fork above Missoula were restricted to the period after June 1, 2006, (start of the permanent drawdown of Milltown Reservoir) to match the period used to develop sediment-transport relations.

Relations between trace-element discharge and suspended-sediment discharge were plotted for the three streamflow-gaging stations bracketing the project area for the same pre-breach and two post-breach (rising limb and falling limb) periods used for examining sediment-transport relations (fig. 3). Suspended-sediment discharge was used as the explanatory variable in the plots because unfiltered-recoverable trace-element concentrations are strongly associated with suspended-sediment concentrations (Lambing, 1991). Before plotting the relations, the trace-element concentration for each periodic water-quality sample was converted to an equivalent trace-element discharge, in tons per day, according to the equation:

$$Q_{te} = C_{te}QK, \tag{2}$$

where

Q_{te} is trace-element discharge, in tons per day;
C_{te} is trace-element concentration, in micrograms per liter;
Q is streamflow, in cubic feet per second; and
K is a units-conversion constant (0.0000027 for concentrations in micrograms per liter) to convert instantaneous trace-element discharge to an equivalent daily trace-element discharge.

After trace-element concentrations were converted to trace-element discharges, the relations between trace-element discharge and suspended-sediment discharge for the pre-breach and post-breach periods were plotted to visually identify changes in trace-element transport characteristics. Examples of trace-element transport relations for the pre-breach and post-breach periods are illustrated by scatter plots for unfiltered-recoverable arsenic discharge (fig. 4) and unfiltered-recoverable copper discharge (fig. 5), which are fit with LOWESS smooth lines showing the central tendencies of the data distribution during the two periods. Although smooth plots were examined for all the trace elements, only arsenic and copper are presented as examples because they represent the greatest difference in relations among the trace elements; the relations for the other trace elements generally were similar to those for copper. The smooth lines are not regression lines and do not imply statistically significant relations, but rather are used as a visual indication of temporal differences in trace-element transport characteristics at each of the three stations.

The relations between unfiltered-recoverable arsenic discharge and suspended-sediment discharge for all three stations (fig. 4) indicate no substantial change in arsenic transport relative to suspended-sediment transport between the various periods before and after the breaching of Milltown Dam, although there appeared to be a minor upward shift in arsenic transport at Clark Fork above Missoula for several samples during the falling limb of the post-breach period (fig. 4*C*). There also was no substantial difference in the relations between unfiltered-recoverable copper discharge and suspended-sediment discharge for Clark Fork at Turah Bridge and Blackfoot River near Bonner for the pre-breach and post-breach periods (fig. 5*A* and 5*B*). In contrast, the relations between unfiltered-recoverable copper discharge and suspended-sediment discharge at Clark Fork above Missoula (fig. 5*C*) revealed a relatively consistent upward shift in transport characteristics during the rising limb of the post-breach period compared to the pre-breach period and falling limb of the post-breach period.

As a result of the similarity of temporal patterns indicated by smooth plots for the different periods, transport relations for all the trace elements at Clark Fork at Turah Bridge and Blackfoot River near Bonner were considered to be equivalent throughout the entire data-analysis period (water years 2004–08). Therefore, trace-element discharge for the entire water year 2008 can be estimated by single regression equations for each trace element at Clark Fork at Turah Bridge (table 3) and Blackfoot River near Bonner (table 4). In contrast to the two stations upstream from the project area, the shifts in smooth plots for arsenic (fig. 4*C*) and especially copper (fig. 5*C*) at Clark Fork above Missoula indicated that separate regression equations for estimating trace-element discharge during different periods were necessary. The same pre-breach and post-breach periods used to segregate data for developing regression equations to estimate suspended-sediment discharge at Clark Fork above Missoula (table 2) were used to develop regression equations to estimate trace-element discharge (table 5). Using the same periods for data segregation ensured that a consistent treatment of data was used to estimate loads during the individual periods when transport characteristics were changing at Clark Fork above Missoula.

Although LOWESS smooth lines of trace-element discharge relative to suspended-sediment discharge were evaluated to identify temporal patterns useful for guiding data segregation in subsequent regression analysis, regression relations were more broadly examined. Various combinations of variables, data segregation, and data transformation were tested and regression diagnostics were reviewed to determine the best possible data fit for estimating trace-element discharge. Regression relations between trace-element discharge and two related variables—streamflow and suspended-sediment discharge—were examined to aid in the selection of the most appropriate explanatory variable in the regression equations. In addition to reviewing regression diagnostics to select the most appropriate explanatory variable, measured instantaneous trace-element discharges for periodic water-quality samples were converted to equivalent daily loads and plotted with estimated daily trace-element loads derived from various forms of regression equations. The estimated daily trace-element loads generated from each combination of data treatments then were compared to measured trace-element loads to identify the form of equation that produced the best matches.

In almost all instances, better relations for estimating trace-element discharge were obtained by using suspended-sediment discharge as the explanatory variable, presumably because of the strong association between suspended-sediment concentrations and unfiltered-recoverable concentrations of trace elements (Lambing, 1991); however, an exception was noted for arsenic. At both stations upstream from the project area (Clark Fork at Turah Bridge and Blackfoot River near Bonner), the regression relations for estimating unfiltered-recoverable arsenic discharge were slightly better using streamflow as the explanatory variable. A possible reason for the slightly better relation with streamflow at these two stations is the greater proportion of dissolved arsenic that composed the unfiltered-recoverable arsenic concentration (*http://waterdata.usgs.gov/mt/nwis*). At Clark Fork above Missoula, regression relations for estimating unfiltered-recoverable arsenic discharge were better using suspended-sediment discharge as the explanatory variable, possibly because the large input of sediment from the project area was sufficiently enriched in arsenic to improve the relation.

Regression equations for estimating unfiltered-recoverable trace-element discharge for Clark Fork at Turah Bridge, Blackfoot River near Bonner, and Clark Fork above Missoula for water year 2008, and the period of record used to develop the equations, are presented in tables 3–5, respectively. As part of regression analysis, the data were transformed to various units and examined to determine which form produced the best linear distribution and fit of a regression line. Values of both trace-element discharge and suspended-sediment discharge were transformed to log units to obtain the best linear distribution and least scatter for all relations, with the exception of arsenic at Clark Fork at Turah Bridge and Blackfoot River near Bonner. Where both trace-element discharge and suspended-sediment discharge were transformed to log units, the equations are presented in exponential form. Equations for estimating unfiltered-recoverable arsenic discharge at Clark Fork at Turah Bridge and Blackfoot River near Bonner used streamflow as the explanatory variable, which was transformed to either the square root ($Q^{0.500}$) or cube root ($Q^{0.333}$); arsenic discharge was transformed to

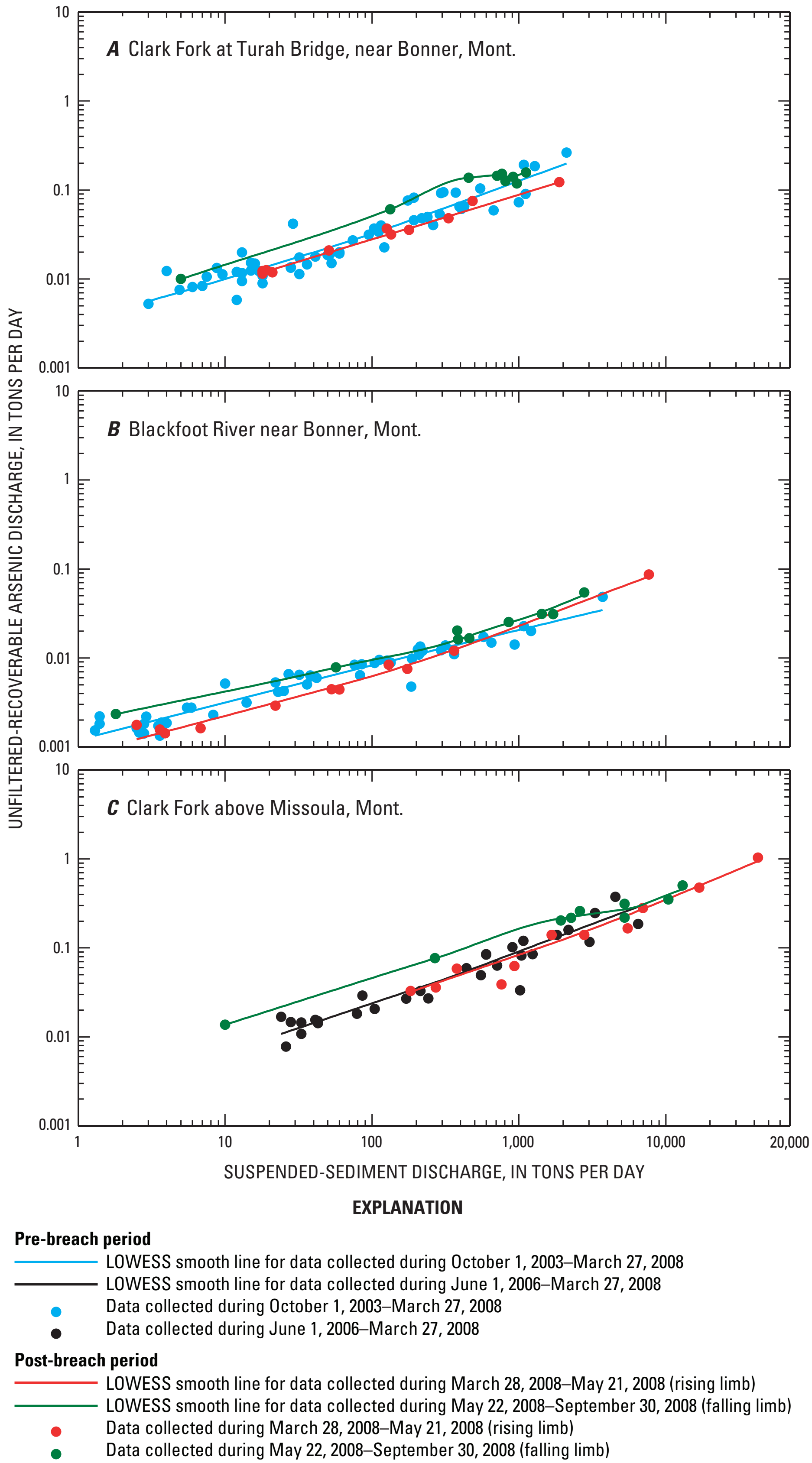
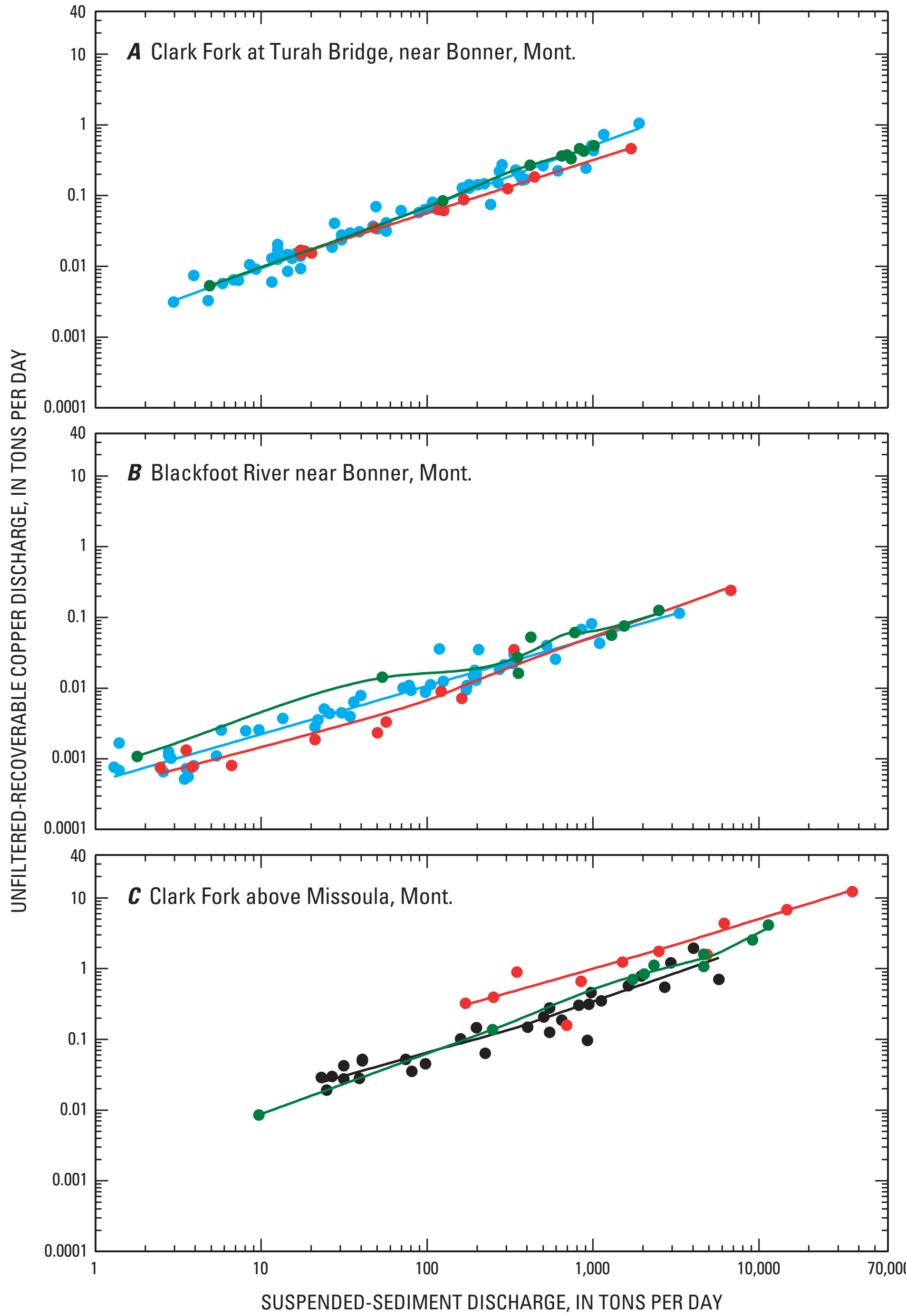


Figure 4. Relations between unfiltered-recoverable arsenic discharge and suspended-sediment discharge before and after March 28, 2008 (breaching of Milltown Dam), water years 2004–08: *A*, Clark Fork at Turah Bridge, near Bonner, Mont.; *B*, Blackfoot River near Bonner, Mont.; and *C*, Clark Fork above Missoula, Mont.



EXPLANATION

Pre-breach period

LOWESS smooth line for data collected during October 1, 2003–March 27, 2008

LOWESS smooth line for data collected during June 1, 2006–March 27, 2008

Data collected during October 1, 2003–March 27, 2008

Data collected during June 1, 2006–March 27, 2008

Post-breach period

LOWESS smooth line for data collected during March 28, 2008–May 21, 2008 (rising limb)

LOWESS smooth line for data collected during May 22, 2008–September 30, 2008 (falling limb)

Data collected during March 28, 2008–May 21, 2008 (rising limb)

Data collected during May 22, 2008–September 30, 2008 (falling limb)

Figure 5. Relations between unfiltered-recoverable copper discharge and suspended-sediment discharge before and after March 28, 2008 (breaching of Milltown Dam), water years 2004–08: *A*, Clark Fork at Turah Bridge, near Bonner, Mont.; *B*, Blackfoot River near Bonner, Mont.; and *C*, Clark Fork above Missoula, Mont.

log units. Single equations describe trace-element discharge for the entire water year 2008 at Clark Fork at Turah Bridge (table 3) and Blackfoot River near Bonner (table 4). Three separate equations describe trace-element discharge for the pre-breach period and two post-breach periods (rising limb and falling limb) at Clark Fork above Missoula (table 5).

All the regression equations for estimating trace-element discharge (tables 3–5) are statistically significant (p-value < 0.001). The large R^2 values (ranging from 0.82 to 1.00) and small to moderate SE values indicate relatively good transport relations for all the trace elements at all three stations. The ranges of SE values in the equations for all three stations were 17.1–32.5 percent for arsenic, 27.3–51.0 percent for cadmium, 19.7–65.7 percent for copper, 10.9–27.5 percent for iron, 24.4–56.2 percent for lead, 9.5–34.2 percent for manganese, and 20.5–47.0 percent for zinc.

The regression equations in tables 3–5 were applied to the appropriate record of either daily mean streamflow or daily suspended-sediment loads (*http://waterdata.usgs.gov/mt/nwis*) to estimate daily trace-element loads for water year 2008. The retransformed results were multiplied by bias-correction factors to compensate for log-transformation bias by using procedures described by Duan (1983); bias-correction factors ranged from 1.00 to 1.03.

The equations for estimating unfiltered recoverable trace-element discharge in tables 3–5 describe the relations only for the range of streamflow that was sampled at each station during the period used to develop the equation; therefore, extrapolation to higher streamflows might be subject to substantial error. Similar to suspended-sediment discharge, the separate equations for estimating trace-element discharge at Clark Fork above Missoula are applicable only to the specific dates indicated in table 5.

Table 3. Regression equations for estimating unfiltered-recoverable trace-element discharge for Clark Fork at Turah Bridge, near Bonner, Mont., water year 2008.

[Abbreviations: N, number of values; R^2, coefficient of determination; p-value, significance level; SE, standard error of estimate, in percent; RBCF, retransformation-bias-correction factor; LOG, base 10 logarithm; ASQ, arsenic discharge, in tons per day; Q, streamflow, in cubic feet per second; CDQ, cadmium discharge, in tons per day; SEDQ, suspended-sediment discharge, in tons per day; CUQ, copper discharge, in tons per day; FEQ, iron discharge, in tons per day; PBQ, lead discharge, in tons per day; MNQ, manganese discharge, in tons per day; ZNQ, zinc discharge, in tons per day. Symbol: <, less than]

Trace element	Equation	N	R^2	p-value	SE	RBCF
Equations developed using data collected October 1, 2003–September 30, 2008						
Arsenic	$LOG(ASQ)=0.136(Q^{0.333})-3.15$	77	0.94	<0.001	25.9	1.01
Cadmium	$CDQ=0.0000138(SEDQ)^{0.765}$	77	.96	<.001	27.3	1.01
Copper	$CUQ=0.00140(SEDQ)^{0.827}$	77	.97	<.001	26.9	1.01
Iron	$FEQ=0.0171(SEDQ)^{0.991}$	77	.98	<.001	21.9	1.00
Lead	$PBQ=0.000114(SEDQ)^{0.969}$	77	.97	<.001	32.1	1.01
Manganese	$MNQ=0.00613(SEDQ)^{0.820}$	77	.98	<.001	21.2	1.00
Zinc	$ZNQ=0.00175(SEDQ)^{0.856}$	77	.97	<.001	28.2	1.01

Table 4. Regression equations for estimating unfiltered-recoverable trace-element discharge for Blackfoot River near Bonner, Mont., water year 2008.

[Abbreviations: N, number of values; R^2, coefficient of determination; p-value, significance level; SE, standard error of estimate, in percent; RBCF, retransformation-bias-correction factor; LOG, base 10 logarithm; ASQ, arsenic discharge, in tons per day; Q, streamflow, in cubic feet per second; CDQ, cadmium discharge, in tons per day; SEDQ, suspended-sediment discharge, in tons per day; CUQ, copper discharge, in tons per day; FEQ, iron discharge, in tons per day; PBQ, lead discharge, in tons per day; MNQ, manganese discharge, in tons per day; ZNQ, zinc discharge, in tons per day. Symbol: <, less than]

Trace element	Equation	N	R^2	p-value	SE	RBCF
Equations developed using data collected October 1, 2003–September 30, 2008						
Arsenic	$LOG(ASQ)=0.0198(Q^{0.500})-3.18$	69	0.97	<0.001	18.2	1.00
Cadmium	$CDQ=0.00000845(SEDQ)^{0.494}$	69	.91	<.001	36.3	1.01
Copper	$CUQ=0.000437(SEDQ)^{0.686}$	69	.93	<.001	43.8	1.02
Iron	$FEQ=0.0210(SEDQ)^{0.921}$	69	.99	<.001	23.5	1.00
Lead	$PBQ=0.0000260(SEDQ)^{0.939}$	69	.99	<.001	24.8	1.01
Manganese	$MNQ=0.00280(SEDQ)^{0.825}$	69	.98	<.001	24.5	1.01
Zinc	$ZNQ=0.000639(SEDQ)^{0.676}$	69	.96	<.001	30.4	1.01

Table 5. Regression equations for estimating unfiltered-recoverable trace-element discharge for Clark Fork above Missoula, Mont., water year 2008.

[Abbreviations: N, number of values; R^2, coefficient of determination; p-value, significance level; SE, standard error of estimate, in percent; RBCF, retransformation-bias-correction factor; ASQ, arsenic discharge, in tons per day; SEDQ, suspended-sediment discharge, in tons per day; CDQ, cadmium discharge, in tons per day; CUQ, copper discharge, in tons per day; FEQ, iron discharge, in tons per day; PBQ, lead discharge, in tons per day; MNQ, manganese discharge, in tons per day; ZNQ, zinc discharge, in tons per day. Symbol: <, less than]

Trace element	Equation	N	R^2	p-value	SE	RBCF
Pre-breach equations developed using data collected June 1, 2006–March 27, 2008						
Arsenic	$ASQ=0.00176(SEDQ)^{0.565}$	30	0.91	<0.001	32.5	1.01
Cadmium	$CDQ=0.0000213(SEDQ)^{0.680}$	30	0.89	<.001	43.5	1.01
Copper	$CUQ=0.00253(SEDQ)^{0.694}$	30	0.90	<.001	42.9	1.01
Iron	$FEQ=0.0281(SEDQ)^{0.853}$	30	0.97	<.001	27.5	1.01
Lead	$PBQ=0.000312(SEDQ)^{0.738}$	30	0.92	<.001	41.6	1.01
Manganese	$MNQ=0.00823(SEDQ)^{0.697}$	30	0.93	<.001	34.2	1.01
Zinc	$ZNQ=0.00351(SEDQ)^{0.732}$	30	0.91	<.001	41.9	1.01
Post-breach rising limb equations developed using data collected March 28, 2008–May 21, 2008						
Arsenic	$ASQ=0.00102(SEDQ)^{0.629}$	11	0.95	<0.001	27.9	1.01
Cadmium	$CDQ=0.0000418(SEDQ)^{0.683}$	11	0.87	<.001	51.0	1.02
Copper	$CUQ=0.00684(SEDQ)^{0.690}$	11	0.82	<.001	65.7	1.03
Iron	$FEQ=0.0344(SEDQ)^{0.848}$	11	0.98	<.001	21.6	1.00
Lead	$PBQ=0.00123(SEDQ)^{0.672}$	11	0.85	<.001	56.2	1.02
Manganese	$MNQ=0.00454(SEDQ)^{0.757}$	11	0.95	<.001	31.7	1.01
Zinc	$ZNQ=0.00944(SEDQ)^{0.697}$	11	0.89	<.001	47.0	1.02
Post-breach falling limb equations developed using data collected May 22, 2008–September 30, 2008						
Arsenic	$ASQ=0.00494(SEDQ)^{0.479}$	9	0.98	<0.001	17.1	1.00
Cadmium	$CDQ=0.00000525(SEDQ)^{0.887}$	9	0.98	<.001	31.2	1.01
Copper	$CUQ=0.00130(SEDQ)^{0.830}$	9	0.99	<.001	19.7	1.00
Iron	$FEQ=0.0243(SEDQ)^{0.894}$	9	1.00	<.001	10.9	1.00
Lead	$PBQ=0.0000905(SEDQ)^{0.927}$	9	0.99	<.001	24.4	1.00
Manganese	$MNQ=0.0145(SEDQ)^{0.659}$	9	1.00	<.001	9.5	1.00
Zinc	$ZNQ=0.00158(SEDQ)^{0.869}$	9	0.99	<.001	20.5	1.00

Estimated Loads Transported through the Milltown Reservoir Project Area

Patterns in daily loads transported past the three streamflow-gaging stations that bracket the project area illustrate the response of constituent transport to streamflow variations, ice conditions, reservoir operations, and discrete erosional events. Daily loads can be summed for individual periods to determine cumulative loads transported over prolonged periods to indicate the most important source areas contributing load to the river on a sustained basis. The cumulative net gains or losses for the periods before and after the breaching of Milltown Dam can identify differences in the mass balance for two distinctly different environmental settings and flow conditions. Also, the cumulative net gains or losses for the entire year can be used to describe the annual mass balance of the suspended-sediment and trace-element loads transported through the project area during water year 2008.

Daily Loads

Variations of estimated daily suspended-sediment, unfiltered-recoverable arsenic, and unfiltered-recoverable copper loads transported as inflow to and outflow from the project area during water year 2008 are shown in figures 6–8, respectively, along with the daily mean streamflow during the year. Daily values for the two streamflow-gaging stations upstream from the project area (Clark Fork at Turah Bridge and Blackfoot River near Bonner) are summed to represent the total inflow of streamflow and constituent loads from the upstream source areas to the project area. Values determined for Clark Fork at Turah Bridge represent the inflow from the upper Clark Fork basin; values determined for Blackfoot River near Bonner represent the inflow from the Blackfoot River basin. The daily values for Clark Fork above Missoula represent the outflow from the project area. Also shown are measured values of instantaneous constituent discharge (converted to equivalent daily loads by assuming the instantaneous discharge is maintained for 24 hours) for the periodic water-quality samples collected during water year 2008 for comparison to the estimated daily loads.

Deposition of constituent load within the project area is indicated in figures 6–8 for days when the combined inflow load to the project area is greater than the outflow load at Clark Fork above Missoula. Conversely, loss of load from the project area is indicated for days when the outflow load at Clark Fork above Missoula is greater than the combined inflow load. Differences in daily loads transported to and from the project area illustrate discrete periods of net balance, deposition, or loss of constituent load within the project area. Generally, deposition of sediment and sediment-associated trace elements within the project area is more likely to occur during low streamflows when velocities are low. Loss of sediment and sediment-associated trace elements is more likely to occur during high streamflows when velocities are high; however, deposition or loss of constituents also can result from discrete events or localized activities not directly related to streamflow magnitude.

The shaded "Pre-breach" area in figures 6–8 represents the approximately 6-month period in water year 2008 before the breaching of Milltown Dam (October 1, 2007–March 27, 2008) when Milltown Reservoir was drawn down to facilitate construction activities related to dam removal. The unshaded "Post-breach" area in figures 6–8 represents the approximately 6-month period in water year 2008 after Milltown Dam was breached (March 28, 2008–September 30, 2008) when the environment of the project area changed from a reservoir to a free-flowing river.

The patterns in daily streamflow (figs. 6–8) illustrate a typical annual hydrograph in which streamflow generally was low to moderate during the fall and winter. The minimum flow for the year occurred in January, followed by relatively steady to slightly increasing streamflow through March. Streamflow started increasing rapidly in mid-April and reached an annual peak on May 21. High flow (near or greater than 10,000 ft^3/s) at Clark Fork above Missoula was sustained for several weeks from about mid-May to late June. Streamflow decreased gradually after the peak through the summer, but did not get as low as the winter minimum. Differences in daily streamflow between the combined inflow to the project area and the outflow at Clark Fork above Missoula were small. Minor differences between combined inflow and outflow could represent inputs from ungaged small tributaries in the reaches between the gaging stations, loss of surface water to ground water in the alluvium underlying the project area, or minor inaccuracies in streamflow records.

Variations in estimated daily suspended-sediment loads transported to and from the project area during water year 2008 (fig. 6) generally coincided with variations in streamflow, although exceptions occurred during a period of ice conditions in the winter and for several days after the breaching of Milltown Dam. Overall, the daily outflow suspended-sediment loads consistently were larger than the combined daily inflow suspended-sediment loads for most of water year 2008, with the largest differences occurring in the post-breach period during the rising limb and peak flow of the annual streamflow hydrograph.

During the pre-breach period of water year 2008, when Milltown Reservoir was drawn down and low flows were prevalent, differences between the inflow and outflow daily suspended-sediment loads indicated relatively small to moderately large net losses from the project area on most days. Although the patterns of increase and decrease during the pre-breach period generally were consistent between the inflow and outflow, there were several days when the patterns did not coincide. Outflow suspended-sediment load spiked on some days without a concurrent large increase in either streamflow or inflow suspended-sediment load, possibly as a result of localized sediment disturbances. The most notable net loss of suspended sediment from the project area in the pre-breach

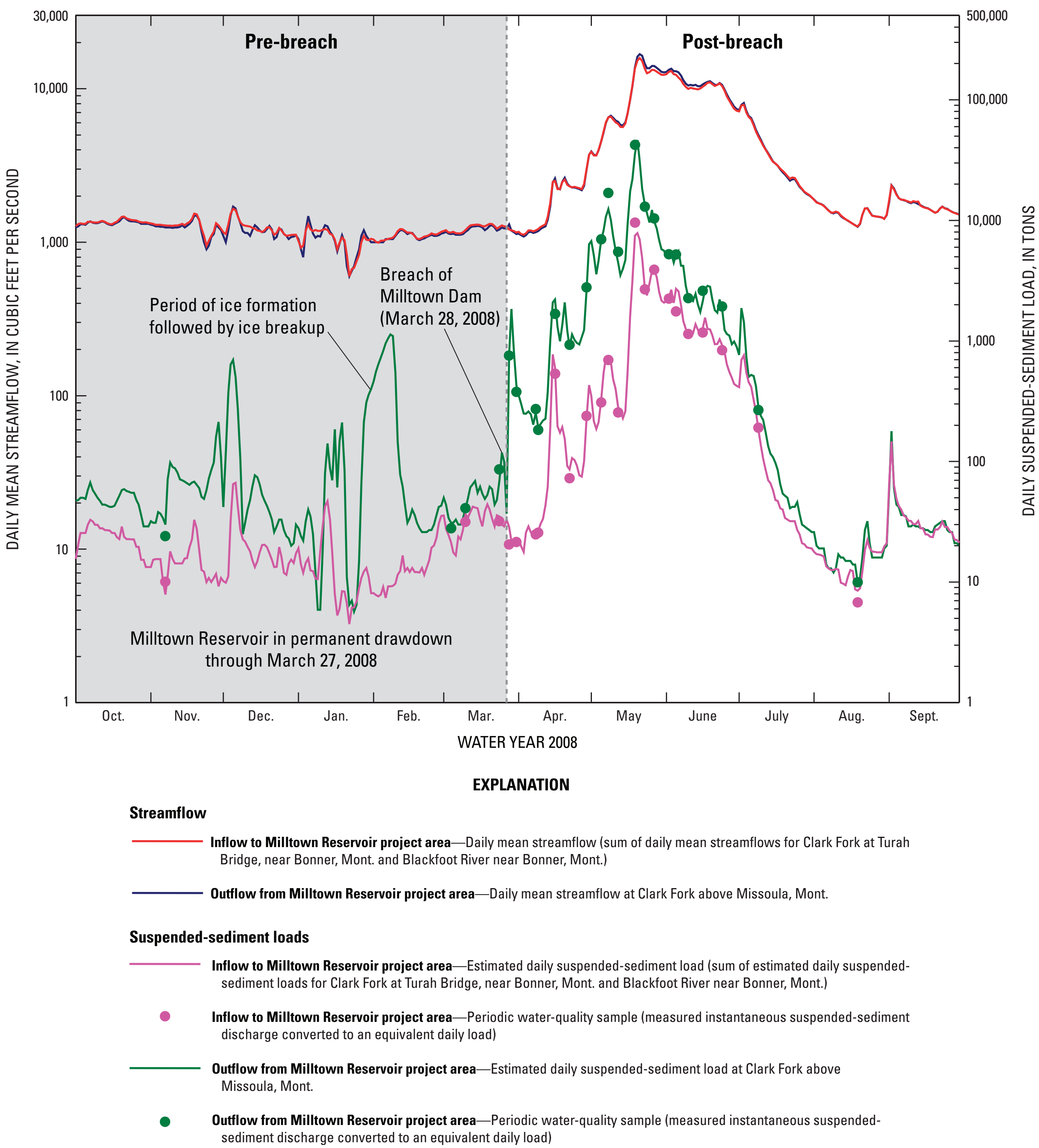


Figure 6. Daily mean streamflow and estimated daily suspended-sediment loads transported to and from the Milltown Reservoir project area, water year 2008.

period occurred from about late January to early February during a time of ice formation and subsequent breakup. This period of ice conditions also coincided with a period of several weeks when water from dewatering wells in the bypass channel was discharged directly into the Blackfoot River, rather than to a sedimentation pond, to facilitate completion of the bypass channel (U.S. Environmental Protection Agency, written commun., January 2008). It is unknown whether or not this discharge of water had any effect on suspended-sediment concentrations, or merely was coincidental.

During the post-breach period of water year 2008, net losses of suspended sediment from the project area were substantially greater than those during the pre-breach period because of increased erosion of sediment sources within the project area. The outflow of suspended sediment from the project area sharply increased immediately after the breaching of Milltown Dam, resulting in large daily net losses. The large post-breach net losses of suspended sediment from the project area continued through the rising limb and peak flow of the annual hydrograph. Net losses of suspended sediment began to decrease after the peak flow, but were still relatively large during the early stages of the falling limb through June. The net losses of suspended sediment continued to decrease during the falling limb and were relatively small by July, reaching an approximate net balance between inflow and outflow loads by mid-August.

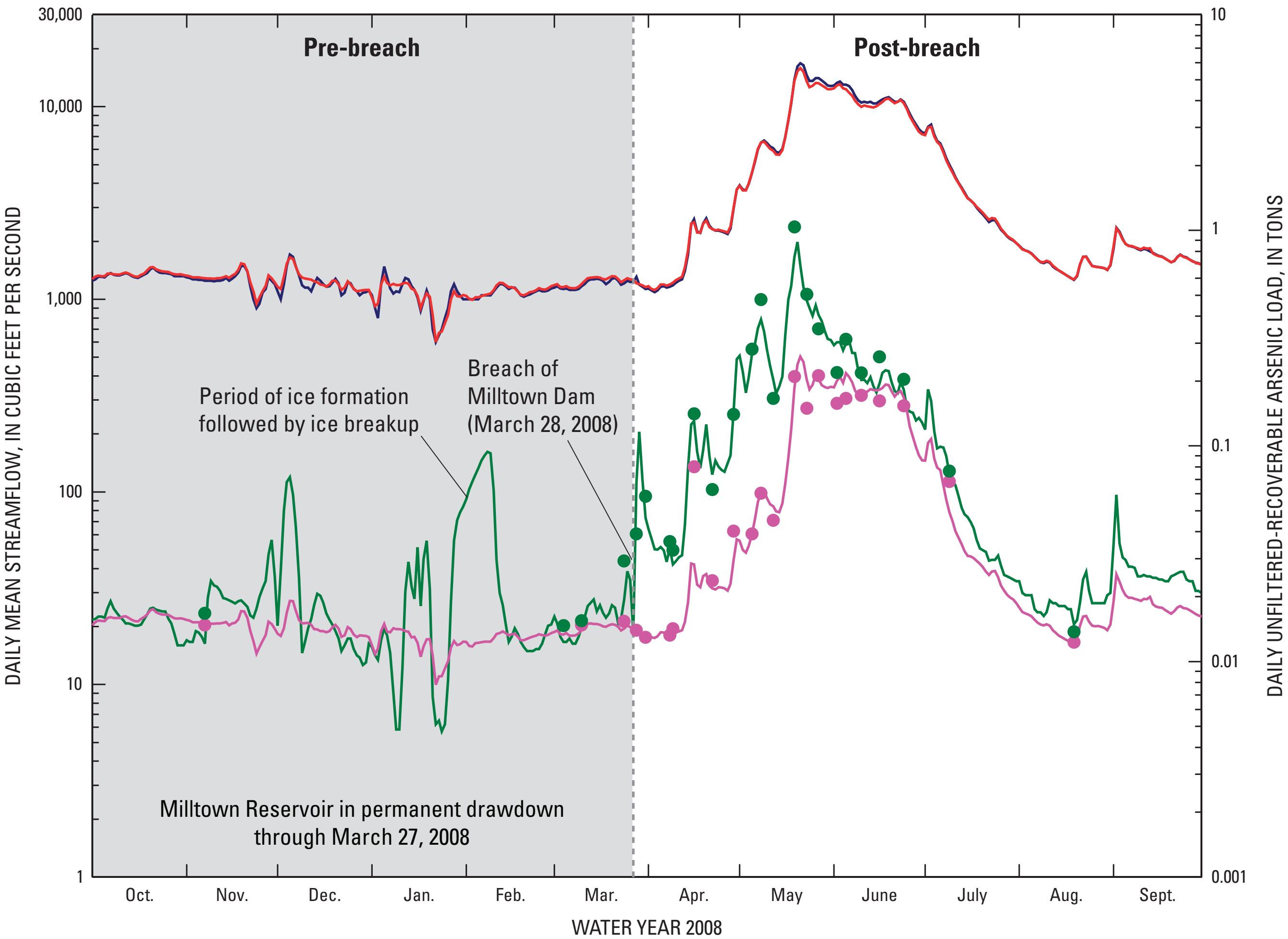
Sample results for the supplemental sampling site Clark Fork Bypass near Bonner (fig. 1) are useful for evaluating contributions from localized areas of erosion within the project area. A comparison of periodic water-quality data (*http://waterdata.usgs.gov/mt/nwis*) for samples collected on 16 concurrent dates during water year 2008 at Clark Fork at Turah Bridge and Clark Fork Bypass near Bonner indicates substantial differences within a short distance (about 5 river mi) of channel between the two sites; the greatest differences occurred during periods of high flow after Milltown Dam was breached. Samples at Clark Fork Bypass near Bonner were collected within 2–3 hours after samples were collected at Clark Fork at Turah Bridge; this time interval approximated the stream travel time, which provided characterization of the same hydrologic condition at both sites. With no major inflows between the two sites, differences in sediment transport presumably can be attributed to erosion from channel sources, such as the streambed and banks, within the intervening reach.

Differences in suspended-sediment concentrations between Clark Fork at Turah Bridge and Clark Fork Bypass near Bonner indicate a substantial input of sediment from the intervening channel, especially during high-flow conditions. The post-breach median suspended-sediment concentration increased from 39 mg/L at Clark Fork at Turah Bridge to 161 mg/L at Clark Fork Bypass near Bonner for the 16 samples collected on concurrent dates. Also notable was the predominance of sand that was eroded from this reach of channel. The post-breach median percent of suspended sediment finer than 0.062 mm for the concurrent sample sets decreased from 72 percent at Clark Fork at Turah Bridge to 28 percent at Clark Fork Bypass near Bonner. A relatively high sand content also was measured in suspended-sediment samples collected at Clark Fork above Missoula, which had a post-breach median of 50 percent finer than 0.062 mm. The higher percent of fine material at Clark Fork above Missoula compared to Clark Fork Bypass near Bonner likely results from the mixing of suspended sediment from the Clark Fork with suspended sediment from the Blackfoot River (post-breach median of 83 percent finer than 0.062 mm at Blackfoot River near Bonner).

The greatest inputs of suspended sediment from the intervening reach between Clark Fork at Turah Bridge and Clark Fork Bypass near Bonner occurred during the rising limb of the post-breach period as flows increased to the annual peak; much of the suspended-sediment input consisted of sand. For example, the sample of May 19 at Clark Fork at Turah Bridge had a suspended-sediment concentration of 151 mg/L, with a size composition of 63 percent finer than 0.062 mm, indicating a predominance of fine sediment. In contrast, the sample collected 2 hours later at Clark Fork Bypass near Bonner had a suspended-sediment concentration of 3,780 mg/L and was predominated by sand, with a size composition of 9 percent finer than 0.062 mm. Although the samples collected on May 19 represent the maximum difference measured between the two sites during water year 2008, the substantial increase in suspended-sediment concentration and proportion of sand within a short distance clearly indicates the dynamic process of post-breach channel erosion that occurred during high flow in the area near the upper end of the Clark Fork arm of the former reservoir.

The temporal variations in daily loads for all the unfiltered-recoverable trace-elements (arsenic, cadmium, copper, iron, lead, manganese, and zinc) estimated for water year 2008 generally were similar. Estimated daily loads of arsenic (fig. 7) and copper (fig. 8) are illustrated as representative examples of trace-element transport to and from the project area during water year 2008. These two elements are presented as examples because they are constituents of concern in terms of potential toxicity and, although generally similar in transport characteristics, they represent the widest range in patterns of transport.

Variations in daily arsenic and copper loads entering and leaving the project area generally coincided with variations in streamflow (figs. 7 and 8) and suspended-sediment loads (fig. 6); the daily loads for the other trace elements similarly coincided with variations in streamflow and suspended-sediment loads. Small to moderately large daily net losses of trace-element loads from the project area were common during the pre-breach period when Milltown Reservoir was drawn down and low flows were prevalent. The inflow and outflow trace-element loads increased during the post-breach period as streamflow increased. Similar to suspended sediment, the outflow of trace-element loads sharply increased immediately after the breaching of Milltown Dam, resulting in large daily net losses. The large post-breach net losses of trace elements from the project area continued through the rising limb and



EXPLANATION

Streamflow

Inflow to Milltown Reservoir project area—Daily mean streamflow (sum of daily mean streamflows for Clark Fork at Turah Bridge, near Bonner, Mont. and Blackfoot River near Bonner, Mont.)

Outflow from Milltown Reservoir project area—Daily mean streamflow at Clark Fork above Missoula, Mont.

Unfiltered-recoverable arsenic loads

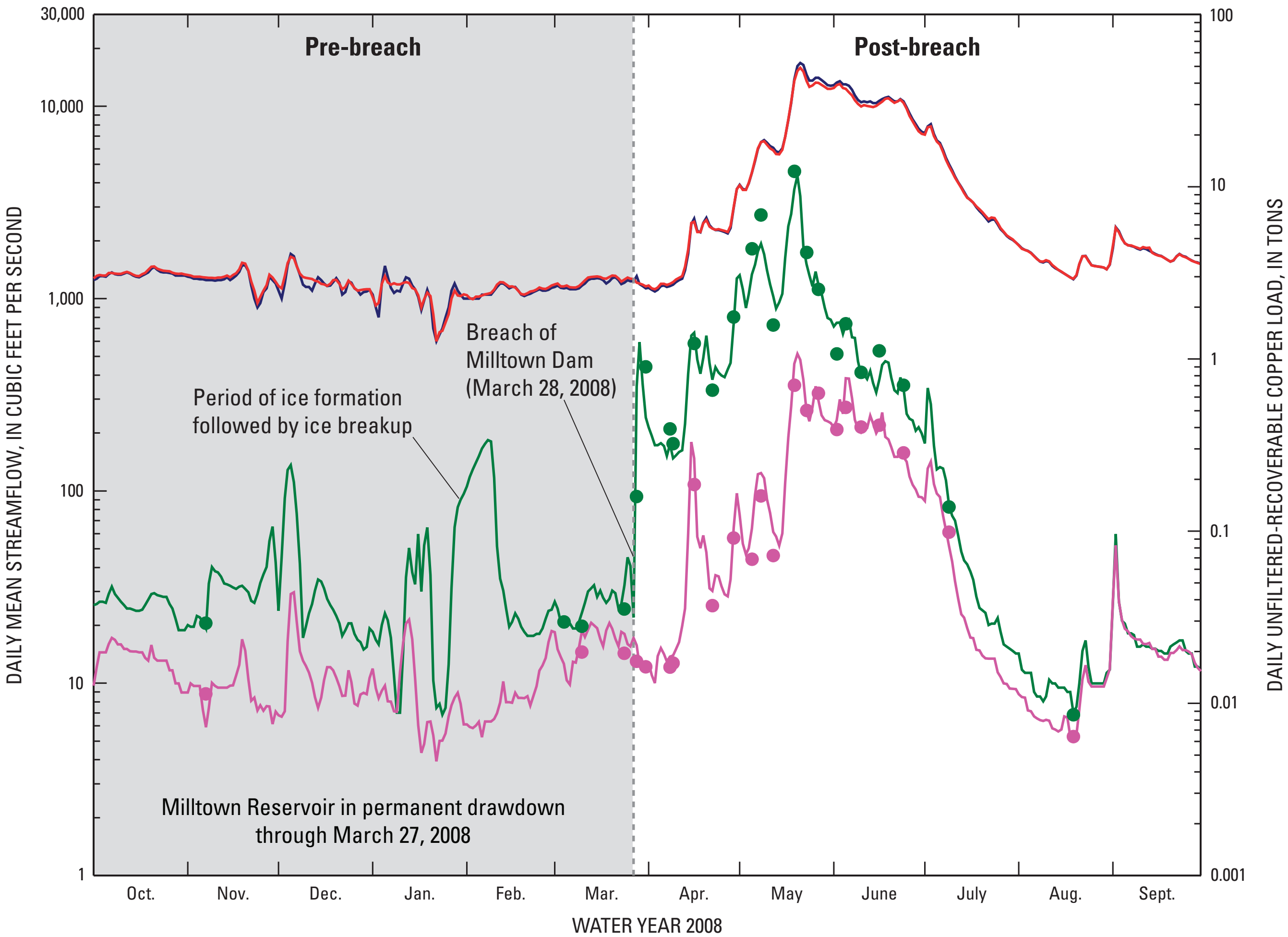
Inflow to Milltown Reservoir project area—Estimated daily unfiltered-recoverable arsenic load (sum of estimated daily unfiltered-recoverable arsenic loads for Clark Fork at Turah Bridge, near Bonner, Mont. and Blackfoot River near Bonner, Mont.)

Inflow to Milltown Reservoir project area—Periodic water-quality sample (measured instantaneous unfiltered-recoverable arsenic discharge converted to an equivalent daily load)

Outflow from Milltown Reservoir project area—Estimated daily unfiltered-recoverable arsenic load at Clark Fork above Missoula, Mont.

Outflow from Milltown Reservoir project area—Periodic water-quality sample (measured instantaneous unfiltered-recoverable arsenic discharge converted to an equivalent daily load)

Figure 7. Daily mean streamflow and estimated daily unfiltered-recoverable arsenic loads transported to and from the Milltown Reservoir project area, water year 2008.



EXPLANATION

Streamflow

Inflow to Milltown Reservoir project area—Daily mean streamflow (sum of daily mean streamflows for Clark Fork at Turah Bridge, near Bonner, Mont. and Blackfoot River near Bonner, Mont.)

Outflow from Milltown Reservoir project area—Daily mean streamflow at Clark Fork above Missoula, Mont.

Unfiltered-recoverable arsenic loads

Inflow to Milltown Reservoir project area—Estimated daily unfiltered-recoverable copper load (sum of estimated daily unfiltered-recoverable copper loads for Clark Fork at Turah Bridge, near Bonner, Mont. and Blackfoot River near Bonner, Mont.)

Inflow to Milltown Reservoir project area—Periodic water-quality sample (measured instantaneous unfiltered-recoverable copper discharge converted to an equivalent daily load)

Outflow from Milltown Reservoir project area—Estimated daily unfiltered-recoverable copper load at Clark Fork above Missoula, Mont.

Outflow from Milltown Reservoir project area—Periodic water-quality sample (measured instantaneous unfiltered-recoverable copper discharge converted to an equivalent daily load)

Figure 8. Daily mean streamflow and estimated daily unfiltered-recoverable copper loads transported to and from the Milltown Reservoir project area, water year 2008.

peak flow of the annual hydrograph, followed by decreasing net losses during the falling limb. The net losses of trace elements were relatively small by July; an approximate net balance between inflow and outflow loads was achieved by mid-August for all the trace elements, except arsenic.

The differences between daily unfiltered-recoverable arsenic loads transported to and from the project area (fig. 7) were small to moderately large for most of the pre-breach period. Net losses of arsenic from the project area were common on numerous days during the pre-breach period, but unlike suspended sediment and the other trace elements, net deposition of arsenic also occurred on some days, although at smaller magnitudes than the net losses. Similar to suspended sediment (fig. 6), there were days when the outflow of arsenic loads spiked relative to streamflow or inflow loads; there also was a sustained, moderate net loss of arsenic for several weeks during a period of ice formation and breakup from about late January to early February (fig. 7). Inflow loads of arsenic displayed less daily variation relative to inflow loads of suspended sediment (fig. 6), presumably because of the greater proportion of arsenic that was in the dissolved phase at the two stations upstream from the project area (*http://waterdata.usgs.gov/mt/nwis*); however, the daily patterns in outflow loads of arsenic were more similar to those of suspended sediment.

Arsenic outflow from the project area increased sharply after the breaching of Milltown Dam, resulting in large daily net losses. The large post-breach net losses of arsenic from the project area continued through the rising limb and peak flow of the annual hydrograph (fig. 7). After the peak flow, the outflow arsenic load decreased more rapidly than the inflow arsenic load during the initial stages of the falling limb, resulting in relatively small net losses of arsenic by mid-June. A net loss of arsenic, although relatively small, continued consistently through the remainder of the post-breach period in water year 2008.

The differences between daily unfiltered-recoverable copper loads transported to and from the project area (fig. 8) were moderately large on most days during the pre-breach period. Net losses of copper from the project area were sustained consistently for essentially the entire pre-breach period, unlike that of arsenic, which varied between periods of net losses and net deposition. The consistent daily net loss of copper during the pre-breach period was a continuation of the pattern that began after the start of the permanent drawdown of Milltown Reservoir on June 1, 2006 (Lambing and Sando, 2008). Daily patterns in copper losses from the project area during the pre-breach period were similar to those for suspended sediment (fig. 6). Outflow loads of copper from the project area (fig. 8) sharply increased immediately after the breaching of Milltown Dam, resulting in large daily net losses. The large post-breach net losses of copper continued through the rising limb and peak flow of the annual hydrograph; moderately large losses continued after peak flow into the initial stages of the falling limb in June. Similar to suspended sediment, net losses of copper decreased during the falling limb and were relatively small by July, eventually reaching an approximate net balance between inflow and outflow loads by mid-August.

Cumulative Loads and Mass Balance

Cumulative loads of suspended sediment and trace elements transported past each of the three streamflow-gaging stations that bracket the Milltown Reservoir project area (table 6) were determined for the pre-breach (October 1, 2007–March 27, 2008) and post-breach (March 28, 2008–September 30, 2008) periods, as well as for the entire water year 2008, by summing the estimated daily loads for each period. Cumulative streamflow during each period also is presented in table 6 to provide a hydrologic perspective on seasonal flow conditions that contribute to load differences. Mass balance was determined as the difference between the combined cumulative inflow of streamflow and estimated loads from the two upstream source areas (basins upstream from Clark Fork at Turah Bridge—station 12334550 and Blackfoot River near Bonner—station 12340000) and the cumulative outflow of streamflow and estimated loads at Clark Fork above Missoula (station 12340500) during each period and for the entire water year 2008.

Cumulative streamflow (expressed as a volume, in acre-ft) indicates substantial differences between the pre-breach and post-breach periods (table 6). At all three streamflow-gaging stations, cumulative streamflow during the post-breach period was several times greater than during the pre-breach period: about 3 times greater at Clark Fork at Turah Bridge, about 6 times greater at Blackfoot River near Bonner, and about 4 times greater at Clark Fork above Missoula. The mass balance for cumulative streamflow discharged to and from the project area during the individual periods indicated relatively small net gains and losses (less than 3 percent), which likely represent small contributions of flow from ungaged tributaries, losses to the underlying alluvium, or minor inaccuracies in the streamflow record. At Clark Fork above Missoula, the annual streamflow (2,210,000 acre-ft) for water year 2008 was slightly greater (105 percent) than the long-term mean annual streamflow (table 1), with about 81 percent (1,790,000 acre-ft) of the annual flow volume discharged during the post-breach period (table 6).

The mass balance of cumulative estimated loads for the individual pre-breach and post-breach periods and for the entire water year 2008 (table 6) provides an indication of erosional and depositional processes within the project area. If less material was transported from the project area than entered, some of the suspended material entering the project area was deposited (net gain, indicated by positive values of mass balance). If more material was transported from the project area than entered, previously deposited sediment (and associated trace elements) within the project area was eroded and put into suspension, added to the suspended material entering the project area from upstream sources, and transported with the streamflow out of the project area (net loss,

Table 6. Mass balance of cumulative streamflow and estimated loads of suspended sediment and unfiltered-recoverable trace elements transported to and from the Milltown Reservoir project area for individual periods and water year 2008.

[All numerical values shown are rounded to three significant figures. In some cases, the combined inflow minus the outflow does not exactly equal the reported mass balance due to rounding effects. When calculating combined inflow or mass balance, all values used in the preliminary calculation were rounded to the same decimal place as three-significant-figure rounding of the smallest number used in the calculation. The final calculated value then was rounded to three significant figures. Abbreviation: USGS, U.S. Geological Survey]

USGS station name and number or summation category	Cumulative streamflow (acre-feet)	Cumulative estimated load (tons)							
		Suspended sediment	Arsenic	Cadmium[1]	Copper	Iron	Lead	Manganese	Zinc[1]
Pre-breach period (October 1, 2007–March 27, 2008)									
Clark Fork at Turah Bridge, near Bonner, Mont. (12334550)	269,000	3,020	2.21	0.0211	2.56	50.5	0.317	10.9	3.47
Blackfoot River near Bonner, Mont. (12340000)	161,000	509	.314	.00247	.158	9.81	.0124	1.17	.227
Combined inflow[2]	430,000	3,530	2.52	.0236	2.72	60.3	.330	12.1	3.70
Clark Fork above Missoula, Mont. (12340500) - Outflow	421,000	20,200	3.80	.0814	10.4	258	1.59	34.0	17.4
Mass balance: net gain (+) or loss (-)[3]	**[4]+9,000**	**-16,700**	**-1.28**	**-.0578**	**-7.65**	**-198**	**-1.26**	**-21.9**	**-13.7**
Post-breach period (March 28, 2008–September 30, 2008)									
Clark Fork at Turah Bridge, near Bonner, Mont. (12334550)	801,000	53,800	10.0	0.164	24.6	872	5.05	103	36.9
Blackfoot River near Bonner, Mont. (12340000)	943,000	61,300	1.76	.0175	3.06	733	1.03	49.7	4.15
Combined inflow[2]	1,740,000	115,000	11.8	.181	27.7	1,600	6.08	152	41.0
Clark Fork above Missoula, Mont. (12340500) - Outflow	1,790,000	490,000	23.7	1.06	177	4,380	27.3	304	273
Mass balance: net gain (+) or loss (-)[3]	**-45,000**	**-375,000**	**-11.9**	**-.880**	**-150**	**-2,780**	**-21.2**	**-152**	**-232**
Water year 2008 (October 1, 2007–September 30, 2008)									
Clark Fork at Turah Bridge, near Bonner, Mont. (12334550)	1,070,000	56,800	12.2	0.185	27.2	923	5.37	113	40.3
Blackfoot River near Bonner, Mont. (12340000)	1,100,000	61,800	2.07	.020	3.22	743	1.04	50.9	4.37
Combined inflow[2]	2,170,000	119,000	14.3	.205	30.4	1,670	6.41	164	44.7
Clark Fork above Missoula, Mont. (12340500) - Outflow	2,210,000	510,000	27.5	1.14	188	4,640	28.9	338	290
Mass balance: net gain (+) or loss (-)[3]	**-40,000**	**-391,000**	**-13.2**	**-.938**	**-157**	**-2,970**	**-22.5**	**-174**	**-245**

[1]Estimated cadmium and zinc loads for Blackfoot River near Bonner (station 12340000) were based on a regression equation developed from a dataset having more than 30 percent of the values censored (reported as less than the laboratory reporting level). Thus, estimated cadmium and zinc loads for this site have greater uncertainty than loads estimated for the other trace elements and the other two sites.

[2]Combined inflow is the sum of streamflow or load transported to the Milltown Reservoir project area from Clark Fork at Turah Bridge, near Bonner (station 12334550), and Blackfoot River near Bonner (station 12340000) for the indicated period.

[3]Mass balance is the difference (net gain or loss) between the combined inflow to the Milltown Reservoir project area and the outflow transported from the Milltown Reservoir project area, as represented by Clark Fork above Missoula (station 12340500). Thus, a net gain (+) indicates net deposition in the Milltown Reservoir project area and a net loss (-) indicates net removal from the Milltown Reservoir project area.

[4]Before the breaching of Milltown Dam, daily mean streamflow for Clark Fork above Missoula (station 12340500) commonly was less than the combined inflow, which results in a calculated net gain of water in Milltown Reservoir. Rather than an actual gain of water (net storage), this calculated difference possibly represents a loss of surface water to the alluvium underlying Milltown Reservoir and the river reaches between the upstream and downstream gages, plus possible small amounts of evaporative loss from the reservoir surface.

indicated by negative values of mass balance). The mass balance results for the pre-breach and post-breach periods indicate the differences in net gains or losses within the project area for distinctly different environmental settings and flow conditions. Overall, the mass balance between combined inflow loads from upstream source areas and the outflow loads at Clark Fork above Missoula during water year 2008 indicates a net loss of suspended sediment and trace elements from the project area during all periods.

Examples of the proportions of cumulative outflow load transported past Clark Fork above Missoula that were contributed from the two upstream source areas and the project area during the pre-breach, post-breach, and water year 2008 periods are illustrated for suspended sediment, unfiltered-recoverable arsenic, and unfiltered-recoverable copper (fig. 9). The cumulative inflow loads contributed from individual upstream source areas are those shown for Clark Fork at Turah Bridge—station 12334550 and Blackfoot River near Bonner—station 12340000 in table 6; the cumulative loads contributed from the project area are those shown as the mass balance in table 6, which represents the net loss from the project area. The percent values are calculated as the cumulative load contributed from an individual source area divided by the cumulative outflow load (shown for Clark Fork above Missoula—station 12340500 in table 6) during the indicated period. In addition to the percent values, the actual loads, in tons, are shown to provide perspective on the large differences in constituent loads transported during the pre-breach and post-breach periods.

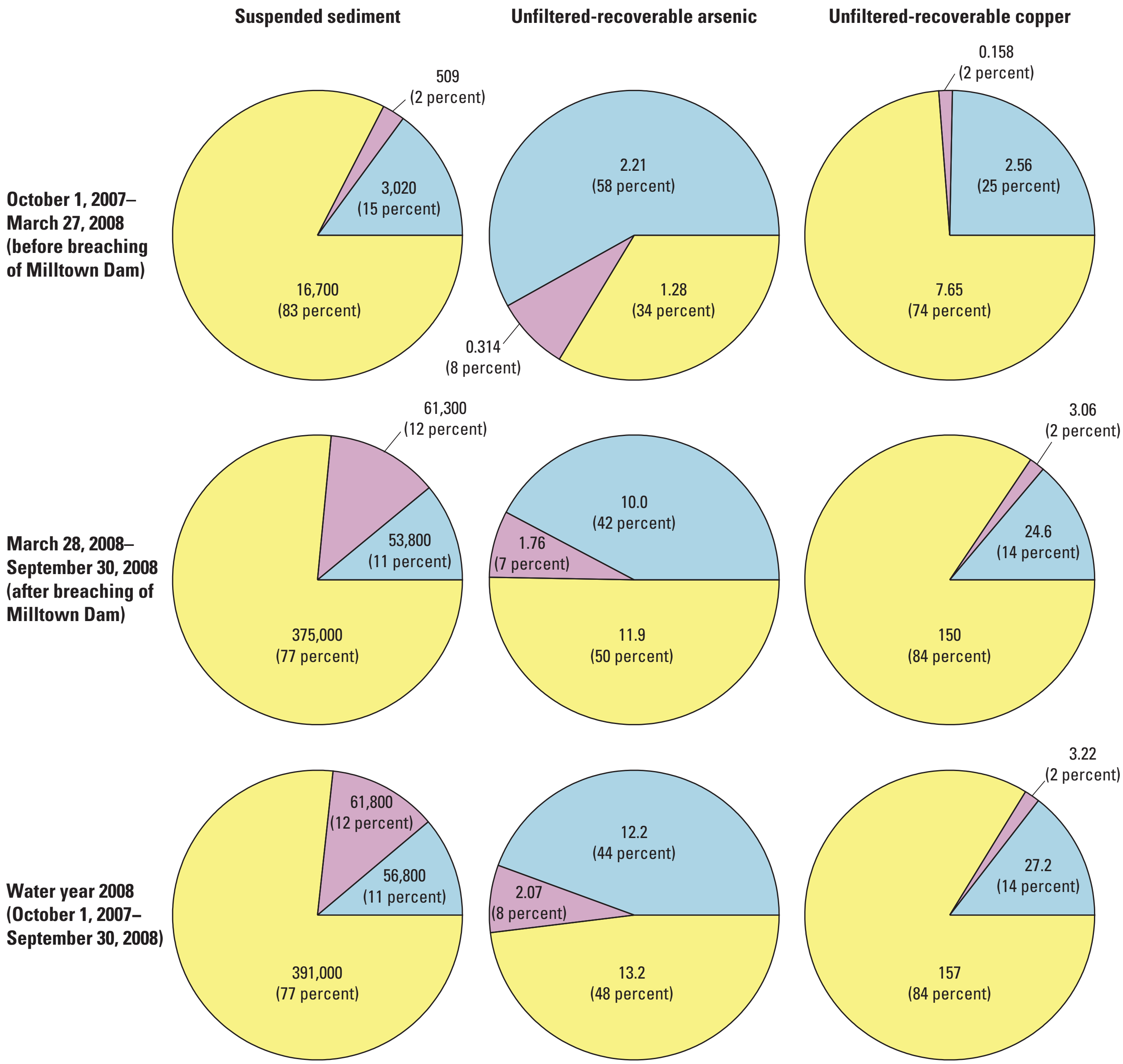
Of the 510,000 tons of outflow suspended-sediment load transported past Clark Fork above Missoula in water year 2008, only 119,000 tons were contributed as combined inflow load from the upper Clark Fork and Blackfoot River basins; thus, 391,000 tons of the outflow load were derived from eroded sediment within the project area (table 6, fig. 9). The suspended-sediment load contributed from the project area in water year 2008 represented about 77 percent of the outflow load, with the upper Clark Fork basin contributing about 11 percent and the Blackfoot River basin contributing about 12 percent. For historical perspective, the annual net loss of suspended sediment from the project area in water year 2008 (-391,000 tons) was more than seven times greater than the annual net losses of -52,000 and -55,000 tons, respectively, that occurred during the high-flow conditions of water years 1996–97 (Lambing, 1998).

The net loss of suspended sediment from the project area (table 6, fig. 9) during the pre-breach period (-16,700 tons), when Milltown Reservoir was drawn down and low-flow conditions were prevalent, was small relative to the post-breach period (-375,000 tons). The much larger net loss of suspended sediment during the post-breach period primarily occurred during the rising limb and peak flow of the annual hydrograph (fig. 6) when erosion within the project area sharply increased in response to the greater hydraulic energy of high flows and adjustment of the river to the steeper channel gradient created by the breaching of Milltown Dam. The net loss of suspended sediment from the project area during the post-breach period represented about 96 percent of the annual net loss (-391,000 tons) for water year 2008, whereas only 81 percent of the annual flow volume was discharged during the post-breach period (table 6).

During both the pre-breach and post-breach periods, the suspended-sediment load contributed from the project area was the largest component of the suspended-sediment load transported past Clark Fork above Missoula (fig. 9). The suspended-sediment load contributed from the project area represented about 83 percent (16,700 tons) of the outflow load (20,200 tons) during the pre-breach period and about 77 percent (375,000 tons) of the outflow load (490,000 tons) during the post-breach period (table 6, fig. 9). Although the percent contributions during the two periods generally were similar, the suspended-sediment load contributed from the project area during the post-breach period was more than 22 times greater than the load contributed during the pre-breach period.

The suspended-sediment loads contributed from the two upstream source areas during both the pre-breach and post-breach periods generally were small (ranging from about 2 to 15 percent) relative to the outflow load transported past Clark Fork above Missoula (table 6). However, similar to loads derived from the project area, loads from the upstream source areas were much larger during the high-flow conditions of the post-breach period compared to the pre-breach period. Because the two sampling stations at Clark Fork at Turah Bridge and Blackfoot River near Bonner are above the erosional effects caused by the dam breach and resulting steeper channel gradient, the increased loads transported from the upstream source areas during the post-breach period illustrate the large effect of seasonal flow increases on sediment transport from a basin. The suspended-sediment loads transported during the post-breach period were about 18 times greater for the upper Clark Fork basin, and about 120 times greater for the Blackfoot River basin, compared to the pre-breach period.

The annual loads of all trace elements from the upper Clark Fork basin were greater than those from the Blackfoot River basin, although the annual suspended-sediment load from the Blackfoot River basin was slightly greater than that from the upper Clark Fork basin in water year 2008 (table 6). The proportional patterns of source-area load contributions for most of the trace elements generally were similar to those for copper (fig. 9). The trace-element loads contributed from the project area were the largest component of the outflow trace-element loads transported past Clark Fork above Missoula, with the exception of arsenic during the pre-breach period (table 6). The proportional patterns of load contributions for arsenic differed the most from the other trace elements, possibly because of the greater percentage of arsenic that occurs in the dissolved phase relative to the other trace elements (*http://waterdata.usgs.gov/mt/nwis*). Thus, the relatively small proportion of arsenic in the particulate phase possibly could have resulted in less historical deposition within the project



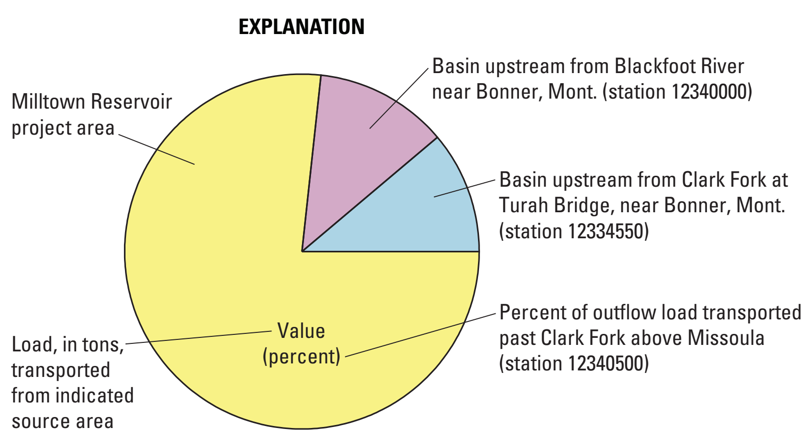


Figure 9. Cumulative estimated loads and percent of suspended sediment, unfiltered-recoverable arsenic, and unfiltered-recoverable copper contributed from upstream source areas and the Milltown Reservoir project area, water year 2008. Percent is based on the load contributed from an individual source area relative to the outflow load transported past Clark Fork above Missoula, Mont. Summation of percent values for a given plot might not equal 100 percent due to rounding effects.

area, which might explain the smaller proportion of arsenic contributed from the project area relative to the other trace elements. Also, arsenic potentially could have been mobilized from the sediment that was deposited in Milltown Reservoir to ground water of the underlying alluvial aquifer (U.S. Environmental Protection Agency, 2004), thereby depleting the sediment of some of the original arsenic content.

Differences in the mass balance of trace-element loads transported to and from the project area during the individual pre-breach and post-breach periods (table 6) indicate the combined effect of the breaching of Milltown Dam and differences in flow conditions between the two periods. Net losses of trace elements from the project area were about 7 to 20 times greater during the post-breach period compared to the pre-breach period. Copper had the greatest proportional difference in net loss between the two periods, with the post-breach loss (-150 tons) about 20 times greater than the pre-breach loss (-7.65 tons). Arsenic and manganese had the smallest proportional difference in net losses between the two periods, with the post-breach loss relative to the pre-breach loss about 9 times greater for arsenic (-11.9 and -1.28 tons, respectively) and about 7 times greater for manganese (-152 and -21.9 tons, respectively). For the remaining trace elements, the post-breach net losses were about 14 to 17 times greater than the pre-breach net losses.

The large annual net loss of suspended sediment from the project area in water year 2008 resulted in large annual net losses for every trace element (table 6). The annual net losses estimated for unfiltered-recoverable trace elements in water year 2008 included arsenic (-13.2 tons), cadmium (-0.938 ton), copper (-157 tons), iron (-2,970 tons), lead (-22.5 tons), manganese (-174 tons), and zinc (-245 tons). The net losses of trace elements in water year 2008 ranged from about 2 to 4 times greater than the net losses in water year 2007, when Milltown Reservoir was drawn down for the entire year (Lambing and Sando, 2008). Also, the annual net losses for copper, lead, and zinc in water year 2008 were substantially greater (about 7 to 17 times) than the annual net losses estimated for those trace elements during the high-flow conditions of water years 1996-97 (Lambing, 1998).

The largest annual net losses of trace elements from the project area in water year 2008 (table 6), in percent of the outflow load transported past Clark Fork above Missoula, occurred for cadmium, copper, lead, and zinc—about 82 percent for cadmium, 84 percent for copper, 78 percent for lead, and 84 percent for zinc. Smaller net losses relative to the outflow load occurred for arsenic, iron, and manganese—about 48 percent for arsenic, 64 percent for iron, and 51 percent for manganese. The large annual net losses of trace elements in water year 2008 indicate that much of the outflow trace-element load transported past Clark Fork above Missoula was derived from eroded sediment within the Milltown Reservoir project area, rather than from inflow loads transported from upstream source areas.

Summary and Conclusions

Milltown Reservoir is a National Priorities List Superfund site in the upper Clark Fork basin of western Montana where sediments enriched in trace elements from historical mining and ore processing have been deposited since the construction of Milltown Dam in 1907. Milltown Dam was breached on March 28, 2008, as part of Superfund remedial activities to remove the dam and excavate contaminated sediment that had accumulated in Milltown Reservoir. Daily and cumulative loads of suspended sediment and selected trace elements transported during water year 2008 were estimated for three streamflow-gaging stations that bracket the Milltown Reservoir project area. The estimated loads transported through the project area during the periods before and after the breaching of Milltown Dam, and for the entire water year 2008, were used to quantify the net gain or loss (mass balance) of suspended sediment and trace elements within the project area during the transition from a reservoir environment to a free-flowing river. This study was done in cooperation with the U.S. Environmental Protection Agency.

Streamflow during water year 2008 compared to long-term streamflow, as represented by the 79-year record for Clark Fork above Missoula (water years 1930–2008), generally was below normal (long-term median) from about October 2007 through April 2008. Sustained runoff started in mid-April, which increased flows to near normal by mid-May. After mid-May, flows sharply increased to above normal, reaching a maximum daily mean streamflow of 16,800 ft^3/s on May 21, which essentially equaled the long-term 10th-exceedance percentile for that date. Flows substantially above normal were sustained through June, then decreased through the summer and reached near-normal by August. Annual mean streamflow during water year 2008 (3,040 ft^3/s) was 105 percent of the long-term mean annual streamflow (2,900 ft^3/s). The annual peak flow (17,500 ft^3/s) occurred on May 21, and was 112 percent of the long-term mean annual peak flow (15,600 ft^3/s). About 81 percent of the annual flow volume was discharged during the post-breach period.

Daily loads of suspended sediment were estimated by using high-frequency sampling of the daily sediment monitoring. Daily loads of unfiltered-recoverable arsenic, cadmium, copper, iron, lead, manganese, and zinc were estimated by using regression equations relating trace-element discharge to either streamflow or suspended-sediment discharge. Regression equations for estimating trace-element discharge in water year 2008 were developed from instantaneous streamflow and concentration data for periodic water-quality samples collected during all or part of water years 2004–08. Single equations were developed for the entire water year 2008 for Clark Fork at Turah Bridge and Blackfoot River near Bonner; separate equations were developed for the pre-breach and two post-breach periods (rising limb and falling limb) for Clark Fork above Missoula. The pre-breach period in water year

2008 was October 1, 2007–March 27, 2008; the post-breach rising limb period was March 28, 2008–May 21, 2008; and the post-breach falling limb period was May 22, 2008–September 30, 2008. All the regression equations for estimating trace-element discharge (tables 3–5) are statistically significant (p-value < 0.001). The large R^2 values (ranging from 0.82 to 1.00) and small to moderate SE values indicate relatively good transport relations for all the trace elements at all three stations. The equations were applied to records of daily mean streamflow or daily suspended-sediment loads to produce estimated daily trace-element loads.

Variations in estimated daily suspended-sediment loads transported to and from the project area during water year 2008 generally coincided with streamflow variations. Overall, the daily outflow suspended-sediment loads consistently were larger than the combined daily inflow suspended-sediment loads for most of water year 2008, with the largest differences occurring in the post-breach period during the rising limb and peak flow of the annual hydrograph. During the pre-breach period when Milltown Reservoir was drawn down and low-flow conditions were prevalent, differences between the suspended-sediment load transported to and from the project area indicated small to moderately large net losses on most days. There was a sharp increase in suspended-sediment outflow from the project area immediately after the breaching of Milltown Dam, resulting in large daily net losses. The large post-breach net losses of suspended sediment from the project area continued through the rising limb and peak flow of the annual hydrograph. Net losses of suspended sediment began to decrease after the peak flow, but were still relatively large during the early stages of the falling limb through June. The net losses were relatively small by July, and an approximate net balance between inflow and outflow suspended-sediment loads was achieved by mid-August.

A comparison of periodic water-quality data for samples collected on 16 concurrent dates during water year 2008 at Clark Fork at Turah Bridge and the supplemental sampling site Clark Fork Bypass near Bonner indicated substantial differences within a short distance (about 5 river mi) of channel between the two sites. The median suspended-sediment concentration increased from 39 mg/L at Clark Fork at Turah Bridge to 161 mg/L at Clark Fork Bypass near Bonner. Also notable was the predominance of sand eroded from this reach of channel. The median percent of suspended sediment finer than 0.062 mm decreased from 72 percent at Clark Fork at Turah Bridge to 28 percent at Clark Fork Bypass near Bonner. The substantial increase in suspended-sediment concentration and proportion of sand within a short distance clearly indicates the dynamic process of post-breach channel erosion that occurred during high flow in the area near the upper end of the former reservoir.

The daily transport characteristics for all the unfiltered-recoverable trace-element loads (arsenic, cadmium, copper, iron, lead, manganese, and zinc) estimated for water year 2008 generally were similar. Variations in daily trace-element loads entering and leaving the project area generally coincided with variations in daily mean streamflow and daily suspended-sediment loads. Small to moderately large daily net losses of trace-element loads from the project area were common during the pre-breach period, when Milltown Reservoir was drawn down and low-flow conditions were prevalent. Outflow loads of trace elements from the project area sharply increased immediately after the breaching of Milltown Dam. Both inflow and outflow trace-element loads increased during the post-breach period as streamflow increased. Large post-breach daily net losses of trace-element load from the project area continued through the rising limb and peak flow of the annual hydrograph. Daily net losses for the trace elements decreased during the falling limb and were relatively small by July; an approximate net balance between inflow and outflow loads was achieved by mid-August for all the trace elements, except arsenic. A relatively small net loss of arsenic continued consistently through the remainder of the post-breach period in water year 2008.

Cumulative loads of suspended sediment and trace elements transported past each of the three streamflow-gaging stations that bracket the Milltown Reservoir project area were determined for the pre-breach, post-breach, and entire water year 2008 periods by summing the estimated daily loads for each period. The difference between the combined estimated inflow loads transported from the two upstream source areas (upper Clark Fork and Blackfoot River basins) and the estimated outflow loads transported past Clark Fork above Missoula were used to quantify the mass balance of suspended sediment and trace elements within the project area. The mass balance for the pre-breach and post-breach periods indicate the differences in cumulative net gains or losses of suspended sediment and trace elements within the project area for distinctly different environmental settings and streamflow conditions. Overall, the mass balance between combined inflow loads from upstream source areas and the outflow loads at Clark Fork above Missoula during water year 2008 indicates a net loss of suspended sediment and trace elements from the project area during all periods.

Of the 510,000 tons of suspended-sediment outflow load transported past Clark Fork above Missoula in water year 2008, only 119,000 tons were contributed from the upper Clark Fork and Blackfoot River basins; thus, 391,000 tons of the outflow load were derived from eroded sediment within the project area. The suspended-sediment load contributed from the project area in water year 2008 represented about 77 percent of the outflow load, with the upper Clark Fork basin contributing about 11 percent and the Blackfoot River basin contributing about 12 percent.

The net loss of suspended sediment during the pre-breach period (-16,700 tons), when Milltown Reservoir was drawn down, was small relative to the post-breach period (-375,000 tons). The much larger net loss of suspended sediment during the post-breach period primarily occurred during the rising limb and peak flow of the annual hydrograph. The net loss of suspended sediment from the project area during the post-breach period represented about 96 percent of the annual net loss (-391,000 tons) for the entire water year 2008.

During both the pre-breach and post-breach periods, the suspended-sediment load contributed from the project area was the largest component of the suspended-sediment load transported past Clark Fork above Missoula, representing about 83 percent of the outflow load during the pre-breach period and about 77 percent during the post-breach period. Although the percent contributions during the two periods generally were similar, the suspended-sediment load contributed from the project area during the post-breach period was more than 22 times greater than the load contributed during the pre-breach period. The suspended-sediment load contributed from the two upstream source areas during both the pre-breach and post-breach periods generally were small (ranging from about 2 to 15 percent) relative to the outflow load. However, the suspended-sediment loads from upstream source areas were much larger during the high-flow conditions of the post-breach period compared to the pre-breach period, illustrating the large effect of seasonal flow increases on sediment transport within a basin. Suspended-sediment loads during the post-breach period were about 18 times greater for the upper Clark Fork basin, and about 120 times greater for the Blackfoot River basin, compared to the pre-breach period.

The annual loads of all trace elements from the upper Clark Fork basin were greater than those from the Blackfoot River basin, although the annual suspended-sediment load from the Blackfoot River basin was slightly larger than that from the upper Clark Fork basin. The proportional patterns of source-area load contributions for most of the trace elements generally were similar to those for copper. The trace-element loads contributed from the project area were the largest component of the outflow trace-element loads transported past Clark Fork above Missoula, with the exception of arsenic during the pre-breach period. The proportional patterns of load contributions for arsenic differed the most from the other trace elements, possibly because of the greater percentage of arsenic that occurs in the dissolved phase relative to the other trace elements.

Net losses of trace elements from the project area were about 7 to 20 times greater during the post-breach period compared to the pre-breach period. Copper had the greatest proportional difference in net loss between the two periods, with the post-breach loss about 20 times greater than the pre-breach loss. Arsenic and manganese had the smallest proportional difference in net losses between the two periods, with the post-breach loss relative to the pre-breach loss about 9 times greater for arsenic and about 7 times greater for manganese. For the remaining trace elements, the post-breach net losses were about 14 to 17 times greater than the pre-breach net losses.

The large annual net loss of suspended sediment from the project area in water year 2008 resulted in large annual net losses for every trace element. The annual net losses estimated for unfiltered-recoverable trace elements in water year 2008 included arsenic (-13.2 tons), cadmium (-0.938 ton), copper (-157 tons), iron (-2,970 tons), lead (-22.5 tons), manganese (-174 tons), and zinc (-245 tons). The largest annual net losses of trace elements from the project area in water year 2008, in percent of the outflow load transported past Clark Fork above Missoula, occurred for cadmium, copper, lead, and zinc—about 82 percent for cadmium, 84 percent for copper, 78 percent for lead, and 84 percent for zinc. Smaller net losses relative to the outflow load occurred for arsenic, iron, and manganese—about 48 percent for arsenic, 64 percent for iron, and 51 percent for manganese. The large annual net losses of trace elements in water year 2008 indicate that much of the outflow trace-element load transported past Clark Fork above Missoula was derived from eroded sediment within the Milltown Reservoir project area, rather than from inflow loads transported from upstream source areas.

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