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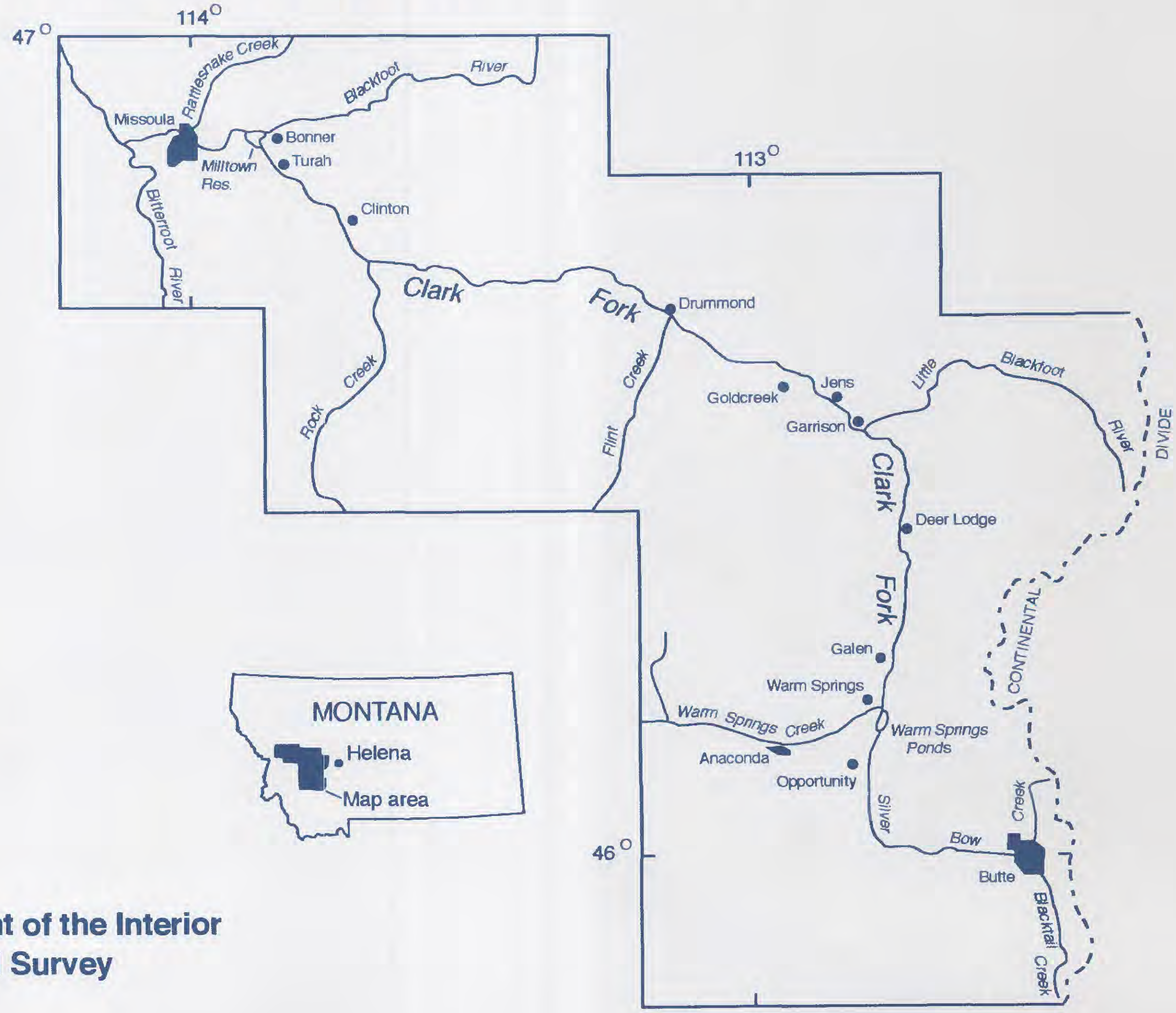
Geomorphology, Flood-Plain Tailings, and Metal Transport in the Upper Clark Fork Valley, Montana

Water-Resources Investigations Report 98-4170



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Geomorphology, Flood-Plain Tailings, and Metal Transport in the Upper Clark Fork Valley, Montana

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U.S. Department of the Interior

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Helena, Montana
October 1998

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CONVERSION FACTORS, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
cubic yards	0.7646	cubic meters
foot (ft)	0.3048	meter
inch (in.)	25,400	micrometer (µm)
	25.4	millimeter (mm)
	2.54	centimeter (cm)
mile (mi)	1.609	kilometer
pound (lb)	453,600,000	microgram (µg/L)
	453,600	milligram (mg)
	453.6	gram (g)
	0.4536	kilogram (kg)
quart	946.4	milliliter (mL)
	0.9464	liter (L)
square mile (mi^2)	2.59	square kilometer
ton (short)	907.2	kilogram (kg)

Water year: A water year is the 12-month period from October 1 through September 30. It is designated by the calendar year in which it ends.

Additional abbreviations used in this report:

kg	kilogram
µg/L	microgram per liter
µm	micrometer
mg	milligram
mm	millimeter
d_{90}	90th percentile diameter

Acronyms used in this report:

ARCO	Atlantic Richfield Company
GIS	geographic information system
GPS	geographic positioning system
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

GEOMORPHOLOGY, FLOOD-PLAIN TAILINGS, AND METAL TRANSPORT IN THE UPPER CLARK FORK VALLEY, MONTANA

By J. Dungan Smith, John H. Lambing, David A. Nimick, Charles Parrett, Michael Ramey, and William Schafer

ABSTRACT

The Clark Fork valley between the Warm Springs Ponds and Milltown Reservoir in western Montana is adversely affected by metals derived from past mining and smelting activities. To aid remediation planning by the U.S. Environmental Protection Agency, the sources, transport, and deposition of metals were assessed during 1995-98 by a technical committee of scientists from the U.S. Geological Survey and private consulting firms. The assessment required examining the geomorphic history and deposition of flood-plain tailings, determining migration rates of the river across the flood plain, quantifying the sediment and metal loads entering the river from all important sources, and tracking the current transport and accumulation of sediment and metals through the 120-mile reach of river.

Because erosion of flood-plain tailings deposits is a major process contributing metals to the river, the areal and vertical extent of tailings were mapped and the range of metals concentrations determined. Average annual meander-migration rates of the river in the Deer Lodge valley were quantified from aerial photographs taken in 1960 and 1989. Migration rates ranged from 0.0 to 5.8 feet per year, with an average rate of 0.6 foot per year over the 43-mile reach.

Sediment and copper loads from individual sources were integrated in mass-balance calculations to estimate input, transport, and deposition. Transport rates were calibrated to hydrologic and water-quality monitoring data for 1985-95, a relatively dry period. Under current (post-1990) source conditions and 1985-95 hydrology, the mass-balance calculations indicate that streambank erosion is the largest source of copper to the river, comprising approximately 56 percent of the total copper input along the 120-mile reach. Upstream input accounts for about 5 percent, whereas tributaries and streambed exchange each account for about 8 percent. Flood-plain runoff and ground water together account for about 24 percent of the total copper input. Not all of the copper entering the river is transported out of the reach. Instead, about 47 percent of the copper input is deposited on point bars.

Estimates of transport and meander-migration rates were adjusted to long-term (1930-95) hydrologic conditions to better represent the effects of high streamflows. Under the higher flows representative of long-term conditions, the estimated percent contributions of copper from individual sources does not change appreciably from those estimated for lower flows; the largest contribution is still provided by streambank erosion (60 percent). The future input of copper from streambanks is predicted to increase to 70 percent of the total copper input as the streambed comes to equilibrium with current sources and becomes depleted of copper historically deposited prior to remedial cleanup efforts in the headwaters. Therefore, regardless of variations in the magnitude of copper loads under differing streamflow conditions, the relative percentage of total load contributed from individual sources remains similar.

INTRODUCTION

Metal concentrations in water, sediment, and biota in the Clark Fork are elevated as a result of mineralization and extensive historical mining and smelting in headwater streams (Hornberger and others, 1997). Some of the waste rock, tailings (mine and mill wastes), and slag produced during more than a century of operations have been eroded and transported through the upper Clark Fork valley. Metal enrichment in the Clark Fork extends for over a hundred miles (Moore and Luoma, 1990). The potential effect of chronic toxicity on biota from metal-enriched sediments already in the river and ongoing erosion and transport of metals from the extensive flood-plain sources in the valley are of continuing concern.

Remediation planning and initial cleanup efforts for the upper Clark Fork were begun in the 1980's as part of a Superfund process. To support these efforts, a committee was established in July 1995 for the purpose of advising the U.S. Environmental Protection Agency (USEPA) on matters pertaining to streamflow, sediment transport, erosion/deposition, and geomorphic processes that affect the input, transport, and accumulation of metals in the Clark Fork between the Warm Springs Ponds and Milltown Reservoir, Montana (fig. 1). The river and its flood plain between these two points comprise the Clark Fork River Operable Unit of the Milltown Reservoir Superfund Site. The committee was composed of three members of the Water Resources Division of the U.S. Geological Survey (USGS) and two consultants to the Atlantic Richfield Company (ARCO). This report describes the principal work of the committee, which was disbanded in December 1997.

The goal of the committee was to provide an assessment of metals input, transport, and deposition in the Clark Fork upstream from Milltown Reservoir. This goal was achieved by synthesizing available data on the water quality of surface and ground water and on metal storage in the flood plain. Historical aerial photography and hydrologic data were used to quantify rates of bank erosion from channel migration and fluvial transport of sediment and metals. These data were integrated using mass-balance calculations and geomorphic principles to account for metal inputs from specific sources in order to determine the most important components of the fluvial system contributing metals to the Clark Fork.

Purpose and scope

This report summarizes and integrates information concerning the geomorphic relation between metals sources and the transport of metals and sediment in the upper Clark Fork valley (fig. 1). This report is a synthesis of several studies and provides an overview of interrelated metals-transport processes. Specific details of the individual investigations whose findings have been incorporated in this overview can be found in the cited references.

Characterization of metals transport required quantifying the loads of metals entering the river from all important sources, and then tracking the transport and accumulation of metals through the entire system to the Clark Fork at Turah Bridge (station 12334550), just south of the town of Turah and the first gaging station upstream from Milltown Reservoir (fig. 1). Metals enter the river from several sources. Sources considered were inflow from headwater streams and tributaries, surface runoff over the flood plain, ground-water inflow, material eroded from streambanks, exchange with previously stored streambed sediment, and inflow of water seasonally stored in the banks. Some of these sources were evaluated as part of the ongoing remedial investigation for this Superfund site, whereas transport rates at sites along the mainstem and on major tributaries were evaluated as part of a USGS long-term monitoring program (Lambing, 1991,1998; Hornberger and others, 1997). Additional information on sources was obtained during this geomorphology investigation in order to supplement aspects of geomorphology and geochemistry that were lacking data. Copper was the metal evaluated to the greatest extent because it occurs in water at concentrations high enough to minimize analytical detection problems, and because copper concentrations in the Clark Fork exceed aquatic-life criteria more frequently than concentrations of other trace elements (Lambing, 1991).

Metal-rich flood-plain deposits flank the Clark Fork from Warm Springs Creek to Milltown Reservoir and erode into the river as the channel migrates. Understanding the geomorphic processes that control the rate of erosion and deposition of these materials is important because these deposits appear to be the largest source of metals to the river. An estimate of the metal supply available in the river's flood plain upstream from Garrison was determined by constructing a map that characterizes the geochemistry and the vertical and horizontal distribution of tailings deposits along the fluvial corridor in the Deer Lodge valley (Reach A in fig. 1) (Schafer and Associates, 1997a).

The data on tailings distribution and metal concentrations in the flood plain, banks, and bars (Schafer and Associates, 1997a; Nimick, 1990) were combined with an evaluation of long-term bank erosion rates determined from analysis of channel movement using available sets of aerial photographs taken in 1960 and 1989 (R2 Resource Consultants, 1997). Finally, the requisite data on tailings distribution and metals content, rates of channel migration, streamflow characteristics, and sediment and metals transport were used to construct a mass-balance estimate that tracked inputs

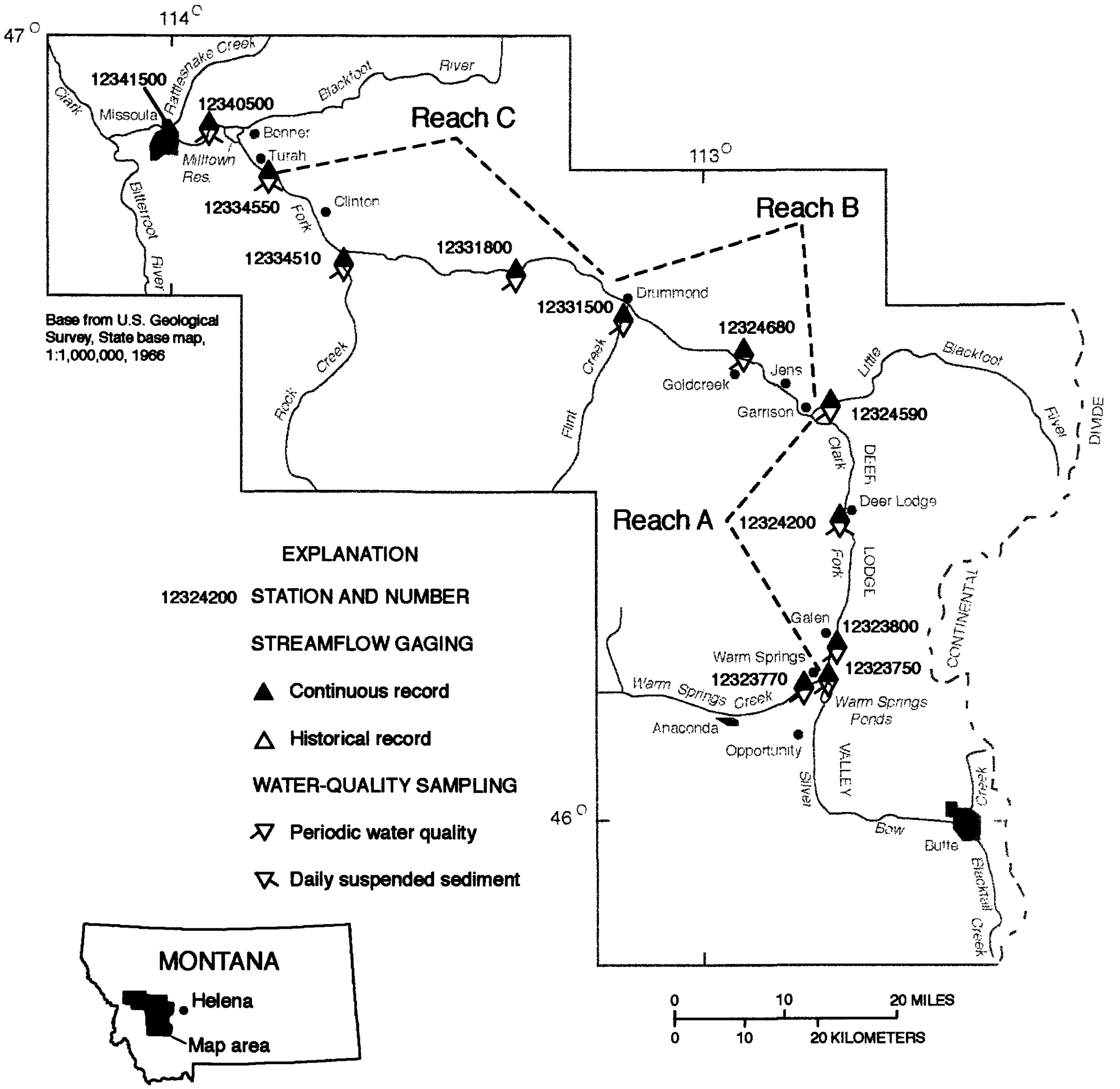

Figure 1. Location of the upper Clark Fork valley and mainstem study reaches, Montana.

from all significant sources, transport down river, and deposition (R2 Resource Consultants, 1998). The estimates predict changes in the flux of copper over time under a steady-state condition of inputs. The estimates were calibrated using sediment- and metals-transport data collected from 1985-95 (Lambing, 1991; Hornberger and others, 1997) and then adjusted for long-term (1930-95) hydrologic conditions (R2 Resource Consultants, 1998). The 1985-95 period was relatively dry, but high flows in 1996 and 1997 resulted in much larger loads than were measured during the calibration period. The adjustment for long-term hydrology, therefore, was subsequently evaluated by comparison to 1991-97 transport estimates, which characterize hydrologic conditions similar to long-term streamflow (Lambing, 1998).

Description of study area

The Clark Fork begins at the confluence of Silver Bow and Warm Spring Creeks below the Warm Springs Ponds (fig. 1). The river flows north from the confluence through the broad Deer Lodge valley for about 43 river miles. Just beyond the confluence with the Little Blackfoot River near Garrison, the Clark Fork valley turns abruptly northwest and becomes narrower. Consequently, the lower river is more channelized, although in geomorphic terms it remains single threaded and sinuous. For purposes of characterization during the Superfund remedial investigation, the Clark Fork was divided into three reaches (fig. 1). Reach A, also referred to as the Deer Lodge valley, extends along the Clark Fork from Warm Springs Creek to the Little Blackfoot River near Garrison, Reach B from the Little Blackfoot River to below Drummond, and Reach C from below Drummond to above Milltown Reservoir.

The Clark Fork in Reach A is a highly meandering river flowing through a broad valley where exposed tailings are extensive. In Reach B, the valley narrows considerably and the river meanders much less than in Reach A, being confined both by the valley walls and embankments for railroads and highways. Exposed tailings are less extensive in Reach B, and streamflow increases from inputs from the Little Blackfoot River and Flint Creek. Reach C is morphologically similar to Reach B, with increasing flow and improved water quality from dilution by tributaries, including Rock Creek. Exposed tailings are not evident in Reach C. Because of the abundance of visually evident streamside tailings and elevated copper concentrations, Reach A was studied in more detail than Reaches B and C.

In the Deer Lodge valley, several perennial tributaries on the west side of the valley flow from the Flint Creek Range, and several small ephemeral tributaries on the east side of the valley flow from the Continental Divide. In recent decades, a large proportion of streamflow from the west-side tributaries has been diverted seasonally for irrigation, and presumably much of the sediment these creeks carry has been transported and deposited onto the fields being irrigated. In contrast, the ephemeral east-side tributaries flow only during spring snowmelt and occasional severe thunderstorms; nevertheless, during these events, these tributaries can contribute a considerable amount of silt, sand, and fine gravel to the Clark Fork, as indicated by broad alluvial deposits on the Clark Fork valley floor.

GEOMORPHOLOGY: HISTORY AND PROCESSES

The determination of the most important sources of metals input to the Clark Fork, and the subsequent processes of transport and deposition, requires that the past and present interaction of the river with its flood plain, streambed, tributaries, and ground water be placed in a geomorphic context. Although this investigation did not specifically obtain additional data to quantify streamflow, land use, or depositional histories in the Clark Fork valley, numerous types of data were compiled, aerial photographs were examined, and field observations were made that were used to construct a conceptual model of the possible geomorphic setting that existed before and during the past century of mining. This conceptual model, coupled with basic principles of sediment transport, provide a basis for evaluating the processes that have led to the current geomorphic conditions in the Clark Fork valley and, possibly, for identifying important considerations as Superfund remediation proceeds.

Conceptual model of geomorphic history

Because little recorded historical information and data exist, the geomorphic history of the Clark Fork was conceptualized and deduced using a comprehensive application of flow, sediment-transport, and fluvial geomorphic principles in combination with observations of the stratigraphy and morphology of the Clark Fork flood plain. The following description of the geomorphic history of the valley is based on these kinds of information.

History prior to 1870

Prior to inhabitation of the Deer Lodge valley by miners and ranchers, the Clark Fork, as well as Silver Bow and Warm Springs Creeks, likely supported dense populations of willow and water birch in a broad flood plain. According to Warren Ferris, a fur trapper who visited the Deer Lodge valley in 1831, the bottomlands were "... decorated with groves and thickets of aspen, birch, and willow and occasional clusters of currant and gooseberry bushes." He found them "rich and verdant" and he noted that the river was "clear, deep, rapid and not fordable at high water" [quoted from Horstman (1984) by PTI (1990)].

Beaver likely played an important role in shaping the river and its flood plain. Silver Bow and Warm Springs Creeks probably were dammed extensively by beaver. Similarly, the upper reach of the Clark Fork through the Deer Lodge valley probably was dammed by beaver, at least intermittently when the streamflow was decreased, either during and after sequences of dry years or where the channel was initially divided by midstream bars. Beaver presumably were eradicated from the area by trapping in the early 1800's. Where beaver were present, the river was spread over a band of the valley broader than the river and its flood plain currently occupy. Evidence for this includes the perched pebble gravel layers and buried peat that can be seen in stratigraphic section. Perched pebble gravel could represent deposits in former channels that meandered from pond to pond. The perched gravel layers were observed to have a characteristic pebble size that is much finer than gravel in the current bed of the Clark Fork and that also is finer than the gravel the river would have transported in the past if the flow were confined to a single, unponded channel. Buried peat is an indication of organic accumulation associated with wet or ponded areas. The presence of peat along the Clark Fork was noted by PTI (1990): "Peat deposits and organic-rich silts and clays, reflecting deposition adjacent to a low gradient (meandering) channel with a low sediment load, can be found at the surface on the floodplain margins and underlying tailings deposits nearer the channel." Peat cannot form on a dry flood plain, so the presence of peat indicates extensive, long-term ponding, and such ponding in a low-order tributary in a semi-arid climate indicates either damming of the stream by beaver or the existence of sloughs and oxbows. Similarly, dense riparian vegetation along the Clark Fork in the Deer Lodge valley noted by fur trappers (Horstman, 1984) indicates a wet flood plain, consistent with a constricted, but still low-banked river and probably a ponded, or at least occasionally ponded, flood plain.

Two other lines of evidence suggest the former presence of beaver. First, for the water in the Clark Fork to be clear at high flow in the Deer Lodge valley, as indicated by Warren Ferris (Horstman, 1984), there must have been substantial sediment traps between the mouths of the east-side tributaries and that part of the river. Owing to their geological and geomorphic setting, the east-side tributaries likely have been bringing fine sediment to the Clark Fork for many centuries; therefore, for the main river to remain clear at high flow, this material likely was trapped in beaver ponds in the upper Deer Lodge valley. Second, evidence for the presence of beaver, at least upstream from Deer Lodge, can be seen in aerial photographs by a branching pattern in the abandoned channels that is characteristic of beaver ponds and related vegetative influences on flow resistance.

In summary, historical and current geomorphic observations support the concept that the major tributaries of the Clark Fork supported dense riparian vegetation, likely were impounded by beaver, and that the river upstream from its confluence with the Little Blackfoot River was impacted, if not substantially altered, by beaver. In contrast, downstream from the confluence with the Little Blackfoot River, little evidence of significant pre-historical ponding by beaver exists, probably because of the larger discharge produced by addition of the tributary inflow and the reduced sinuosity of the lower river resulting from greater confinement in the narrower valley.

Early mining years: 1870 to 1908

Mining in the upper Clark Fork basin began in 1864 and developed into large-scale operations by about 1870 (Miller, 1973). By the time extensive mining began along Silver Bow Creek in the late 1800's, the riparian vegetation that for millennia had buffered the fluvial system from extreme hydrologic events was severely reduced along the creek (Weed, 1912). Similar effects probably were caused to some extent by agricultural and mining activities along other tributaries of the Clark Fork. The Clark Fork in the Deer Lodge valley was downstream from the areas of intensive mining, and its riparian vegetation probably also was somewhat reduced. Moreover, much erodible material, typically in the form of tailings, had been placed near the banks of Silver Bow Creek and Warm Springs Creek during the first few decades of mining and smelting. With the reduction of riparian vegetation, those tributaries probably had become vulnerable to substantial erosion during extreme hydrologic events. During floods, contaminated material was being transported down the Clark Fork and deposited on the flood plain or being incorporated into channel deposits, such as bars. By the early 1900's, all of these conditions had been exacerbated throughout the upper Clark Fork valley.

During the late 1800's and early 1900's, several floods occurred that were capable of putting the silty-sand tailings into suspension and depositing them on the flood plain of the Clark Fork. Data collected from streamflow gaging, which started in 1899 near Missoula (discussed in "Flood Magnitude and Frequency" section), indicate that large floods occurred in 1899 and 1902. The largest recorded flood occurred in 1908. Although pre-1899 streamflow records are sparse (CH2M Hill, 1989), Wheeler (1974) ranked the magnitude of historical floods from newspaper and other accounts and determined that floods with magnitudes between that of the 1908 flood and the smaller floods of 1899 and 1902 occurred in 1887, 1892, and 1894. These large floods affected both the Clark Fork and Blackfoot River drainage basins but were measured only downstream from their confluence; therefore, an accurate estimate of the magnitude of streamflow in the Clark Fork during these floods is difficult to determine. Indirect evidence of prolonged high stages during the floods is indicated by tailings deposits that average 3 to 4 feet thick along Silver Bow Creek (Titan Environmental Corp., 1995) and commonly 1 foot thick along the Clark Fork in the Deer Lodge valley (Nimick and Moore, 1994) and that could have resulted from a prolonged overbank flux of fine tailings onto the flood plains in areas covered by ponded water.

The likely existence of a beaver-pond setting along the Clark Fork in the upper Deer Lodge valley prior to the 1908 flood is important because it provides a possible explanation for why the large floods of the late-1800's and early 1900's were able to deposit such thick layers of fine sediment on the flood plain. In particular, channel blockages or intermittent ponds caused by the remnants of dams after the trapping of beavers could have resulted in a wet flood plain that would have supported thick residual riparian flora. This dense vegetation would have formed substantial barriers to the relatively deep overbank flow of a large flood, slowing it enough to deposit fine material in layers up to 1-foot thick in a broad swath down the center of the Deer Lodge valley. Areas previously occupied by beavers are typically characterized by irregular flood-plain topography, which could explain the variations in thickness of the tailings deposits. The tailings are primarily silt, and silt could not have settled quickly in substantial amounts unless (1) very deep water was sustained over the flood plain, or (2) the silt was being continuously advected onto a flood plain with substantial barriers to significant return flow. To deposit silt layers up to a foot thick from relatively still water over the flood plain would have required very deep pools (tens of feet) of nearly static water to allow for gravitational settling of the silt-size fraction. This very deep, low-velocity flow scenario is unlikely for the large floods in the Deer Lodge valley near the turn of the century. In contrast, weak advection would not require excessively deep water on the flood plain but would, rather, require a steep gradient in river surface slope directed away from, rather than along, the main channel. This, in turn, would cause the water and suspended sediment to flow overbank and the velocities, therefore, would decline substantially and steadily along the downstream path, resulting in substantial deposition of suspended material. Such flow away from the main channel and into depositional areas on the flood plain could persist for several days in a flood of extended duration. According to historical flood analysis (PTI, 1990), the 1908 flood lasted from May 25 to June 5. The fact that the river channel retained its single-thread integrity in spite of the intensity of the 1908 flood provides supporting evidence that the flood plain still was sufficiently vegetated to provide ample resistance to bank erosion and overbank flow.

Downstream from Garrison, where the discharge was higher and the river likely was lined with cottonwoods rather than willows, substantial bank erosion probably occurred during the several large pre-1908 floods because cottonwoods, which have a relatively wide spacing, provide less bank protection than dense willow thickets. Under prolonged flood conditions, cottonwoods are undercut and fall into the river causing log jams on bars. Flow can be diverted towards the banks causing further bank erosion, bank undercutting, and avulsions. Owing to the narrowness of the valley and the active in-channel erosion, some tailings were deposited locally as a thin, incoherent layer on the flood plain downstream from Garrison, but most were probably incorporated into the active bed of the channel. During the 1908 flood, the newly created (1907) Milltown Reservoir very likely filled with channel material derived from local upstream reaches. (This material would have contained tailings transported downstream during the large floods of the previous two decades.) Consequently, Milltown Reservoir likely had an insufficient storage capacity during the 1908 flood to trap a substantial portion of the sediment and metal loads transported from the upper basin by this flood. The long-term storage capacity in the reservoir has been small ever since.

Because the Clark Fork downstream from Garrison does not show signs, either stratigraphically or geomorphically, of having been impounded historically to any significant extent by beaver dams, it probably did not have a dense riparian flora, and it is likely that distinct flood-plain tailings deposits were always thin or absent along this segment of the river. Rather, some of the finer tailings transported by the turn-of-the-century floods probably were flushed downstream, while some were quickly incorporated with the coarse sand fractions into flood deposits of gravels in and along the margins of the main channel. Because deposits in and near the channel can move and interchange under relatively frequent (2-5-year recurrence) bankfull-flow conditions, most of the original tailings deposits probably have been reworked one or more times. As a consequence, the metal concentrations in bed sediment in this segment of the river system probably are in equilibrium with the concentrations in the suspended sediment and bedload that are currently being transported down the river.

Post-1908 flood

Large areas of tailings deposits, up to several feet thick in places, that accumulated during the multiple floods of the late 1800's and early 1900's apparently proved toxic to the willows in the Deer Lodge valley and produced "slickens," or bare tailings, that are visually evident today (fig. 2). After the 1908 flood in the Deer Lodge valley, some willows re-rooted and have grown in areas where the flood-plain tailings deposits were overlain by levy sands (natural berms along the top of streambanks where overbank flow deposited sand advected from the river channel). Metals phyto-

Figure 2. Tailings deposit on the flood plain of the Clark Fork near Galen, Montana. Deposit is about 3 feet thick. Unvegetated, exposed tailings such as this are locally known as "slickens." Photograph taken by David A. Nimick (USGS) in 1988.

toxicity, combined with reduction of the willow thickets by grazing and plowing of fields, probably caused what originally were highly stable streambanks to become much more erodible. Currently, many banks are particularly susceptible to erosion where slickens or grassy fields extend all the way to the river's edge, and in areas where non-cohesive gravel layers make the river banks especially vulnerable to cut-bank erosion.

Incision of the Clark Fork channel after the beaver dams began to break up, combined with collective human impacts and the floods of the late-1800's and 1908, likely scoured the channel bottom and produced a dense cobble armor that barely moves now in the upper reaches of the Clark Fork, even during bankfull flows. This nearly immobile cobble layer prevents further down cutting of the river and functions as a gravel platform on which the current river meanders back and forth across the flood plain. In most areas, the gravel platform must be eroded at the toe of banks for the bank to retreat. Therefore, the coarse cobble layer tends to protect the banks from substantial erosion during less than bankfull flows. However, where the cobble layer is overlain by perched layers of non-cohesive pebble-sized gravel and the bank is unprotected by woody vegetation, such as willows, the coarse layer is destabilized and erosion rates can be extremely high. During 1995-97, three bankfull or near-bankfull events resulted in substantial bank retreat in areas such as these that were particularly vulnerable to erosion (R2 Resource Consultants, written commun., 1998). In contrast, the banks in the thickly vegetated parts of the upper 1-2 miles of the Clark Fork in the Deer Lodge valley have been relatively immobile, even during the relatively high streamflow peaks of 1996 and 1997, making clear the importance of woody bank vegetation as a means of substantially reducing cut-bank erosion.

Flood magnitude and frequency

Floods are the predominant natural force affecting the transport and flood-plain deposition of tailings; consequently, flood magnitude and frequency provide important insight for understanding geomorphic processes. Although general flooding has occurred in the Clark Fork valley upstream from Garrison over the past century, determination of the magnitude and frequency of flooding is complicated by the sparse peak-discharge data at mainstem streamflow-gaging stations. For example, the gaging stations Clark Fork at Deer Lodge (station 12324200) and Clark Fork at Goldcreek (station 12324680) each have only 16 years of peak-flow data through 1994. No significant floods occurred on the Clark Fork at Deer Lodge during the period of gaged record through 1994, while one large peak flow occurred on the Clark Fork at Goldcreek. The large peak flow at Goldcreek was the result of the large flood on the Little Blackfoot River in 1981.

Flood magnitudes and frequencies commonly are determined by fitting a log-Pearson type 3 probability distribution to the gaged peak-flow data. However, this method likely is unreliable for any station with a short period of record. For the Clark Fork at Deer Lodge, flood magnitudes for given frequencies are likely to be underestimated using a log-Pearson analysis because the lack of flooding during the short period of record is presumed to be unrepresentative of floods over a longer period of time, such as the past 100 years. On the other hand, a log-Pearson analysis of peak-flow data for the Clark Fork at Goldcreek is likely to overestimate flood magnitudes because of the large influence given to the 1981 peak discharge in such a short record length.

To determine the frequency of past flooding in the upper basin more reliably, historical and gaged information from other sites was incorporated into the flood-frequency analyses. Fortunately, a much longer period of gaged record is available for the Clark Fork above Missoula (station 12340500). The annual-peak record at this site includes 1908 as well as the continuous period from 1930-94. In addition, recorded peak flows from 1899-1907 at a nearby site at Missoula (station 12341500) can, after some adjustment for estimated peak flows in Rattlesnake Creek, be added to the record of flows for station 12340500 to produce a peak-flow record for 1899-1908 and 1930-94. The general trend of annual peak discharge in the Clark Fork valley can be inferred from the long-term record at station 12340500 (fig. 3). Peak discharges at this station have been less than average for most of the 16 years of gaged records at Deer Lodge (1979-94) or Goldcreek (1978-83; 1985-94), indicating that hydrologic conditions during recent years of water-quality monitoring probably under-represent long-term rates of sediment and metals transport.

The flood-frequency curve for the Clark Fork at Deer Lodge for the period of gaged record was adjusted to the longer base period available at the site above Missoula using a two-station comparison procedure (Interagency Advisory Committee on Water Data, 1982). In this procedure, the peak-discharge data for

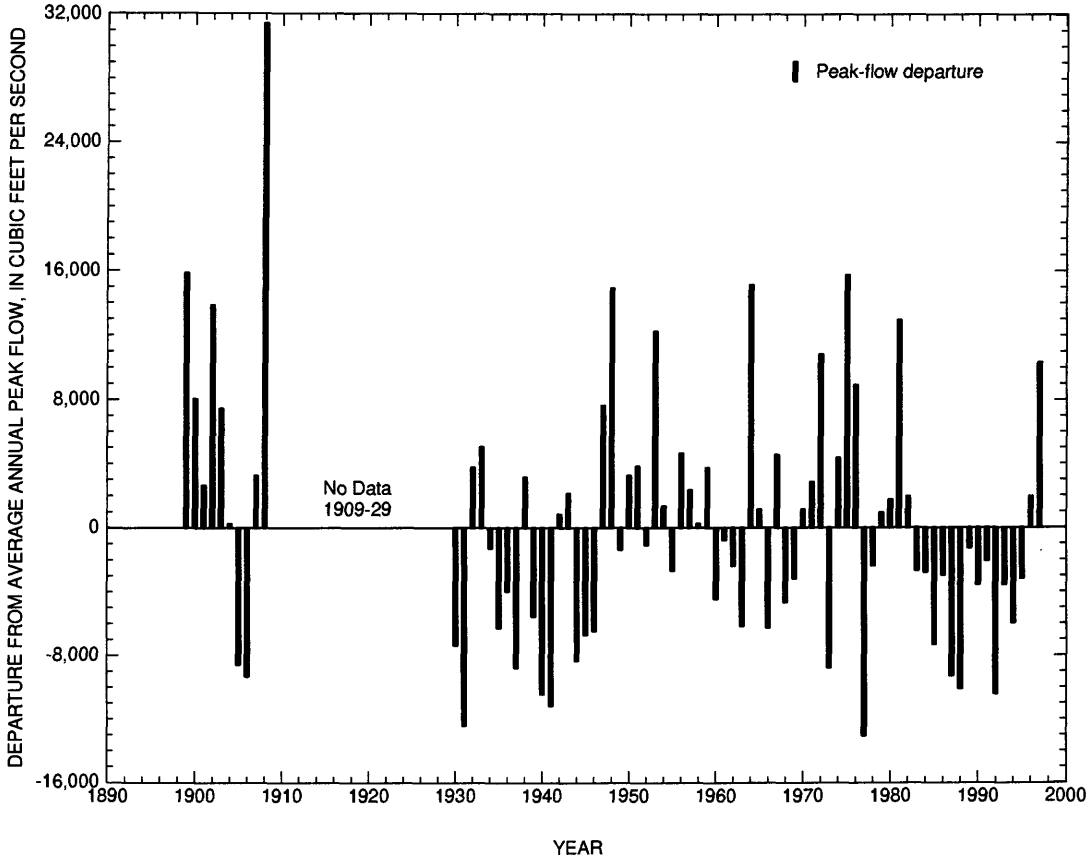

Figure 3. Departures from average annual peak flows for the Clark Fork above Missoula (station 12340500), Montana.

the short-record station are adjusted based on the relation between concurrent peak discharges at the short-term and the long-term stations. Table 1 shows flood magnitudes for various recurrence intervals for Clark Fork at Deer Lodge estimated from actual flow record and based on adjustment to the combined periods 1899-1908 and 1930-94. Flood-frequency curves based on the data in table 1 are shown in figure 4.

For the Clark Fork at Goldcreek, a different method for adjusting the flood-frequency characteristics was used. In this instance, flood-frequency characteristics based only on the short-term record were considered to be biased high because of the large influence of one large peak flow from the Little Blackfoot River. Thus, adjustment on the basis of comparison with flow records at Clark Fork above Missoula was not appropriate for Clark Fork at Goldcreek. Rather, adjustment for the site at Goldcreek was based on the historical information. Although the Clark Fork at Goldcreek was not gaged before 1978, large mainstem peak flows are believed to have occurred in 1975, 1964, 1948, and 1908. Although the relative magnitudes of these peak flows are unknown, the peak flow recorded in 1981 for the Little Blackfoot River near Garrison (station 12324590) was more than twice the peak flow recorded in 1975. On that basis, the recorded large peak flow at the Goldcreek site in 1981 is believed to be the largest since at least 1964. The historical period of record at the Goldcreek site was thus considered to be 30 years, and the log-Pearson analysis was applied using the historical-period adjustment (Interagency Advisory Committee on Water Data, 1982). Flood-magnitude and frequency information for the Clark Fork at Goldcreek, with and without the historical-period adjustment, is shown in table 2. Flood-frequency curves based on the data in table 2 are shown in figure 5.

An indication of the reasonableness of the adjusted 100-year flood estimates for the Clark Fork can be obtained from a plot of 100-year peak discharge in relation to drainage area for the Clark Fork at Deer Lodge, at Goldcreek, and above Missoula (fig. 6). The

Table 1. Flood magnitude for various recurrence intervals for the Clark Fork at Deer Lodge (station 12324200), Montana

Recurrence interval, in years	Peak discharge, in cubic feet per second	
	Actual record	Adjusted
2	891	1,060
5	1,530	1,990
10	2,010	2,750
25	2,690	3,880
50	3,240	4,840
100	3,820	5,900

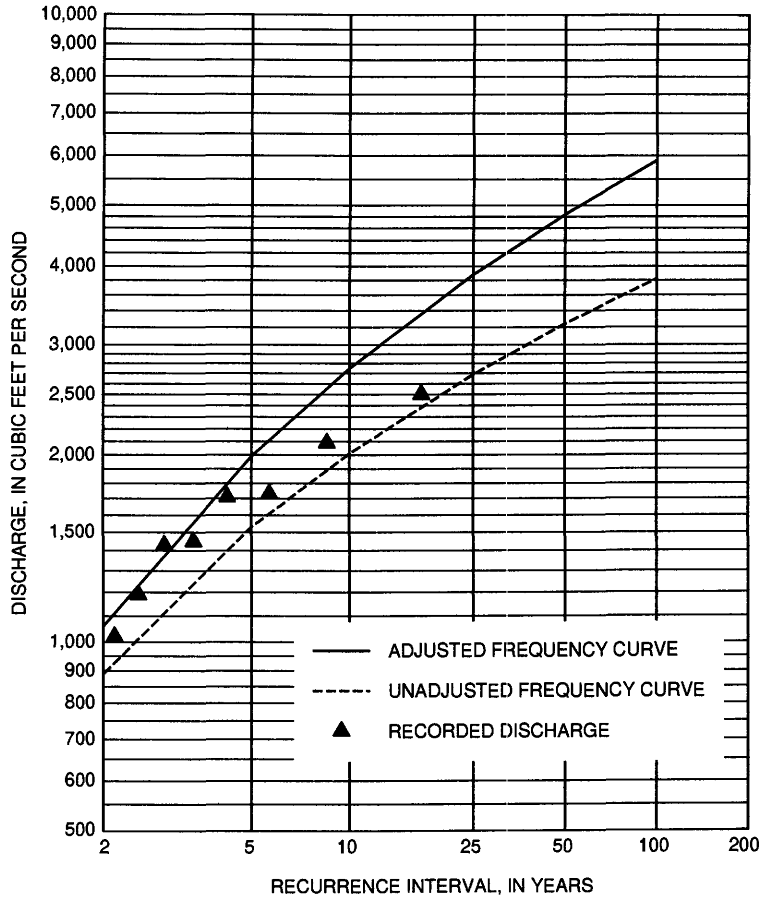

Figure 4. Flood-frequency curves for the Clark Fork at Deer Lodge (station 12324200), Montana. Adjustments to the period 1899-1908 and 1930-94 were made using available streamflow records for the Clark Fork above Missoula (station 12340500), Montana.

Table 2. Flood magnitude for various recurrence intervals for the Clark Fork at Goldcreek (station 12324680), Montana

Recurrence interval, in years	Peak discharge, in cubic feet per second	
	Actual record	Adjusted
2	2,240	2,120
5	4,340	3,910
10	6,100	5,350
25	8,720	7,450
50	11,000	9,210
100	13,400	11,100

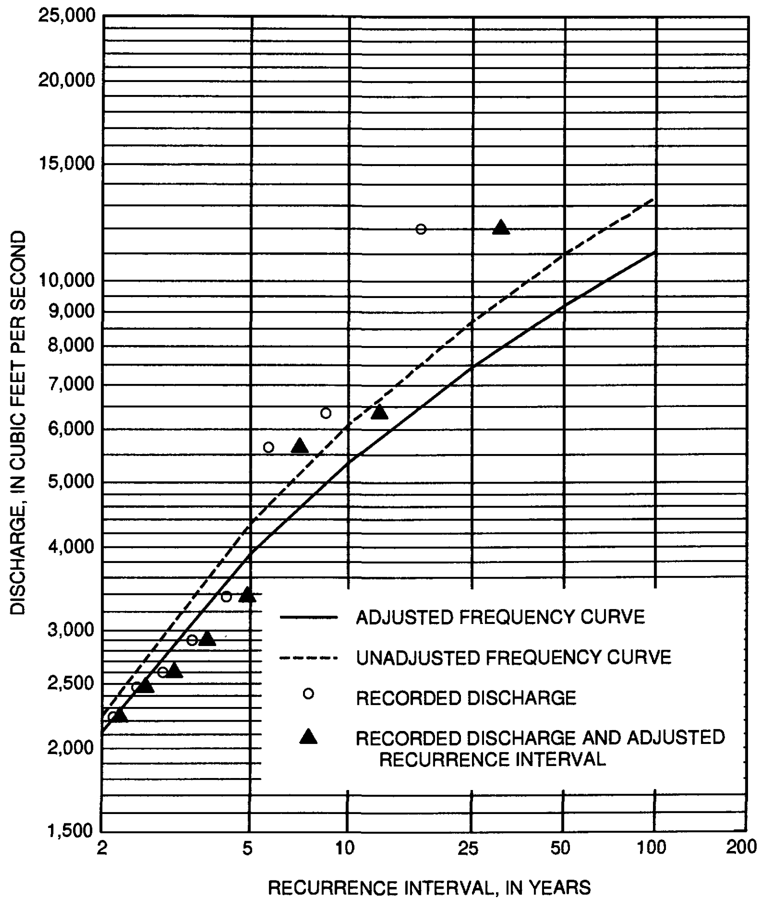

Figure 5. Flood-frequency curves for the Clark Fork at Goldcreek (station 12324680), Montana. Adjustments are based on the assumption that 1981 peak discharge was the largest since 1964.

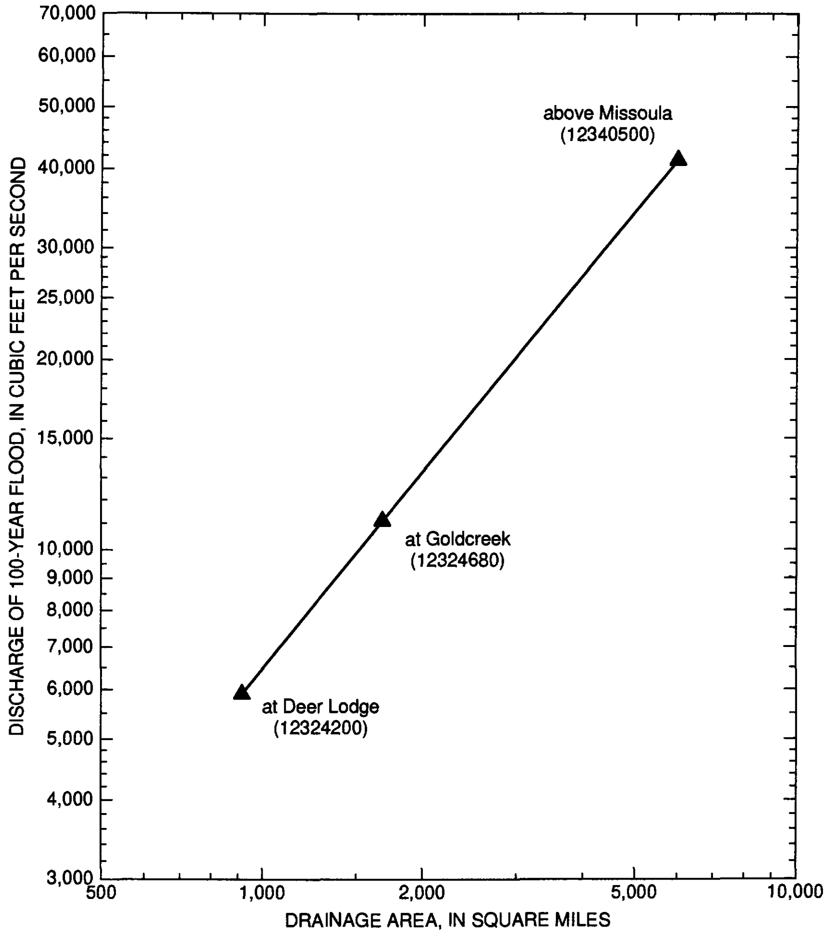

Figure 6. Estimated discharge of the 100-year flood at selected streamflow-gaging stations on the Clark Fork, Montana.

plot indicates that the log of discharge increases linearly with the log of drainage area from Deer Lodge to Missoula. The slope of the line is 1.03, which indicates that discharge per square mile increases slightly from Deer Lodge to Missoula. The increase from Deer Lodge to Garrison is considered reasonable because of the large flood contributions from Little Blackfoot River, whereas the increase from Garrison to Missoula is considered reasonable because of the large flood contributions from the Blackfoot River.

The flood-frequency analyses for the Clark Fork at Deer Lodge and Goldcreek are based on the assumption that annual flood peaks at the two sites are stationary over time. Although flood peaks are believed to be generally stationary over the past 100 years, future flood peaks on the Clark Fork upstream from Galen likely will be less than in the past because of the increased flood storage in the recently renovated Warm Springs Ponds. Thus, the flood-frequency analyses described above are representative of past conditions in the basin, but may not be representative of future flood magnitudes and frequencies in the basin.

Sediment-transport processes

Understanding sediment-transport processes is essential for evaluating the movement and distribution of metals in the Clark Fork because much of the metal in the river is attached to sediment (Lambing, 1991). In gravel-bedded rivers such as the Clark Fork, sediment is transported either as bedload or in suspension. Material that rolls or hops along the streambed is considered to move as bedload. Material that diffuses upward from the bed, supported by the random velocity field associated with turbulent fluctuations in flow, is considered to move in suspension. The concentration of suspended sediment is a balance between the upward diffusion of material in a turbulent flow and the downward settling of that same material (Graf, 1971; Yalin, 1977; Middleton and Southard, 1984).

The bed of the Clark Fork is armored by pebbles and cobbles; however, a thin active bed layer of fine sediment (silt and sand) resides in the interstices of the armor and moves around and over these pebbles and cobbles, even during periods of relatively low streamflow. This active layer consists of recently eroded sand and other bank materials that have been deposited on the bed. The active layer moves intermittently as bedload at low streamflow, but can be mobilized into suspension when streamflow is near bankfull. Bedload in gravel-bedded streams generally represents only a small percentage (<10 percent) of the total sediment transport (Emmett, 1984).

The actual bed of the Clark Fork is composed of a broad suite of sediment sizes, and different size classes of material move in different ways at different times. The coarse cobble armor barely moves in the reach of the river upstream from Garrison (Reach A, fig. 1), even during bankfull flows. Sand, in contrast, moves in bands (in the active layer) over the pebble and cobble armor during subbankfull flows and can go into suspension as the flow increases toward bankfull. During subbankfull flows, while coarse sand is transported as bedload, fine sand often moves in suspension, and silt almost always moves in suspension. Currently, at bankfull flow, the Clark Fork through the Deer Lodge valley probably transports pebble gravel in the thalweg as bedload and sand as suspended load.

In a typical meandering river, material is eroded from cut banks during high flows and transported downstream. Meandering rivers migrate laterally across their flood plain by systematically transferring sediment from cut banks to downstream point bars. The banks of the Clark Fork generally are composed of material that is finer than that found on the bed, at least on those portions of the bed along the thalweg of the river. Owing to the nature of the near-bed velocity field in sinuous rivers, eroded bank material typically is carried across the river toward the next downstream point bar, where a substantial fraction of the material is deposited. Depending on its size, some material is maintained in suspension for a greater distance and added to point bars one to several bends downstream (Dietrich and Smith, 1983; 1984). Some of the silt from the cut bank is transported a substantially greater distance downstream than the sand, but even most of the silt is almost entirely redeposited within about 10 river bends (Dietrich and Smith, 1983).

As long as the Clark Fork remains a meandering river and maintains its channel integrity, contaminated material that was deposited on the flood plain will continue to be systematically eroded at the cut banks, transported in equilibrium with its sedimentology, either as bedload or in suspension, and redeposited a short distance downstream on point bars. In this manner, tailings that started out as a thin layer of overbank deposition on the flood plain in the Deer Lodge valley become mixed throughout the point bars, which typically have a thickness equal to an average channel depth (Dietrich and Smith, 1983; 1984). This sediment-transport process supports a continuous downstream flux of metal at a concentration approximately equal to the metal concentrations in the mixture of the eroded cut-bank material and any clean sediment that may be added by tributaries in that part of the river. At present, relatively clean sediment is added to the Clark Fork upstream from Garrison by the ungaged west- and east-side tributaries and from a few high terraces and alluvial fans that are undercut by the river on the east side of the Deer Lodge valley.

Processes controlling bank erosion

Because cut banks are the actively eroding vertical surface of the flood plain, which is the repository for previously deposited sediment and tailings, it is essential to recognize the factors controlling rates of erosion in order to understand metals input from this source. The rate of cut-bank erosion depends largely on the sedimentology, stratigraphy, and irregularity of the cut bank. Banks of an irregular shape are more difficult to erode than smooth arcuate ones because, in the latter case, the high-velocity thread of the stream can travel adjacent to the bank. If velocities near the bed are sufficiently high, the flow can undercut the bank structure and transport any material that falls into the river. In the case of an irregular bank, the high-velocity flow is pushed outward from the bank by the resistance provided by roughness elements, making it more difficult to remove material from the toe of the cut bank. The root mass and clustered structure of a dense woody thicket on the bank produces substantial roughness and can effectively prevent rapid bank erosion, as evidenced by the stable banks observed along the upper 1-2 miles of the Clark Fork. Cottonwoods are much less effective at preventing bank erosion because they typically are spaced farther apart compared to willows or other small trees and shrubs.

The near-bed velocity depends on the boundary shear stress, which in turn, depends on the depth of the river and its slope. Locally, the boundary shear stress can deviate from that given by the depth-slope product because of accelerations and decelerations of the fluid above the bed caused by turbulent flow, which is characteristic of natural rivers. But, on average, through an entire meander bend, the magnitude of the boundary shear stress depends primarily on the slope of the river and its depth. From a geomorphic point of view, the bankfull depth together with the river slope along its center line determines the scale for the boundary shear stress. This is a consequence of the fact that, over time, a gravel-bedded river develops a cobble armor that is immobile during all but near-bankfull and higher flows, which is the case in the Clark Fork. Thus, the bed material is adjusted to the force applied and neither incision or aggradation occurs, and the river is said to be in equilibrium. If one or more bends are cut off, either naturally or for some engineered purpose, the river is effectively shortened and the local slope of the river becomes substantially steeper. The boundary shear stress thus increases over that with which the bed material had come to equilibrium. This increase causes the bed material to become mobile, especially near the toes of the cut banks, and allows the banks of the river to be eroded rapidly. The bank erosion then increases the sinuosity of the river until the boundary shear stress comes to equilibrium with the size of the material in the bed. If the material comprising the bed of the river is so fine that no such equilibrium is possible, then the river banks become so unstable that the geomorphology changes from a single channel to multiple threads, as discussed in the following section.

Process controlling flood-plain stability

Flood plains remain stable as long as erosion rates are not excessively rapid. Typically, as discharge increases above bankfull stage, water spreads out onto the flood plain, and the river depth rises very slowly as the discharge increases. Nevertheless, very large floods, such as the 1908 event in the Clark Fork basin, can produce sufficiently deep flows on the flood plain that unvegetated or sparsely vegetated sandy banks and flood plains cannot resist rapid erosion. When this happens, a meandering river can evolve, or unravel, into a braided system. The extent of this geomorphic unraveling is dependent on the water depth and velocity, and on the vegetative condition of the banks and flood plain. The unraveling could either be confined to a short reach of river or extend for miles; however, where precipitation is intense and river stage increases rapidly, the latter is more likely. This process can occur catastrophically during a large flood (on a time scale of hours to a day or so), as evidenced by a flood on Plum Creek along the Colorado Front Range in 1965 (Matthai, 1969).

Once the vegetation is penetrated and the roots no longer can hold the soil, bank erosion is very rapid and leads to further undercutting of the vegetative armor. This erosion occurs either in the main channel at the cut banks, which can retreat rapidly and eventually cause cutoffs of a meander loop, or by the development of new channels on the flood plain between the meander bends. In either case, once the root masses in the flood-plain soils have been penetrated, the new channel deepens rapidly, further undercutting the vegetation lateral to it, and thereby causing soil blocks held together by roots to fall into the river. Normally, eroded soil blocks fall close to cut banks and protect them, but when the erosion rates are very high, soil blocks detach rapidly and roll far enough away from the bank to be caught in the high-velocity zone of streamflow. Once removed from the immediate vicinity of a bank, these blocks become obstructions to the flow and cause it to accelerate between the blocks and the banks, thus accelerating erosion. When cutoffs develop and substantial amounts of water begin to move through the channels cut into the surface of the flood plain, the river slope increases as the river length decreases, resulting in increased boundary shear stress, erosion rate, and sediment-transport rate.

As the rates of bank and flood-plain erosion increase, the amount of sand added to the river from this erosion exceeds the amount that can be transported over a gravel bed. Consequently, some sand is deposited over the gravel layer. Although this increases the amount of bed covered with fine material, and thus increases the sand transport, it also produces a much smoother streambed, reduces the bed friction, and results in substantially increased flow velocities. The resulting higher velocities further increase the bank-erosion potential and erosion rates in the meandering river, potentially leading to severe destabilization and unraveling into multiple channels. As meandering rivers with sandy flood plains unravel, more sand is supplied to the river than can be transported by the flow, causing the bed of the river to aggrade and the banks to diminish in height. The final state, which can be achieved quickly, is a braided river. A braided river that formed in this fashion would have multiple channels, each of which would be straighter and shallower than in the original meandering channel. One of the best examples of a sandy-banked, gravel-bedded river in a semi-arid region that came unraveled during a severe flood is Plum Creek, which joins the South Platte River just south of Denver, Colo. (Matthai, 1969). As is the case with the Clark Fork in the Deer Lodge valley, Plum Creek had a gravel bed prior to the 1965 flood and meandered through a thinly vegetated, sandy flood plain in a valley with extensive agricultural development (Osterkamp and Costa, 1987). Now, more than thirty years after the flood, the stream is still braided with several threads, a gravely sand bed, and bars that are sufficiently mobile to prevent stabilization by plants (Friedman and others, 1996).

Because the extensive network of beaver dams that trapped sediment, roughened the flood plains, and promoted dense willow thickets in the headwater basins are long gone, the river through the Deer Lodge valley currently has a vulnerable riparian corridor owing in large measure to the extensive loss of riparian vegetation over the past century. The Clark Fork flood plain conceivably could suffer considerable destabilization during a major flood in areas where streambank vegetation is sparse over extended distances. Although many cutoffs and a few minor avulsions may have occurred along the Clark Fork during the 1908 flood, the geomorphic evidence indicates that bank stability was sufficient at that time to prevent the single-threaded channel system from unraveling into a braided system. The likely reason for maintenance of channel stability in 1908 was the heavy, extensive riparian flora and the rough flood plain of that era, neither of which exist today in the Deer Lodge valley.

Processes controlling streambed exchange

Streambed exchange occurs when the river mobilizes, or scours, sediment from the bed. The process ends when sediment transported from upstream is deposited in the scoured area. Understanding streambed-exchange processes is important because the bed could be a source or sink for metals. In particular, understanding streambed exchange can help conceptualize how and where tailings might have been incorporated initially into the streambed as a consequence of the 1908 and other large turn-of-the-century floods, as well as how these tailings might be remobilized into the river today.

Streambed sediment can be divided into three categories: the pebble and cobble armor, the material that underlies this coarse armor, and the fine surficial sediment of the active layer that fills the interstices and occasionally covers the armor layer. Not all of these materials play a role in exchanging metals to and from the streambed. The armor layer, or gravel platform, protects underlying material from scouring and thereby inhibits the exchange of the underlying sediment with the sediment carried in the active layer or in suspension in the river. In contrast, surficial sediment consists of generally fine-grained material that is in transit in the active layer from upstream eroding banks to downstream point bars. This fine-grained sediment is in equilibrium with the fluxes from the sediment sources to the sediment sinks and with the flow under almost all streamflow conditions; therefore, surficial bed sediment is derived from other sources and is not considered a separate source of metals to the river. It is important to note that virtually all of the metals data collected for bed sediment in the Clark Fork valley are for the surficial bed sediment. No systematic sampling to determine the depth or magnitude of potential metal enrichment below the armor layer has been conducted. Therefore, the quantity of metals present in the bed below the armor layer and the contribution to downstream metals transport are not known.

At any given time, only the surface layer of streambed sediment is in contact with water that is traveling at a sufficient rate to cause the sediment to move. Particle-to-particle forces can move sediment in the bed only on slopes that approach the bulk angle of repose; thus, the process of exchange of deep bed and bed-surface sediment proceeds through local scour. Most scour affects only about twice the thickness of the armor layer. The maximum scour depth below the streambed is equal to about one mean bankfull channel depth, but scour to this depth is extremely rare. During very large floods, the river bed still scours in the same way as it does during lower flows, but it is unlikely that, even during these large flows, the scour depth would exceed the mean bankfull depth by more than about 20 percent.

Two processes can penetrate the armor layer and cause deeper bed materials to be exchanged with material at the bed surface and, thereby, be put in contact with the flow. First, systematic penetration of the armor layer occurs where high-flow scour maintains pools near the toes of cut banks. These deep pools on the outside of the meander bends migrate as the banks cut and the channel migrates across the flood plain. Second, random penetration of the armor layer occurs where small transient topographic features on the streambed cause high boundary-shear-stress divergences, particularly at near bankfull stages and above, that may result in local scour of the armor and underlying bed material. Shallow scour features are produced, for example, by large clasts on the streambed rolling and skidding, and in the process forming temporary clusters. Deeper scour of the streambed occurs when trees, bushes, or ice become lodged on riffles and bars, causing erosion at the margins of these flow barriers. This type of local erosion can penetrate the armor layer when streamflow is well below bankfull stages and, in deeper flows, it can penetrate into the river to about a third of the bankfull depth. After these obstructions move on downstream, the holes are filled with the surficial sediment that is being transported over the streambed. The result is a local net exchange of deeper bed material with bed-surface material in the active layer, the exchange rate being dependent on the frequency of occurrence of the obstructions.

In addition to flow magnitude, the frequency with which the streambed is scoured depends on channel pattern. The more systematic the channel pattern, the less frequently the channel bed is scoured and the shallower the scour depth. For the Clark Fork in the Deer Lodge valley, where the river has a systematic meandering pattern, the greatest scour depths occur at a small number of cut banks, particularly those on the outside of extremely sharp bends. In these nearly right-angle bends, a three-dimensional, non-hydrostatic circulation can scour a pool to a depth of up to two mean bankfull depths. Other than at these infrequent sites, the deepest scour is related to the random occurrence of physical obstructions. Because these locations are more or less randomly located in meandering rivers, over a long period of time most of the streambed will be affected and eventually be reworked.

In contrast to the Deer Lodge valley (Reach A), the channel pattern is less systematic in the braided and single threaded, forested reaches of the Clark Fork downstream from Garrison (Reaches B and C), and the scour is more frequent and deeper. Here, pools about twice the mean depth of flow are situated between bars that are quite mobile at bankfull stage. After one to several decades of typical hydrology, most of the streambed has been reworked to approximately one mean bankfull depth below the mean streambed elevation.

The likely distribution of tailings in the streambed and the frequency of subsequent reworking can be hypothesized based on the conceptual understanding of streambed exchange presented above. In the Deer Lodge valley, it appears that the riparian vegetation was thick enough for the river to maintain its geomorphic integrity during the1908 flood but, owing to the presumably high boundary shear stresses, there must have been significant bank erosion in places, and there probably were many willow trees floating downstream. Because of the greater than bankfull flow depth, few of these trees probably would have become lodged on the streambed, and many could have been carried out of the channel onto the flood plain by secondary circulation (Dietrich and Smith, 1983) and caught in the relatively dense riparian vegetation. Some willows would have been stranded on point bars, but not likely in positions that resulted in substantial scour of the channel bed. Scour pools created by three-dimensional circulation probably were common during the flood, and all of the pools opposite point bars would have deepened by a significant fraction of a present mean bankfull depth. The average bed level would have been lowered to a small extent by removal of sand and small granules that could be put in suspension and then deposited on the flood plain, but typically the streambed would have remained at essentially the same level as it is at present. The primary in-stream repositories for significant amounts of metal-rich material, therefore, were the scour holes (and pools) associated with normal and extra sharp meander bends that were overdeepened by the 1908 flood and which then were filled back to a normal, bankfull-related depth by metal-rich sediment on the waning limb of that event. The metal concentrations in the deposited material would have been the concentration which existed on the suspended sediment and in solution in the flow at the time of deposition. Because the cutbanks have migrated during the last 90 years, some of the metal-rich deposits presumably would now be mostly beneath the present streambed. Sampling of metals at depth in the bed of the Clark Fork through the Deer Lodge valley to date has not been systematic or sufficiently detailed to either confirm or negate this predicted depositional structure.

The Clark Fork valley below Garrison likely was substantially denuded of large cottonwood trees and other channel-protecting vegetation during the large floods of the late 1800's and early 1900's, leaving the river corridor a broad zone composed of channels, bars, and small segments of old flood plain, much like a braid plain. Owing to the mobility of a braided channel during large floods, overbank deposits are thin and rare. Assuming this scenario, the river probably moved freely back and forth across its valley downstream from Garrison during the 1908 flood, which was high enough in discharge and long enough in duration that much of the riverine corridor could have been reworked. If most of the riverine corridor was reworked during the 1908 flood, then tailings would have been incorporated throughout the perpetually moving bars to a depth equivalent to that of the river during the flood. This flow depth would likely have been about 1.5 times the present bankfull depth. Therefore, metal-rich sediment may be contained in a band that is 1.5 present bankfull depths thick, filling most of the valley where the valley is narrow. Metal-rich sediment may also fill a broad swath through the valley where it is wide, but where the river was not in a meandering mode during the flood. Those reaches in the valley below Garrison where the river remained in a meandering mode during the flood would have scoured and filled in the same way as the river did in the Deer Lodge valley, possibly with a small increase in scour caused by stranded cottonwoods during the falling limb of the flood hydrograph.

In summary, contaminated material in meandering and braided rivers is deposited in the active bars. In meandering reaches, the active bars are point bars, and point bars eventually become flood plain. In braided reaches, the bars sometimes become banks and then later get eroded again. Whether the contaminated material is considered to be (1) in the river bed or (2) in its banks is a matter of semantics. In both meandering and braided rivers, the contaminated material is best thought of as being in the bars, which are depositional features. The contaminated material in the bars is unlikely to be eroded for a long time (centuries) in the meandering reaches of a river, but it may not survive long (decades) before being eroded again in the braided reaches. The meandering river situation is found in the Deer Lodge valley reach of the Clark Fork and the braided river situation is more common downstream from Garrison.

A comprehensive metals-sampling program for the bed and flood plain to evaluate this predicted contaminant distribution in the lower river (Reaches B and C) has not been done. The available data for Reaches B and C are too sparse and for soil depths that are too shallow to be of use in this regard. The width of the zone most likely affected in the above-described manner possibly could be delineated by locating and mapping the standing cottonwood trees more than 90 years old that were outside the 1908 flood zone and by using high-quality aerial photographs to examine cottonwood distribution.

FLOOD-PLAIN TAILINGS

Large quantities of flood-deposited tailings rich in arsenic, cadmium, copper, iron, manganese, lead, and zinc are spread over the upper Clark Fork flood plain (Nimick and Moore, 1994; Schaefer and Associates, 1997a). The tailings originated primarily from the disposal of mining and smelting wastes into Clark Fork headwater tributaries draining Butte and Anaconda during 1864-1915. Wastes were transported to the Clark Fork by at least six major floods in the late 1800's and early 1900's, including the largest flood on record in 1908 (CH2M Hill, 1989). Although the flood plain aggraded during this period, analysis of the relative position of the recent and pre-mining flood-plain deposits indicates that the bed of the present channel is near its pre-mining altitude (Nimick and Moore, 1991). Even though migrating channel meanders and channel avulsions have eroded some of the original tailings deposits, these deposits still overlie pre-mining flood-plain deposits in large areas of the valley.

Flood-plain tailings in Reach A have been examined by a number of investigators. In particular, investigations documenting the extent, stratigraphy, and chemistry of tailings have been completed by Brooks (1988), CH2M Hill (1991), Nimick (1990), Rice and Ray (1985), and Schafer and Associates (1988, 1997a). Additional chemical data for flood-plain deposits are available in other reports as well.

Stratigraphy of flood-plain tailings

Flood-plain sediment on the valley floor can be separated into three categories: pre-mining flood-plain deposits, overbank tailings, and reworked tailings.

Most of the tailings are in widespread overbank deposits that have remained undisturbed since initial deposition over 90 years ago. Except for some limited historically irrigated areas, all tailings-impacted deposits are within the 100-year flood plain of the river.

The pre-mining flood-plain deposits that were buried by the overbank flux of tailings consist of fine-grained overbank deposits on top of thin-bedded silt and sand overlying sand and gravel. Pre-mining overbank deposits are easily distinguished from overbank tailings by their dark-brown color and sandy texture. Pre-mining sediment typically has a buried A-horizon over subsoil.

Overbank tailings consist of the essentially pure tailings deposited on the flood plain during the large floods of the 1890's and early 1900's. These tailings are visibly identifiable as yellow, orange, and tan fine sandy silt to silty sand. In some areas, particularly in Reach A, tailings deposits are thick and unvegetated, forming slicken areas. Tailings also were deposited in former river channels and sloughs.

The supply of tailings from the Butte area was restricted after about 1911, when the first settling pond was built on Silver Bow Creek (Montana Department of Health and Environmental Sciences, 1989). Although tailings continued to be carried downstream, the construction of sediment controls decreased the influx of tailings from upstream sources to the Clark Fork and allowed natural sediment from tributaries and uncontaminated soils to more effectively dilute the tailings transported from upstream sources or eroded from flood-plain deposits.

Reworked tailings are mixtures of tailings and cleaner sediment and are found as silty, fine sand in overbank, crevasse-splay, natural-levee, and delta-like deposits on the flood plain where levees were breached by flood waters. Reworked tailings also occur as silty sand and sand in channel-accretion deposits along the margins of channels, and as silt, sand, and gravel in point bars. Reworked tailings support vegetation and generally are light brown. Of all reworked tailings, reworked overbank tailings have the greatest areal extent. Reworked overbank tailings were deposited by overbank flows subsequent to the 1908 flood and overlie the original tailings deposits. These overbank tailings deposits are called "cover soils" in the mapping of tailings and soils (Schafer and Associates, 1997a) described in the "Flood-Plain Tailings and Soils Map" section.

Geochemistry of tailings

The current distribution of trace elements within the Clark Fork flood plain has been affected by both depositional and geochemical processes. Whereas the lateral (cross-valley) and longitudinal (downstream) distribution of trace elements is largely the result of the depositional history, the vertical distribution of trace elements within the flood-plain deposits has been altered by post-depositional geochemical processes. The current trace-element chemistry of flood-plain deposits depends on the initial composition of the tailings/sediment mixtures, subsequent chemical and solubility changes brought about by oxidation of the sulfidic tailings, and by transport processes within the deposits, such as infiltration of rainfall, trace-element attenuation, capillary rise of ground water, and salt formation.

Original composition of tailings

Tailings deposited by flooding in the late 1800's and early 1900's were enriched in trace elements, many of which may have occurred in a sulfide form. High-grade copper ore mined in Butte prior to 1910 occurred within a supergene enrichment zone, where primary sulfides--especially pyrite (FeS_2), arsenopyrite ($FeAsS$), and chalcopyrite ($CuFeS_2$)--were enriched in copper leached from an overlying oxidized zone. The resulting enriched sulfides included chalcocite (Cu_2S), enargite (Cu_3AsS_4), bornite (Cu_5FeS_4), and other minerals. Presumably, mineral processing would have extracted most of the copper-enriched sulfides. Roasting may also have oxidized some of the non-copper-containing sulfides. (Weed, 1912; Meyer and others, 1968; Miller, 1973)

During fluvial transport from source areas, soluble trace elements contained in the tailings would have been carried downstream as dissolved load. Soon after deposition, therefore, tailings deposits primarily would have contained relatively insoluble trace-element compounds.

Geochemical evolution of tailings

Tailings in overbank deposits were exposed to ample supplies of oxygen soon after flooding. Consequently, the sulfides would have oxidized, resulting in the formation of sulfuric acid. Typically, the carbonate content of residue from high-grade ores was low, and thus the tailings layers on the flood plain would have quickly become acidic, with pH values declining, possibly to values of 4 or less. After many years of continued oxidation, most of the reactive sulfides in the tailings probably oxidized. This could explain why most Clark Fork tailings today have low pyritic sulfur concentrations (Schafer and Associates, 1997a), high acid-extractable trace-element concentrations relative to total concentrations (Nimick and Moore, 1994), and few, if any, primary sulfide minerals based on mineralogic analyses using electron microprobe techniques (PTI, 1997).

Where oxidation of the reactive sulfides has been complete, natural neutralization of the acidic by-products would cause the soil pH to increase. This process may be occurring in thinner tailings layers in the Clark Fork flood plain. Layers of mixed soil/tailings and cover soil probably contained higher carbonate levels than tailings (as is indicated by results of acid-base accounting using static tests) (Schafer and Associates, 1997a). Consequently, these mixed materials may have sustained near-neutral pH levels despite the gradual oxidation of sulfide minerals.

Vertical redistribution of trace elements

Flood-plain tailings contain high concentrations of trace elements. The highest concentrations of arsenic, copper, lead, manganese, and zinc generally are found at the ground surface, at depth in tailings that are chemically reduced, or in buried soils (fig. 7). Concentrations generally are less in the oxidized portion of thick tailings. This vertical distribution of trace elements within the flood-plain deposits indicates that trace elements released by sulfide oxidation in tailings have been remobilized and transported to varying degrees.

The chemical mobility of trace elements varies greatly in tailings, cover soil (reworked tailings), and the pre-mining buried soil layers (Nimick and Moore, 1994). The solubility of trace elements is affected by pH, although the effect is different for each trace element. Trace elements contained in thin tailings deposits, cover soil, and buried soil generally have a low solubility owing to the near neutral to alkaline pH values in these materials. Consequently, the chemical mobility of trace elements generally is low. The solubility of trace elements is much higher in thick tailings layers where pH values typically are low. Copper and zinc are readily soluble at pH values less than 3.5 to 4.5 observed in some tailings layers. Lead and arsenic are less soluble at low pH values. Consequently, oxidation and acidification of overbank tailings increases the solubility of copper and zinc, but lead and arsenic remain somewhat insoluble. Therefore, water that moves through the tailings will carry high concentrations of dissolved copper and zinc and lower concentrations of dissolved arsenic and lead. Soluble trace elements can move downward as water flows through the tailings or upward if water is pulled to the surface by capillary action driven by evaporation.

The pre-mining flood-plain soils buried by tailings typically contain organic materials or carbonates and have a neutral to alkaline pH. Consequently, trace elements leached from overlying tailings layers have been adsorbed in these underlying soils. This process of mobilization from tailings layers and adsorption in underlying soils explains the trace-element enrichment observed in buried soils. This enrichment is most pronounced near the soil/tailings boundary and decreases with depth in the buried soil.

Soluble trace elements in acidic tailings layers can also move upward by capillarity as soil moisture is drawn to the surface and evaporated during warm weather. Upward movement is more pronounced where ground water is close to the ground surface. In areas of bare tailings, metal-rich efflorescent salts form on the surface. Surface runoff across these areas can be an important mechanism for transporting trace elements to the Clark Fork (Nimick and Moore, 1991; Schafer and Associates, 1996).

Flood-plain tailings and soils map

A map depicting the areal and vertical extent of tailings and impacted soils in Reach A was identified as a primary data need for the Clark Fork River remedial investigation in 1995. Therefore, a tailings and soils map was produced that identified the spatial extent and depths of soil horizons containing elevated levels of arsenic and metals (Schafer and Associates, 1997a). The map shows the aerial extent and the volume of affected soils, the range of trace-element concentrations in different units, and the location of affected soils relative to the present Clark Fork channel. A section of the flood-plain tailings and soils map is shown as an example in figure 8.

Tailings, cover soil, and mixed soil/tailings were the three depositional layers containing elevated trace-element concentrations recognized within the flood plain. In tailings, copper and zinc concentrations typically are 1,000 to 2,000 mg/kg, and arsenic and lead

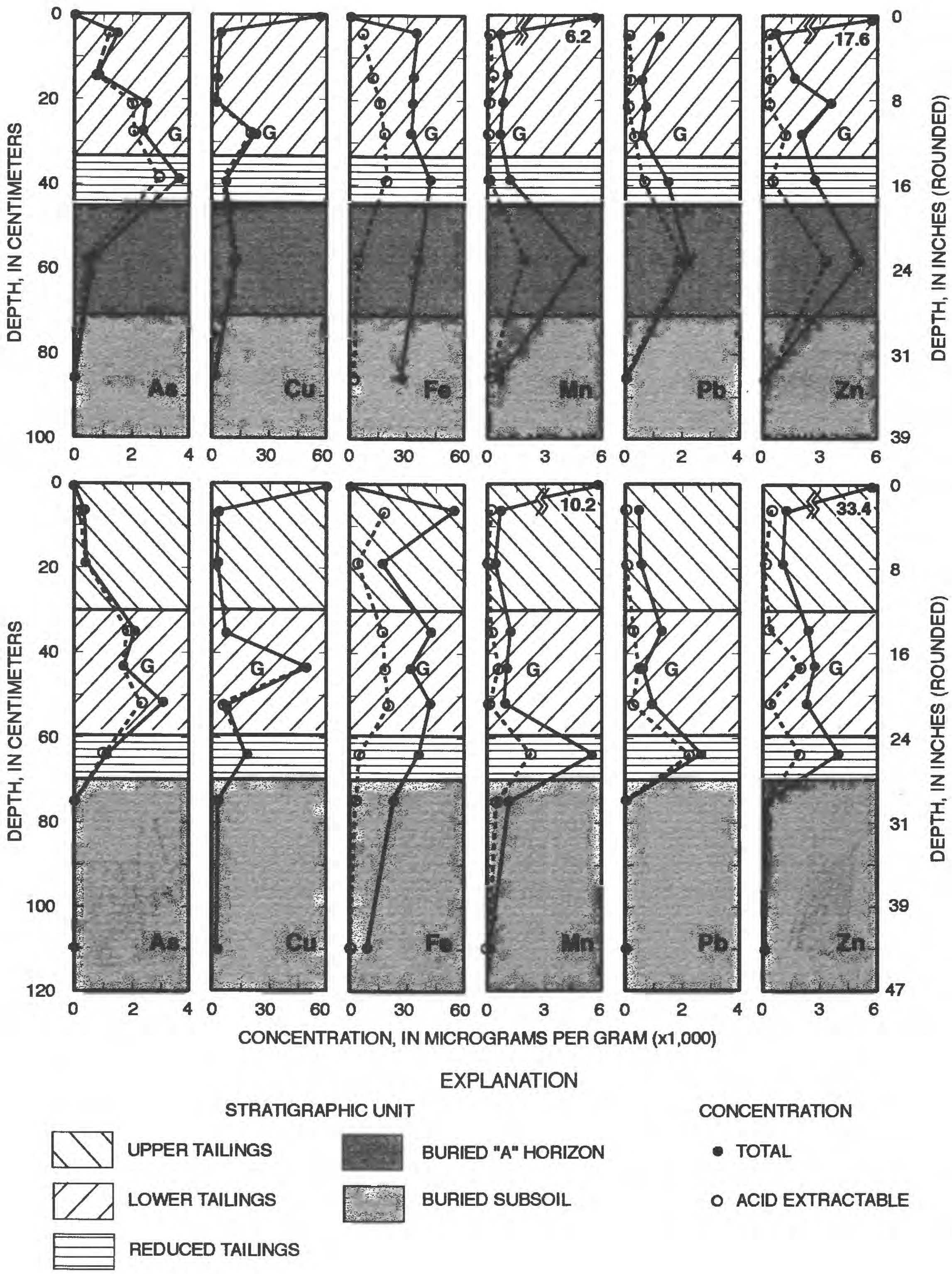

Figure 7. Vertical concentration profiles of trace elements in flood-plain tailings and soils for two sampling pits in the Clark Fork valley near Galen, Montana (modified from Nimick and Moore, 1994). Not all stratigraphic units are present at each site. Data for surficial material (0-2 cm) are water-soluble concentrations. "G" indicates green sand layer in lower tailings.

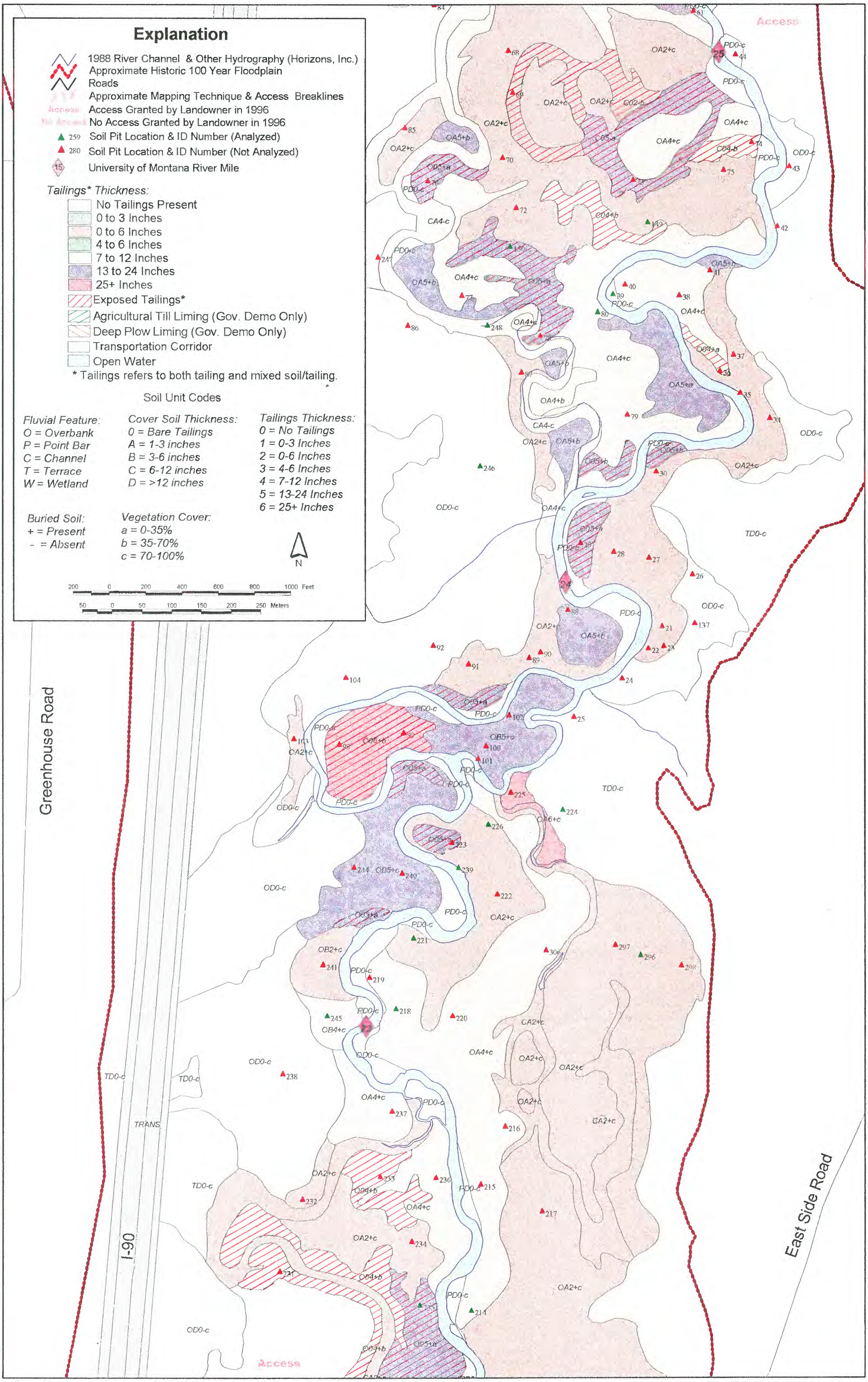

Figure 8. Flood-plain tailings and soils map for a section of the Clark Fork valley upstream from Deer Lodge, Montana (modified from Schafer and Associates, 1997a, Soil Map 9).

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concentrations are 200 to 800 mg/kg. Tailings generally were distinguished by their prominent iron-staining, textural stratification, and sandy loam to loamy sand soil texture. Tailings commonly are moderately acidic (pH values less than 5.5). Mixed soil/tailings have less distinct morphology and share certain features of both tailings and cover soil. Cover-soil layers always overlie tailings or mixed soil/tailings deposits but resemble natural surface soils in most other respects. Consequently, cover-soil layers were defined by their stratigraphic relation to tailings layers.

Two other types of depositional layers contained elevated trace-element concentrations: buried organically enriched soil and buried alluvium (sand and gravel). The elevated trace-element content of these buried horizons resulted from the downward migration of trace elements since tailings deposition. Where the attenuation capacity of soil is strong, as in organic soils, the degree of trace element enrichment is pronounced near the tailings boundary and decreases markedly with depth, typically within 4 to 12 inches of the tailings boundary.

Methods

The flood-plain mapping method used employed standard National Cooperative Soil Survey standards for Order 1 (most detailed) mapping (U.S. Department of Agriculture, 1975), but modified the taxonomic system to address the deposition and extent of tailings as well as the identification of tailings-impacted soils. Soils mapped as part of an Order 1 soil survey have a minimum map-unit size of 2.5 acres. In mapping the Clark Fork valley, soil map units also were based on fluvial features (overbank deposits, abandoned channels, point bars, and terraces); the geomorphic landscape position; the thickness, kind, and arrangement of soil horizons; and the proportion of vegetative cover. Soil pits were excavated at 515 sites to observe and describe the soil horizons. Each pit was hand dug to a depth approximately 1 foot below the base of visible tailings. Information from the pits was used to summarize the average thicknesses and particle-size distribution of tailings, cover soil, and mixed tailings layers throughout the flood plain. Samples for analysis of total and extractable arsenic and metal concentrations were collected at selected sites representative of individual map units.

The area covered by the tailings and soils map generally was within the 100-year flood plain of the Clark Fork. Soil mapping was completed for all of Reach A (fig. 1), a 7-mile stretch near Jens in Reach B where the river gradient is low, and in three 1,000-foot bands in Reach B where the river gradient is higher. The furthest downstream map area consisted of about 2 river miles in Reach C. Prior mapping efforts by Schafer and Associates (1988, river mile 1 to 3) and Nimick (1990, river mile 1 to 11) and measurements compiled by the University of Montana (1996) of thickness of tailings exposed in streambanks also were incorporated into the tailings and soils map.

Access to about 60 percent of the land area in Reach A was unavailable to mapping crews. Consequently, the distribution of tailings and soils was estimated in these areas using aerial photographs to aid in extrapolating boundaries of soil map units from accessible areas.

Designations for soil map units consist of the fluvial geomorphic feature, tailings and cover-soil thicknesses, the type of soil underlying the tailings, and the percent vegetative cover (table 3). For example, a soil map unit designated as OA4+c was an overbank

Table 3. Explanation of map-unit designations used in the tailings and soils map for the Clark Fork flood plain, Montana (modified from Schafer and Associates, 1997a)

[Symbol: >, greater than]

Fluvial feature		Tailings thickness		Cover-soil thickness		Buried-soil type		Vegetative cover	
Key	**Description**	**Key**	**Description**	**Key**	**Description**	**Key**	**Description**	**Key**	**Description**
O	Overbank	0	no tailings	0	bare tailings	+	Buried organic soil	a	0-35 percent cover
P	Point bar	1	0-3 inches	A	1-3 inches	-	Buried sand and gravel	b	35-70 percent cover
C	Channel	2	0-6 inches	B	3-6 inches			c	70-100 percent
T	Terrace	3	3-6 inches	C	6-12 inches				
		4	6-12 inches	D	>12 inches				
		5	12-24 inches						
		6	>24 inches						

deposit (O) with 1-3 inches of cover soil (A), underlain by 6 to 12 inches of tailings (4), was deposited on an organically enriched natural soil (+), and was located in an area having 70-100 percent vegetative cover (c).

A combination of techniques was used to compile the soil map and to develop a geographic information system (GIS) to facilitate queries of the spatial data. Where land access was granted, boundaries of soil map units were delineated on aerial photographs in the field. The boundaries in other areas were delineated in the office by examination of surface features on aerial photographs. Control points were located on each photograph using differentially corrected, sub-meter geographic-positioning-system (GPS) measurements. These points were used to rectify each photograph to a standard coordinate system. The map-unit boundaries were then digitized to form unique soil map-unit polygons. Each polygon was assigned a numeric identifier that was used to relate the soil polygon with its extended attributes in a database. Soil-pit locations were determined using GPS or by digitizing the location from the rectified photographs. Each pit also was assigned a numeric identifier and related to a database containing the field and analytical parameters for each horizon at the site.

A number of measures were used to verify the accuracy of soil map delineations. A field review was conducted by the USEPA technical oversight contractor, Schafer and Associates staff, and the USGS within areas previously mapped by Nimick (1990) to insure that historical map information was properly incorporated into the new map. The USEPA technical oversight contractor made weekly trips to review the field mapping effort and to assist in mapping. Draft maps were compared to historical soil-sample information to see if tailings and cover-soil thicknesses corresponded to previously mapped thicknesses. Map-unit boundaries were carefully matched on photograph edges. Finally, all field notes and map-unit descriptions in the database were reviewed against final map-unit designations.

Total arsenic and metal concentrations were determined using x-ray fluorescence spectroscopy for 239 tailings and soils samples collected during the mapping effort: 137 from Reach A, 59 from Reach B, and 43 from Reach C. Water-extractable arsenic and metal concentrations, pH, and electrical conductivity were measured, and static tests were performed to determine acid-generating and neutralization potential. Results from this sampling effort, described in the "Chemical Properties" section, were comparable with data from historical samples. Multiple discrete-depth samples were routinely collected at a site in order to evaluate the vertical changes in trace-element concentrations with increasing depth.

Generalized spatial distribution of tailings

In Reach A, tailings and mixed soil/tailings layers are found in a nearly continuous band on the flood plain ranging from 500 to 2,000 feet wide paralleling the Clark Fork channel. Roughly one-third of the 100-year flood plain contains tailings or mixed soil/tailings layers. The thickest tailings (up to 4 feet near Warm Springs) are mostly in a narrow band several hundred feet wide (up to twice the amplitude of meanders) near the river, but some are near the course of the late-1800's channel. Thick tailings are extensive at the upstream end of the valley (near Warm Springs) and in downstream areas where the flood plain is narrow. Relatively level portions of the flood plain also tend to contain thicker and more spatially extensive tailings deposits than steeper portions. Most (95 percent by area) of the flood-plain tailings are in overbank deposits while the remainder are in abandoned channels. Thickness of tailings deposits generally ranged from less than 1 to 34 inches. About half of the tailings deposits were more than 6 inches thick and about 10 percent were greater than 18 inches thick. All tailings greater than 15 inches thick were less than about 450 feet from the river. About 50 percent of bare tailings were 14 inches or more in thickness. There is no correlation between tailings thickness and distance down river in the Deer Lodge valley.

Tailings usually are overlain by a thin (2 to 6 inch) cover-soil layer except for thicker overbank tailings deposits (>12 inches thick) that generally are located within channel meander loops. Cover soil ranged in thickness from less than 1 inch to more than 12 inches and about 50 percent of the deposits were less than 4 inches thick. The portion of the flood plain located at a distance greater than the width of the meander amplitude (>300 feet) away from the channel typically contains thin tailings (<6 inches) overlain by thin, well-vegetated cover soil.

Area and volume estimates

The soil map includes the 100-year flood plain, or approximately 10,500 acres, in Reach A between the

Warm Springs Ponds and the mouth of the Little Blackfoot River. Roughly one-third of this area (3,494 acres) contained tailings horizons, and the average thickness of tailings was about 6 inches. Impaired vegetation is most commonly associated with bare tailings (191 acres) or with tailings thicker than about 12 inches (less than 20 percent of all tailings mapped). The estimated volume of tailings ranges from 2.0 to 3.5 million cubic yards (table 4). The total volume of soils (tailings, cover soil, and the upper 8 inches of buried soil) impacted with arsenic and metals ranges from 6.8 to 8.7 million cubic yards. Most of the impacted area of the flood plain has only a relatively thin, well-vegetated layer of tailings.

Chemical properties

The geometric mean total concentrations of arsenic and metals in flood-plain sediments in Reach A are summarized in table 5. Trace-element concentrations were highest in Reach A and tended to decrease downstream. Distinct tailings layers were scarcer in Reach B than in Reach A and were not discernible in Reach C.

Cover soil and mixed soil/tailings had higher average copper and zinc concentrations (1,980 to 2,360 mg/kg) than did tailings (1,530 and 1,760 mg/kg). Tailings, however, had lower average pH values and higher concentrations of soluble metals than either cover-soil or mixed soil/tailings layers. Concentrations of some metals in tailings may be lower than in overlying and underlying layers because the low pH in tailings tends to mobilize metals, which then could be drawn to the land surface as soil moisture evaporates, or leached into underlying buried soil layers. Metals in more alkaline cover-soil and mixed soil/tailings layers are not as mobile and have been largely retained. In contrast to

Table 4. Estimated area and volume of trace-element-enriched soil materials in Reach A of the Clark Fork flood plain, Montana (modified from Schafer and Associates, 1997a, table 2.1)

Soil-material type	Area (acres)	Volume (million cubic yards)[1]		
		25th percentile	50th percentile	75th percentile
Tailings[2]	3,494	2.0	2.9	3.5
Cover soil	3,338	1.0	1.1	1.5
Buried soil[3]	3,494	3.8	3.8	3.8
Total	3,494	6.8	7.7	8.7
Bare tailings[4]	156	.3	.4	.4

[1]Volume calculated using the 25th, 50th, and 75th percentile thickness for the mapped thickness class.

[2]Includes 191 acres of bare tailings (unvegetated slickens); 156 acres were mapped and approximately 35 acres were in numerous areas too small to be mapped individually.

[3]Thickness of buried soil containing elevated trace-element concentrations assumed to be 8 inches.

[4]Mapped portion of the total 191 acres; volume included in estimate for tailings.

Table 5. Geometric mean concentrations of total arsenic and metals in flood-plain sediments in Reach A of the Clark Fork valley, Montana (modified from Schafer and Associates, 1997a)

Soil-material type	Number of samples	Geometric mean concentration (milligrams per kilogram)			
		Arsenic	Copper	Lead	Zinc
Tailings	21	766	1,760	665	1,530
Mixed soil/tailings	24	419	2,360	359	2,320
Buried soil	37	32	373	42	410
Buried alluvium	3	203	1,330	270	1,190
Cover soil	22	330	1,980	318	2,060
Unflooded soil	30	63	303	60	401

copper and zinc, arsenic and lead concentrations were higher in tailings (766 and 665 mg/kg, respectively) than in cover-soil (330 and 318 mg/kg) or mixed soil/tailings layers (419 and 359 mg/kg). Arsenic and lead are relatively immobile at the lower pH levels typical of tailings. Consequently, these elements have not been removed from the tailings to as great a degree as copper and zinc. Concentrations of trace elements in buried soils support this concept. Whereas copper and zinc are elevated (373 and 410 mg/kg, respectively) in buried soils to a depth of 8 inches or more, arsenic and lead are not as enriched (32 and 42 mg/kg, respectively) and are enriched to a lesser depth in buried soils (4 to 6 inches).

Estimated metal concentration in banks

Flood-plain deposits, which are eroded into the river from outside banks as the channel migrates laterally, are an important source of metals to the Clark Fork. Quantifying the mass of metals delivered to the river by bank erosion requires information describing the volume and metal content of eroded banks. The flood plain contains a number of distinct soil horizons, each differing in metal concentration. Therefore, the average metal content of a streambank depends on the thickness and metal content of individual soil horizons and the overall bank height. Average metal concentrations in streambanks were calculated with equation 1:

$$\bar{C}_x = \frac{\Sigma(z_1 \times C_1 + \ldots + z_n \times C_n)}{z_{total}} \qquad (1)$$

where $\bar{C}_x$ = average concentration of metal x in bank sediment

z_n = thickness of horizon n,

C_n = concentration of metal x in horizon n, and

z_{total} = total height of bank

The procedure for estimating metal concentrations in banks of the Clark Fork (Schafer and Associates, 1997b) used the following data collected during the Clark Fork River remedial investigation:

- geometric mean metal concentrations in tailings, mixed soil/tailings, cover soils, and buried soils and alluvium (table 5);
- average bank height and average channel depth (average bank height from base of channel was 40 inches);
- ratio of metal concentrations in fine-grained (<50 µm) and sand (50-2,000 µm) fractions of soil horizons exposed in banks (average ratio was 1:1);
- the river miles of intersections of soil map units with the Clark Fork channel for the left and right bank (developed from GIS query);
- estimated thickness of tailings, mixed soil/tailings, and cover soil in each soil map unit (from regression model developed from the soil-morphology data collected from soil pits); and
- the distance of migration of metals into soils buried beneath tailings layers (based on analysis of total metals in buried soil).

Estimated bank metal concentrations are summarized in table 6. The predicted metal concentrations were lower than those obtained for banks in the same river reach by Moore (1985) and Axtmann and Luoma (1991). The lower metal concentrations estimated by Schafer and Associates (1997b) may result from the various sampling strategies used among the three studies. Moore (1985) analyzed bulk samples that were collected from fine-grained layers in only the mid and upper portion of the bank and that were thought to represent recently deposited material. By not sampling coarse material, concentrations may have been biased high relative to the complete range of sediment sizes present in the banks. Axtmann and Luoma (1991) collected composite samples from that part of the streambank that was above water and below the root zone and analyzed only the <60-µm fraction. Similarly, analyzing only the <60-µm fraction may have caused a high bias relative to the bulk metal concentrations. Samples collected by Schafer and Associates (1997b) were composited from the entire bank, and bulk samples were analyzed. Moore (1985) and Axtmann and Luoma (1991) also sampled cut banks, and therefore, sampling locations potentially were biased toward areas with more tailings, whereas all bank types were used in the estimation procedure of Schafer and Associates (1997b).

The estimated metals concentrations can also be compared to the average metals concentrations in suspended sediment in the river (table 6). Lead concentrations in left and right banks generally are similar to lead concentrations in suspended sediment in the river. The similarity indicates that bank erosion may be the primary source of lead. Zinc concentrations in suspended

Table 6. Comparison of estimated metal concentrations in banks and suspended sediment from several studies of the Clark Fork upstream from Garrison, Montana

[Symbol: --, no data]

Sample source	Data source	Estimated concentration (milligrams per kilogram)			
		Cadmium	Copper	Lead	Zinc
Left bank	Schafer and Associates (1997b)	4.12	928	139	739
Right bank	Schafer and Associates (1997b)	4.10	899	136	718
Cut bank (4 samples)	Axtmann and Luoma (1991)	21.4	2,930	359	3,770
Cut bank (10 samples)	Moore (1985)	9.8	1,900	499	1,360
Suspended sediment at Clark Fork near Galen[1]	Hornberger and others (1997)	--	1,590	137	2,510
Suspended sediment at Clark Fork at Deer Lodge[1]	Hornberger and others (1997)	--	1,350	158	1,550

[1]Metal concentrations in suspended sediment were calculated by dividing the annual suspended-metal load by the annual suspended-sediment load. The suspended-copper load was reported by Hornberger and others (1997). For lead and zinc, the suspended loads were derived by assuming that dissolved loads were about 10 and 20 percent of the total-recoverable loads, based on median concentrations in periodic water samples (Dodge and others, 1997).

sediment are 2-3 times higher than in banks. This may indicate that either sources of zinc other than bank sediments are contributing a substantial portion of the zinc in surface water or that the differences in concentration are caused by grain-size differences between suspended and bank sediments. Results for copper are intermediate between lead and zinc.

METAL TRANSPORT

Tracking the movement of metals past multiple locations in the upper Clark Fork basin is essential to understanding the relative importance of individual source areas and how transport rates vary with streamflow. Metal transport in the Clark Fork is controlled primarily by the supply and input rates of metal from various sources in the basin, the strong tendency for metals to be associated with sediment, and the downstream transport of water and sediment. The dynamic balance of these multiple transport processes, shown in figure 9, determines the overall flux of metals in the Clark Fork.

Metal transport in the Clark Fork: 1991 to 1995

The fluvial transport of suspended sediment and total-recoverable copper, lead, and zinc have been estimated from water-quality and continuous streamflow data collected as part of a long-term monitoring network for water years 1985-90 (Lambing, 1991) and for 1991-95 (Hornberger and others, 1997). Because the monitoring network included more data-collection sites in the later period, the discussion presented here is for 1991-95. Daily loads of suspended sediment and metals were estimated for each gaged mainstem and tributary station by applying transport relations to daily records of streamflow. The daily loads were summed and expressed as an average annual load for the period. The difference in load between mainstem stations, after subtracting loads from the tributaries, was attributed to "other sources" in the intervening reach between mainstem stations. Estimated average annual suspended-sediment and metals loads and relative percent of the total downstream load at the Clark Fork at Turah Bridge (the downstream end of the study reach) are presented in tables 7 through 10. Total-recoverable metal loads include the combined load of metals in the dissolved and suspended forms.

Sources of metals

Characterization of metals transport in the Clark Fork required quantifying the loads of dissolved and particulate metals entering the river from all important sources. Metal sources considered were inflow from headwater streams (Warm Springs and Silver Bow Creeks) and tributaries, overland runoff from the flood plain, ground-water and bank-storage inflow, material eroded from banks, and sediment exchanged from the streambed (fig. 9). Some of these sources were newly evaluated as part of this project, whereas some were

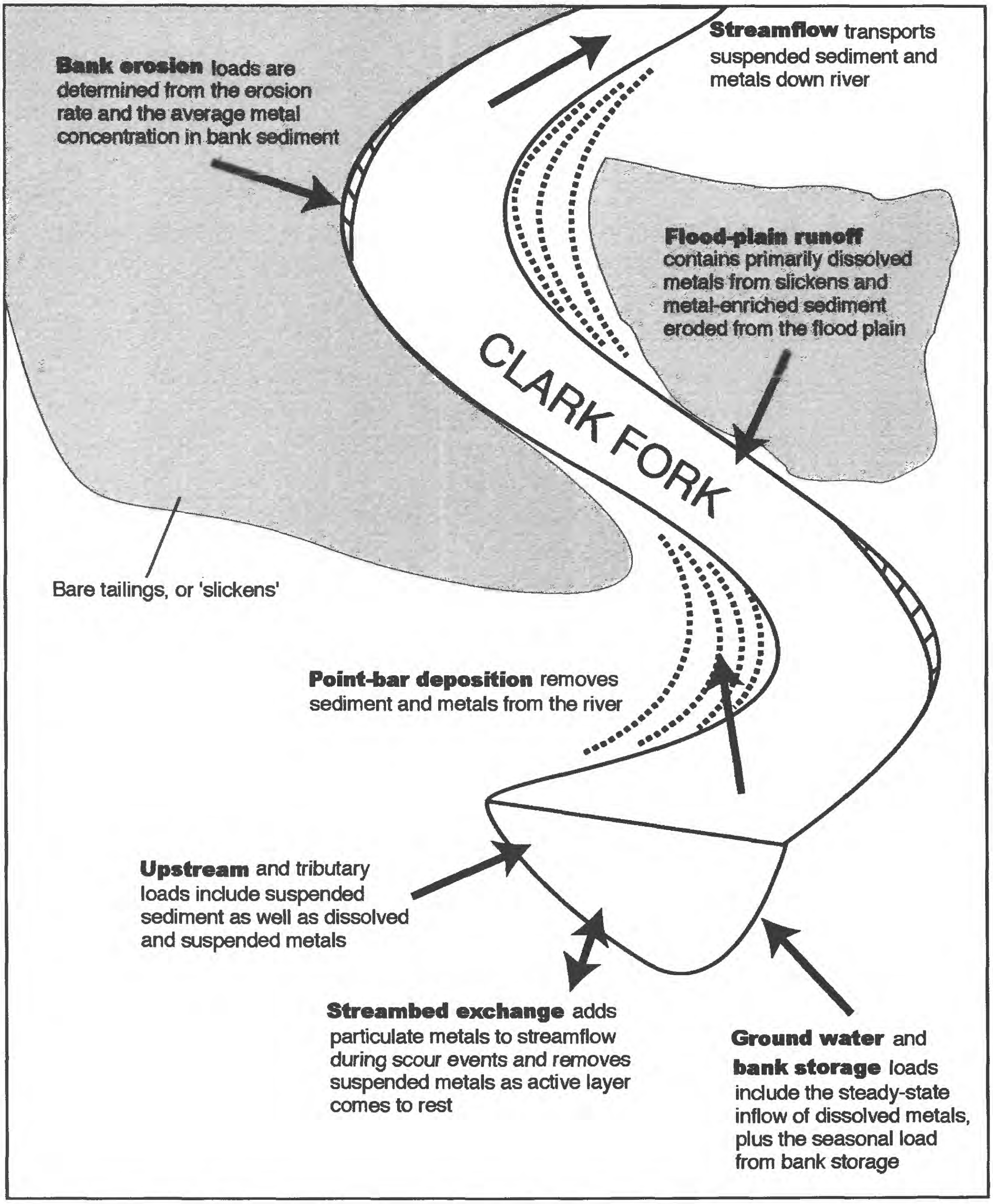

Figure 9. Conceptual diagram showing metal-transport processes in the Clark Fork valley, Montana.

Table 7. Estimated average annual suspended-sediment loads and percent of total load at Clark Fork at Turah Bridge, Montana, water years 1991-95 (modified from Hornberger and others, 1997)

Location (fig. 1)	Station number	Average annual suspended-sediment load and percent of total load at downstream end of study reach (Turah Bridge)			
		Mainstem station (tons/year)	Tributary station (tons/year)	Other sources (tons/year)[1]	Percent of total suspended-sediment load[2]
Silver Bow Creek at Warm Springs[3]	12323750	832			2.5
Warm Springs Creek at Warm Springs	12323770		598		1.8
Intervening reach (4.2 miles)				543	1.7
Clark Fork near Galen	12323800	1,970			6.0
Intervening reach (24.8 miles)				5,430	17
Clark Fork at Deer Lodge	12324200	7,400			22
Little Blackfoot River near Garrison	12324590		3,380		10
Intervening reach (25.5 miles)				4,340	13
Clark Fork at Goldcreek	12324680	15,100			46
Flint Creek near Drummond	12331500		2,900		8.8
Intervening reach (31.3 miles)				6,900	21
Clark Fork near Drummond	12331800	24,900			76
Rock Creek near Clinton	12334510		4,560		14
Intervening reach (33.4 miles)				3,450	10
Clark Fork at Turah Bridge	12334550	32,900			100

[1]Other sources of load in the intervening reach between mainstem stations include the channel and flood plain, ungaged tributaries, and ground water. Loads from intervening reaches represent the difference in loads between mainstem stations, minus the load from gaged tributaries entering the reach.
[2]Percentages may not sum to 100 owing to rounding.
[3]For purposes of load routing, Silver Bow Creek is treated as a mainstem station.

Table 8. Estimated average annual total-recoverable copper loads and percent of total load at Clark Fork at Turah Bridge, Montana, water years 1991-95 (modified from Hornberger and others, 1997)

Location (fig. 1)	Station number	Total-recoverable copper load and percent of total load at downstream end of study reach (Turah Bridge)			
		Mainstem station (tons/year)	Tributary station (tons/year)	Other sources (tons/year)[1]	Percent of total-recoverable copper load[2]
Silver Bow Creek at Warm Springs[3]	12323750	2.1			9.5
Warm Springs Creek at Warm Springs	12323770		0.6		2.7
Intervening reach (4.2 miles)				1.2	5.5
Clark Fork near Galen	12323800	3.9			18
Intervening reach (24.8 miles)				7.9	36
Clark Fork at Deer Lodge	12324200	11.8			54
Little Blackfoot River near Garrison	12324590		.3		1.4
Intervening reach (25.5 miles)				1.7	7.7
Clark Fork at Goldcreek	12324680	13.8			63
Flint Creek near Drummond	12331500		.4		1.8
Intervening reach (31.3 miles)				3.6	16
Clark Fork near Drummond	12331800	17.8			81
Rock Creek near Clinton	12334510		.7		3.2
Intervening reach (33.4 miles)				3.5	16
Clark Fork at Turah Bridge	12334550	22.0			100

[1]Other sources of load in the intervening reach between mainstem stations include the channel and flood plain, ungaged tributaries, and ground water. Loads from intervening reaches represent the difference in loads between mainstem stations, minus the load from gaged tributaries entering the reach.
[2]Percentages may not sum to 100 owing to rounding.
[3]For purposes of load routing, Silver Bow Creek is treated as a mainstem station.

Table 9. Estimated average annual total-recoverable lead loads and percent of total load at Clark Fork at Turah Bridge, Montana, water years 1991-95 (modified from Hornberger and others, 1997)

Location (fig. 1)	Station number	Total-recoverable lead load and percent of total load at downstream end of study reach (Turah Bridge)			
		Mainstem station (tons/year)	Tributary station (tons/year)	Other sources (tons/year)[1]	Percent of total-recoverable lead load[2]
Silver Bow Creek at Warm Springs[3]	12323750	0.1			2.4
Warm Springs Creek at Warm Springs	12323770		0.1		2.4
Intervening reach (4.2 miles)				0.1	2.4
Clark Fork near Galen	12323800	.3			7.3
Intervening reach (24.8 miles)				1.0	24
Clark Fork at Deer Lodge	12324200	1.3			32
Little Blackfoot River near Garrison	12324590		.2		4.9
Intervening reach (25.5 miles)				.4	9.8
Clark Fork at Goldcreek	12324680	1.9			46
Flint Creek near Drummond	12331500		.7		17
Intervening reach (31.3 miles)				.7	17
Clark Fork near Drummond	12331800	3.3			80
Rock Creek near Clinton	12334510		.3		7.3
Intervening reach (33.4 miles)				.5	12
Clark Fork at Turah Bridge	12334550	4.1			100

[1]Other sources of load in the intervening reach between mainstem stations include the channel and flood plain, ungaged tributaries, and ground water. Loads from intervening reaches represent the difference in loads between mainstem stations, minus the load from gaged tributaries entering the reach.
[2]Percentages may not sum to 100 owing to rounding.
[3]For purposes of load routing, Silver Bow Creek is treated as a mainstem station.

Table 10. Estimated average annual total-recoverable zinc loads and percent of total load at Clark Fork at Turah Bridge, Montana, water years 1991-95 (modified from Hornberger and others, 1997)

Location	Station number	Total-recoverable zinc load and percent of total load at downstream end of study reach (Turah Bridge)			
		Mainstem station (tons/year)	Tributary station (tons/year)	Other sources (tons/year)[1]	Percent of total-recoverable zinc load[2]
Silver Bow Creek at Warm Springs[3]	12323750	4.7			13
Warm Springs Creek at Warm Springs	12323770		0.5		1.3
Intervening reach (4.2 miles)				1.0	2.7
Clark Fork near Galen	12323800	6.2			17
Intervening reach (24.8 miles)				8.1	22
Clark Fork at Deer Lodge	12324200	14.3			38
Little Blackfoot River near Garrison	12324590		1.0		2.7
Intervening reach (25.5 miles)				4.6	12
Clark Fork at Goldcreek	12324680	19.9			53
Flint Creek near Drummond	12331500		2.6		6.9
Intervening reach (31.3 miles)				8.9	24
Clark Fork near Drummond	12331800	31.4			84
Rock Creek near Clinton	12334510		2.2		5.9
Intervening reach (33.4 miles)				3.9	10
Clark Fork at Turah Bridge	12334550	37.5			100

[1]Other sources of load in the intervening reach between mainstem stations include the channel and flood plain, ungaged tributaries, and ground water. Loads from intervening reaches represent the difference in loads between mainstem stations, minus the load from gaged tributaries entering the reach.
[2]Percentages may not sum to 100 owing to rounding.
[3]For purposes of load routing, Silver Bow Creek is treated as a mainstem station.

evaluated previously as part of the ongoing remedial investigation for this Superfund site.

Upstream sources

The upstream input of sediment and metals to the Clark Fork is derived from the headwater basins of Silver Bow and Warm Springs Creeks. These streams drain the extensive areas associated with the Butte-Anaconda mining and smelting complex. The Warm Springs Ponds capture a portion of the sediment and metals transported down Silver Bow Creek; thus, the current annual loading to the Clark Fork is less than the historical, pre-impoundment loading prior to 1911, when the first of three ponds was constructed.

Silver Bow and Warm Springs Creeks collectively transported an average of 1,430 tons of suspended sediment annually during 1991-95, which represented about 4 percent of the sediment passing the downstream end of the Clark Fork study reach at Turah Bridge. The copper delivered from these headwater basins (2.7 tons) represented about 12 percent of the annual copper load at Turah Bridge. The combined headwater loads of lead (0.2 tons) and zinc (5.2 tons) represented about 5 and 14 percent, respectively, of the loads at Turah Bridge. The most upstream station on the mainstem, Clark Fork near Galen, receives the upstream inputs from the two headwater basins, plus additional material derived from the 4.2-mile intervening reach downstream from the Silver Bow Creek station. This short reach contributed an average of 543 tons of suspended sediment and 1.2 tons of copper annually, which represented about 2 and 5 percent of the sediment and copper loads, respectively, at Turah Bridge (Hornberger and others, 1997).

Tributary sources

Major tributaries. The major tributaries to the Clark Fork between Galen and Turah Bridge (Little Blackfoot River, Flint Creek, and Rock Creek) currently are sampled as part of the USGS long-term monitoring program. The moderate to large inflows from these tributaries substantially affect water quantity and quality in the mainstem and add to the mainstem loads of sediment and metals (Hornberger and others, 1997). Smaller, ungaged tributaries affect the mainstem to an unknown, but presumably lesser, extent.

Tributaries contribute the greatest loads during snowmelt runoff, which is commonly augmented by rainfall runoff during the spring. Mountain snowmelt typically occurs between April and June, although early thaws can cause substantial runoff from valleys and foothills during the winter. The three major tributaries collectively discharged an average of almost 11,000 tons of suspended sediment annually during 1991-95, or about 33 percent of the sediment load passing Turah Bridge (table 7). In contrast, the average annual copper load contributed by the three tributaries (1.4 tons) accounted for only 6 percent of the load at Turah Bridge (table 8). This disparity in proportion of sediment and copper loads indicates that the major tributaries are not significant sources of copper in the Clark Fork.

The three major tributaries collectively contributed substantially larger proportions (2-5 times) of lead and zinc to the mainstem compared to copper: 29 percent of the lead load and 15 percent of the zinc load at Turah Bridge during 1991-95. Flint Creek accounted for 17 percent of the lead at Turah Bridge, which is the largest tributary contribution of metal and more than three times the combined load from Silver Bow and Warm Springs Creeks. The relatively large load of lead in Flint Creek presumably is related to mineralization and associated historical mining in this basin.

Ungaged tributaries. To better evaluate the relative importance of sediment inputs from ungaged tributaries within intervening reaches, nine tributaries in the upper Deer Lodge valley between Galen and Deer Lodge were sampled in 1996 (J.H. Lambing, U.S. Geological Survey, unpub. data). Tributaries in the upper valley consist primarily of perennial streams that drain the Flint Creek Range, and ephemeral streams that drain either the Continental Divide area to the east or the semi-arid terraces on both flanks of the valley bottom. The east-side tributaries were not sampled because all are ephemeral and flow for only very short periods. Ungaged perennial streams draining the west side of the Deer Lodge valley were sampled five times during February to June, and ephemeral west-side tributaries were sampled once during snowmelt runoff in February. The sampling period represents the time when the tributaries were most likely to contribute maximum amounts of sediment to the mainstem.

All west-side tributaries were sampled within one-day periods for the five sampling episodes; therefore, the data represent synoptic conditions. The suspended-sediment loads for each tributary were added together to derive an estimate of the total west-side tributary input for each of the five sampling dates. The combined sediment loads from the tributaries were correlated by regression analysis to the daily sediment loads measured at the Clark Fork at Deer Lodge (a daily sediment station) for the same five days. The resulting transport relation ($r^2 = 0.92$) was applied to the daily sediment record for Deer Lodge to estimate a daily record of combined ungaged tributary suspended-sediment load. A daily sediment record also was estimated for the Clark Fork near Galen (Lambing, 1998) using correlation between suspended-sediment discharge and streamflow data routinely collected at this site as part of the USGS monitoring program. The estimated daily ungaged tributary loads and daily loads from the Clark Fork near Galen were summed into monthly and annual values to determine the proportion of the total suspended-sediment load at Deer Lodge that was derived from the west-side tributaries in the intervening reach and upstream input to the reach. These calculations (J.H. Lambing, written commun., 1997) indicate that the west-side tributaries contributed 2,120 tons in 1996 to the reach between Galen and Deer Lodge, or about 11 percent of the total sediment load at Deer Lodge. The upstream input at the Clark Fork near Galen accounted for about 19 percent of the annual load at Deer Lodge; therefore, 70 percent of the suspended-sediment load at Deer Lodge was derived from sources other than the upstream input to the reach or west-side tributaries.

Similar methods were used to generate a regression relation ($r^2 = 0.89$) for estimating streamflow contributions from the west-side tributaries (J.H. Lambing, written commun., 1997). Streamflow sources exhibited quite different proportional patterns than those of suspended sediment. Whereas the combined suspended-sediment load from the upstream input and west-side tributaries comprised only 30 percent of the load at Deer Lodge, streamflow from these two sources accounted for 88 percent of the total streamflow at Deer Lodge. The disproportionately greater input of water than sediment indicates that a major sediment source exists in the upper Deer Lodge valley that is not associated with the primary sources of water. This sediment presumably is derived either from erosion of high terraces adjacent to the river or from inflow of east-side tributaries, which are ephemeral.

Metals in perennial west-side tributaries were sampled once in June 1996 during snowmelt runoff from the Flint Creek Range. Total-recoverable copper concentrations ranged from <1 to 57 μg/L. The sample concentrations and streamflow were used to calculate instantaneous total-recoverable copper loads from the west-side tributaries, which were summed to obtain a combined load for the sampling date. This estimated daily load was compared to the estimated daily copper load at Deer Lodge for the same date determined from a copper-transport equation developed for the site (Lambing, 1998). The combined west-side tributary daily copper load for the single sampling date represented 3 percent of the daily copper load at Deer Lodge. On the basis of this single sampling episode for copper, the ungaged west-side tributaries do not appear to be a significant copper source.

Mainstem sources

The network of tributary and mainstem sampling sites allows an accounting of cumulative load increases from the upstream input to the downstream output of the Clark Fork study reach (Warm Springs to Turah Bridge). The difference in loads between successive mainstem sites, after subtracting gaged tributary loads, indicates the input of suspended sediment and metals from the intervening reaches of the Clark Fork. Sources within intervening reaches can include ungaged tributaries, flood-plain runoff, sediment eroded from the streambanks and bed, or ground water. Contributions from each specific source cannot be directly quantified from the monitoring data; however, on the basis of limited sampling (described in previous section), sediment and metal inputs from ungaged tributaries are assumed to be small.

The intervening reaches contributed substantial amounts of suspended sediment, accounting for an average annual load of about 20,700 tons during 1991-95 (Hornberger and others, 1997). This amount represented about 63 percent of the average annual load of 32,900 tons at Turah Bridge (table 7). The copper load from intervening reaches (17.9 tons, table 8) accounted for 81 percent of the average annual load at Turah Bridge. The lead and zinc loads from intervening reaches represented 66 (table 9) and 71 (table 10) percent of the total load, respectively.

Because the lengths of intervening reaches vary, loads expressed on a unit-length basis can be used to compare differences in the yield of suspended sediment and metals along the 120-mile reach between Silver Bow Creek at Warm Springs and the Clark Fork at Turah Bridge. Estimates of sediment and metal inputs, in tons per river mile, are presented in table 11.

Suspended-sediment inputs, in tons per river mile, varied among the five intervening reaches. In general, differences in unit-length sediment loads were only moderate, ranging from 103 to 220 tons per mile with no distinct spatial pattern, although the middle three reaches from Galen to Drummond had the highest yields. In contrast, the copper yield was higher in the two upstream reaches between Silver Bow Creek and Deer Lodge. The yields of about 0.3 tons of copper per mile from both of these reaches were about 3-5 times greater than yields from the downstream reaches between Deer Lodge and Turah Bridge. Patterns in lead yields were not clearly discernible owing to the small values, however, the highest yield of lead (0.04 tons per mile) was from the reach between Galen and Deer Lodge and was about double that of most other reaches. Zinc yields ranged from about 0.1 to 0.3 tons per river mile and generally varied in a spatial pattern similar to that for suspended sediment.

The general estimates of sediment and metal inputs based on load differences between the mainstem sampling sites indicate that a substantial amount of sediment and metals are derived from sources other than the upstream headwater basins or the major tributaries. The following sections present information that describes the estimated inputs from specific sources within the mainstem corridor of the Clark Fork.

Surface runoff from the Clark Fork flood plain. Surface runoff from the flood plain can carry metals in dissolved form or in suspension attached to eroded sediment. The loading of particulate metals from eroded flood-plain sediment depends on the erosivity of the metal-enriched layers. Because most metal-enriched flood-plain soils are well-vegetated and have slopes less than 2 percent, rates of metal loading from surficial erosion generally are small. However, runoff from exposed tailings at unvegetated slickens (fig. 2) typically contains high concentrations of dissolved metals and is considered the largest surface-runoff source of metals to the river. Copper loads in surface runoff from the Clark Fork flood plain were estimated by adding dissolved metal loads calculated for runoff from slickens areas (191 acres, table 4) and total copper loads calculated for sediment eroded from the vegetated remainder of the flood plain having a tailings horizon (3,338 acres).

Schafer and Associates (1996) measured substantial mass loads of dissolved metals in runoff from slickens during 1994-96 in response to summer thunderstorms in a small (0.9 acre), untreated watershed on the Clark Fork flood plain near Galen. Runoff volume and chemistry from this gaged microwatershed were used to characterize runoff from other slickens areas in the valley by extrapolating the average copper-loading rate determined from these data to the total area of slickens that could potentially produce runoff to the river (Titan Environmental, 1997). The estimated copper load from exposed tailings along the upper Clark Fork flood plain between Warm Springs Creek and Deer Lodge was 1.95 tons/year, whereas the estimated copper load from exposed tailings on the flood plain between Deer Lodge and Drummond was 2.1 tons/year. No slickens have been observed along the Clark Fork flood plain below Drummond. Therefore, a total copper load of 4.0 tons/year from exposed tailings was estimated for the entire 120-mile flood plain (Titan Environmental,

Table 11. Estimated average annual suspended-sediment and total-recoverable metal yields, in tons per river mile, transported in the Clark Fork, Montana, water years 1991-95 (from Hornberger and others, 1997)

Intervening reach between mainstem stations (fig. 1)	Average annual yield (tons per river mile)[1]			
	Suspended sediment	Copper	Lead	Zinc
Silver Bow Creek at Warm Springs to Clark Fork near Galen (4.2 miles)	129	0.29	0.02	0.24
Clark Fork near Galen to Clark Fork at Deer Lodge (24.8 miles)	219	.32	.04	.33
Clark Fork at Deer Lodge to Clark Fork at Goldcreek (25.5 miles)	170	.07	.02	.18
Clark Fork at Goldcreek to Clark Fork near Drummond (31.3 miles)	220	.12	.02	.28
Clark Fork near Drummond to Clark Fork at Turah Bridge (33.4 miles)	103	.10	.01	.12

[1]Yields from intervening reaches represent a unit-length input expressed as the average annual load originating from the reach, in tons, divided by the reach length, in river miles. Expressing yields in this manner assumes that sediment and metals are derived primarily from channel and flood-plain sources.

1997). This input represents about 18 percent of the copper load at Turah Bridge.

Loads from vegetated tailings areas of the flood plain were estimated using the revised Universal Soil Loss Equation (Titan Environmental, 1997). Based on the equation, 38.7 tons of soil are eroded from the flood plain annually (Titan Environmental, 1997). Assuming an average soil copper concentration for cover soil of 1,980 mg/kg (table 5), copper eroded from vegetated tailings would equal about 0.08 tons/year, which is a negligible amount relative to runoff from slickens. Therefore, the estimated average annual copper load in surface runoff from the Clark Fork flood plain between Warm Springs and Turah Bridge is 4.0 tons/year.

Ground water. Metal transport in ground water can be evaluated for two different flow conditions. The Clark Fork is the discharge area for shallow ground water in the valley, and for much of the year, ground water flows to the river (Nimick and others, 1993). Metals leached from flood-plain tailings to this ground water potentially could be transported to the river. When the river stage increases during spring snowmelt, ground-water gradients may be reversed near the river, leading to flow from the river to ground water, or bank storage. If metal-enriched sediments are saturated by bank storage, extractable metals conceivably could be mobilized and carried in dissolved form to the river when the river stage declines and reversal of hydraulic gradients causes bank storage to discharge back to the river.

On the basis of sampling results from monitoring wells completed in gravel underlying flood-plain deposits, elevated metal concentrations are uncommon in shallow ground water along the Clark Fork (Nimick and others, 1993; Schafer and Associates, 1997c). However, elevated concentrations are most likely to occur in the shallowest part of the ground-water system, which is in closest proximity to the flood-plain tailings and for which few data are available.

Schafer and Associates (1997c) estimated the mass load of metals reaching the Clark Fork from the shallow ground-water system. Shallow ground water is defined as ground water that is less than approximately 30 feet below ground surface within the 100-year flood plain. A conceptual model similar to the model presented in Brooks and Moore (1989) for the shallow ground-water system was developed from information collected during the installation of observation wells and aquifer analysis performed at a micro-watershed site on the Clark Fork flood plain near Galen (Schafer and Associates, 1996). Drill logs indicated that the shallow alluvial ground-water system includes three distinct hydrologic/soil units, or layers. The top unit is composed primarily of tailings material. This layer has low hydraulic conductivity and is only partially and seasonally saturated at the site. The site does not have a well-developed buried soil beneath the tailings material, in contrast to most observed soil profiles in the flood plain where tailings are present. The second layer consists of a mixture of sand, gravel, and fines and has a moderate hydraulic conductivity. Commonly, the top portion of the second layer is unsaturated. The third layer is saturated and is dominated by clean sand with a high hydraulic conductivity. Some zones in this layer contain mixtures of sand, gravel, and cobbles.

Ground-water flux was determined with Darcy's Law using the near-stream hydraulic gradient and hydrologic properties derived from measurements and aquifer tests in shallow wells completed in the flood plain. Metal loads were determined by multiplying ground-water flux by metal concentrations typical for the shallow ground water (Schafer and Associates, 1997c). The variability in available chemical and hydrologic data was described using population-frequency distributions. A Monte Carlo simulation was performed to determine the range in possible ground-water mass loads for key metals. The flux of shallow ground water and metals from the three layers were summed for each river segment.

The estimated ground-water flux determined for the shallow ground-water system was 175 ft^3/s (Schafer and Associates, 1997c). This estimate is similar to the estimate of 180 ft^3/s calculated by Nimick and others (1993) from synoptic streamflow measurements made during base-flow conditions in late October 1986. The 1986 estimate was calculated as the difference between total streamflow at Turah Bridge and the sum of all measured tributary inflows. On the basis of the close agreement of these two independent estimates, the estimated values of ground-water flux appear to be reasonable.

The estimated total arsenic and metal loads from ground water that are transported annually in the streamflow at Turah Bridge are presented in table 12. The median copper load from ground water at Turah Bridge is 1.46 tons/year. With respect to the overall load carried by the Clark Fork (tables 8-10), ground water is not a primary source of copper and lead, accounting for about 7 percent of the total load at Turah Bridge. The median zinc load from ground water, however, represents almost half of the 1991-95 average load in the Clark Fork at Turah Bridge. The groundwater loads listed in table 12 may overestimate actual loads because geochemical attenuation within the aquifer was not considered in the calculations.

Schafer and Associates (1997d) used seasonal changes in ground-water gradient, flow direction, and chemistry in 1997 at two instrumented microwatersheds near Galen to assess the importance of bank storage as a potential transport mechanism. The shallow ground-water flow direction and gradient did not change appreciably when the shallow ground-water elevations changed in response to increases and decreases in river stage. Water samples collected from shallow monitor wells indicated no change in chemistry in response to changes in river stage and groundwater elevation. Because ground-water gradients and ground-water flux did not increase and because concentrations of constituents of concern did not appear to increase when river stage and ground-water elevation increased during spring runoff, little increase in load is expected as a result of changes in river stage. Therefore, bank storage likely has little effect on the metal loads transported by ground water to the river.

Bank erosion. Meander migration resulting in bank erosion and point-bar deposition is a natural process in meandering rivers (Leopold and others, 1964). However, because the Clark Fork flood plain contains tailings and soils with elevated metals concentrations, this process provides a mechanism for delivering metal-enriched sediment to the river. Estimating the metal transport and loading from this erosional process required data characterizing the annual bank erosion rates along the Clark Fork, as well as data describing the metal concentrations in the banks (see "Estimated metal concentration in banks" section) for both the silt and sand fractions.

R2 Resource Consultants (1997) estimated average annual meander-migration rates for Reach A (fig. 1) of the Clark Fork by quantifying the change in position of the river channel shown in aerial photographs taken in 1960 and 1989 (fig. 10). Stream segments affected by channel cutoffs, avulsions, island formations, or other signs of channel alterations were not included in the analysis (approximately 2 miles of the 43-mile reach). Meander-migration rates were estimated about every 20 feet along the center line of the 1989 river channel and are shown on detailed maps in R2 Resource Consultants (1997). The estimated rates may overestimate long-term rates because streamflow during 1960-89 was slightly higher than the long-term period of record (1930-95) for the Clark Fork above Missoula (fig. 11). Additional information on bank erosion is available from a study in which actively eroding banks were identified visually and field mapped (University of Montana, 1996).

Estimated average annual meander-migration rates ranged from 0 to 5.8 ft/year (fig. 12), with an average rate of 0.6 ft/year over the 43-mile reach. Table 13 classifies the meander-migration rates along the river into five categories. The table also presents the total length of streambank within each category and the proportion of the total river length each category represents. Erosion from the total length of streambank

Table 12. Estimated trace-element loads in the Clark Fork at Turah Bridge, Montana, derived from ground water (modified from Schafer and Associates, 1997c)

Trace element	Percentile range of load, in tons per year: 10%	Median (50%)	90%
Arsenic	0.26	0.90	3.41
Cadmium	.06	.16	.40
Copper	.46	1.46	5.20
Lead	.07	.30	1.79
Zinc	6.10	17.3	52.0

Figure 10. Aerial photograph of a section of the Clark Fork valley upstream from Deer Lodge, Montana, showing the change in channel position between 1960 and 1989 (modified from R2 Resource Consultants, 1997). Areas of greatest change in channel position represent locations with high rates of bank erosion.

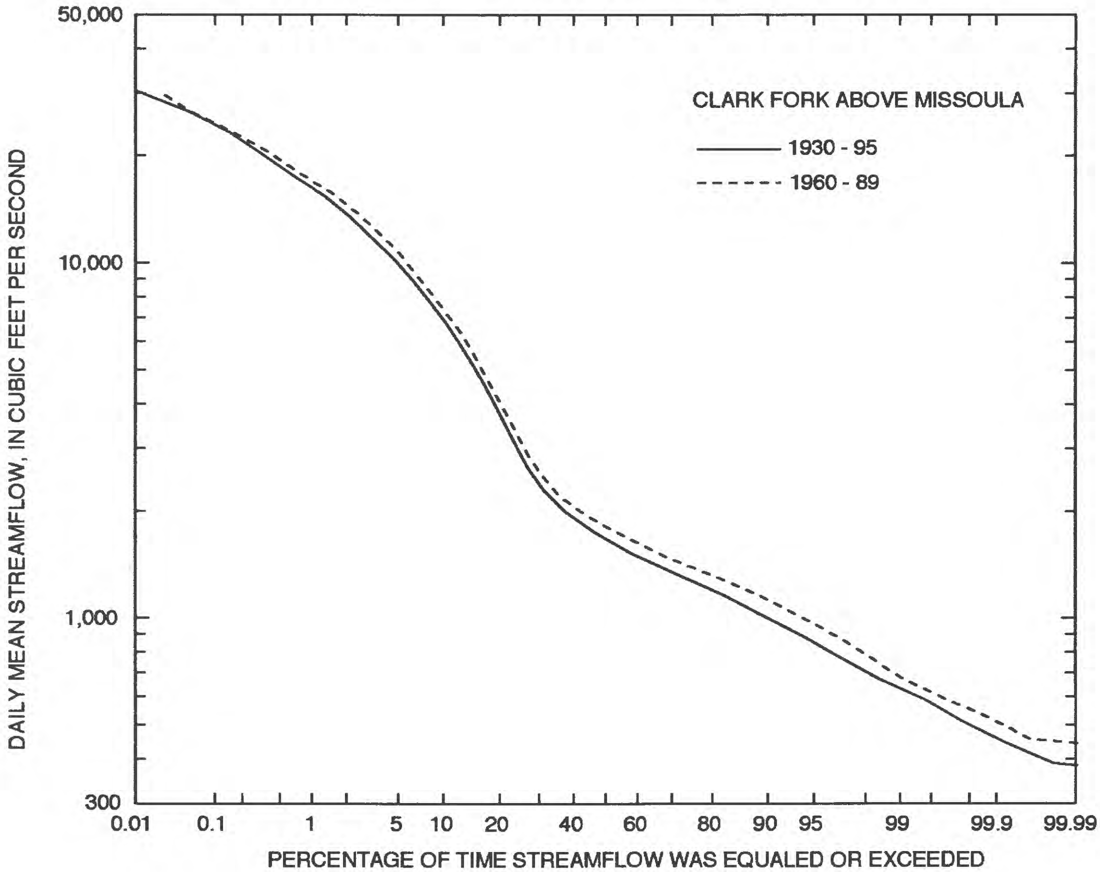

Figure 11. Streamflow-duration curves for the Clark Fork above Missoula (station 12340500), Montana, for the period of record (water years 1930-95) and the period between years of aerial photography (1960-89).

in each category introduces approximately the same amount of material to the river.

Streambed exchange. The streambed of the Clark Fork beneath the pebble and cobble armor layer presumably contains some metal-enriched sediments derived from historical deposition of tailings transported from the upper basin. During high flow, the armor layer may be mobilized locally, and it might be expected that the streambed would release stored metals through exchange processes and come to equilibrium with metal concentrations in the remaining sources below the ponds (flood plain, channel, tributaries, and ground water). However, the depth of possible scour and the concentration of metals in sediment in and below the armor layer have not been measured. Therefore, quantifying the release of metals from streambed exchange is difficult. Analysis of the metals mass balance for the river (see "Metals Mass Balance") suggested that bed sediment is a relatively minor source of the metals transported by the Clark Fork. Thus, quantifying bed-exchange processes probably is not critical to understanding the sources and overall transport of metals through the river system.

Metal-concentration data for Clark Fork bed sediment are available from several studies (Axtmann and Luoma, 1991; Brook, 1988; Davis, 1995; Dodge and others, 1997; and PTI, 1990). These data sets provide information for sediment collected from the active, or surficial, layer but not for sediment in or below the armor layer. Most of these data sets provide metal-concentration data for different sediment-size fractions. Metal concentrations in surficial bed sediment generally decrease in a downstream direction. In addition, metal concentrations in the fine-grained (silt-clay) fraction generally are several times higher than in the sand fraction for a particular location along the river.

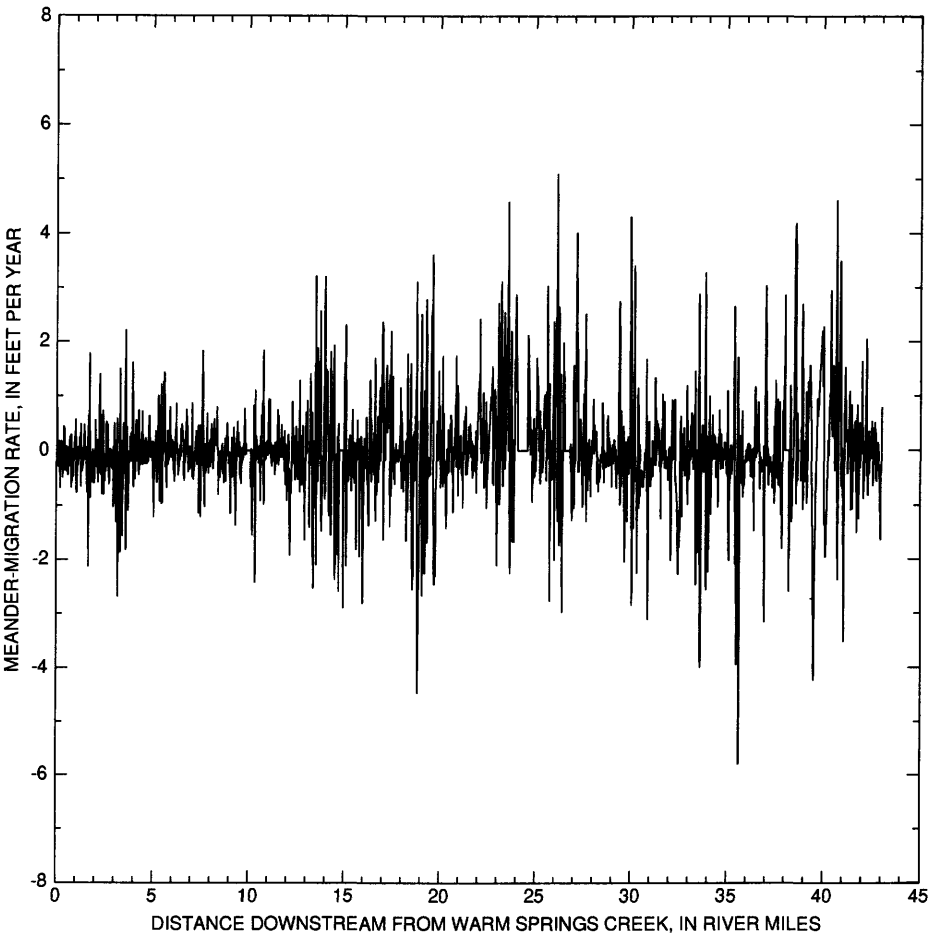

Figure 12. Historical meander-migration rates in Reach A of the Clark Fork, Montana, determined from 1960 and 1989 aerial photographs. A positive rate indicates migration towards the right bank (looking downstream); a negative rate indicates migration towards the left bank. (Modified from R2 Resource Consultants, 1997).

Table 13. Meander-migration rates in Reach A of the Clark Fork valley, Montana, determined from 1960 and 1989 aerial photographs (modified from R2 Resource Consultants, 1997)

Average annual meander-migration rate (feet/year)	Total length of streambank (miles)	Percent of total length
0-0.5	25.5	62.3
0.5-1.0	7.5	18.3
1.0-1.5	3.5	8.5
1.5-2.5	3.2	7.8
2.5-5.8	1.3	3.2
Total	[1]41.0	100.0

[1]Stream segments affected by channel cutoffs, avulsions, island formation, or other signs of channel alteration were not included in analysis (2 miles of the 43-mile reach)

METALS MASS BALANCE

To aid in the evaluation of metal supply, transport, and deposition in the Clark Fork, a mass-balance algorithm was developed to estimate the spatial and temporal transport of metal through the river. The algorithm was used to evaluate the mass balance of copper because copper occurs in water at measurable concentrations and exceeds aquatic-life criteria more frequently than other metals. The algorithm provides a tool to estimate the relative magnitude of inputs from various sources and to examine possible effects of changes in source inputs. The mass-balance calculations account for copper derived from headwater and tributary inflow, ground water, flood-plain runoff, erosion of tailings contained in streambanks, and exchange with mobile bed sediment. The algorithm was calibrated with 1985-95 data on suspended-sediment and 1991-95 data on total-recoverable copper loads (Lambing, 1991; Hornberger and others, 1997). The estimated loads then were used to evaluate the relative contribution of copper from different sources. The mass-balance computation simulates the physical transport of particulate copper because the suspended portion averages about 70-80 percent of total-recoverable copper in water-quality samples (Dodge and others, 1997). Owing to differences in transport characteristics and metal concentrations of different grain sizes, the transport of copper in the sand and silt-clay fractions is tracked separately. A brief description of the mass-balance calculations is presented in the rest of this section. For a more complete discussion, the reader is referred to R2 Resource Consultants (1998).

Description of mass-balance calculations

Mass balance was estimated using a one-dimensional algorithm that tracks transport of sediment and associated copper through the Clark Fork from the Warm Springs Ponds to Turah Bridge (R2 Resource Consultants, 1998). The algorithm consists of three major nested loops that cycle through the reaches of the river in one-mile increments, then through different hydrologic conditions, and finally through the years within a period of interest. Duration curves for streamflow and suspended-sediment discharge are used to distribute streamflow as well as suspended-sediment and copper loads throughout the year. Streamflow- and sediment-discharge-duration curves were developed for five control points that coincide with USGS streamflow-gaging stations along the Clark Fork. Duration curves for intermediate points at one-mile increments along the river were interpolated from the control-point duration curves using gaging records and a drainage-area relationship. The streamflow- and sediment-discharge-duration curves developed for each mile of the river were divided into 15 intervals, with the average streamflow and sediment discharge for each duration interval representing a specific hydrologic and sediment-transport condition occurring for a given length of time. Summation of the sediment loads derived from each duration interval produced a time- and discharge-weighted annual load passing each mile of the river.

Within each one-mile increment of the river channel and for each streamflow condition represented by the duration-curve intervals, the mass-balance algorithm mixes suspended sediment (silt/clay and sand fractions) transported from the upstream reach with sediment introduced from tributaries, eroded from the mainstem streambanks, and exchanged from the bed. An average copper concentration for each sediment source is used for the mixing calculation. Sediment-transport equilibrium is assumed, whereby the mixed sediment is redeposited on point bars at a rate roughly equal to the erosion rate that introduced the bank sediment to the system. The resulting copper concentration in the deposited material and in the suspended sediment transported downstream is assumed to be equal to the average copper concentration of the uniform mixture of sediment from all sources. For each streamflow condition, the quantity of sediment from bank erosion and the quantity of bed sediment available to mix with other sources varies with streamflow and associated shear stress on the bed and banks of the river. Temporal changes are simulated by sequentially repeating the flow-duration curve on an annual basis, thus allowing the algorithm to project future loading that would accompany changes in the magnitude of copper inputs as source conditions change. Individual components of the mass-balance calculations are further discussed in the following sections.

Suspended-sediment transport

Suspended-sediment transport was calculated using sediment-discharge-duration curves developed by combining flow-duration curves and sediment-rating curves for the five mainstem stations, or control points. Flow-duration curves were developed for two periods: (1) 1985-95 for mass-balance calibration with measured water-quality data, and (2) 1930-95 for calculating long-term mass balance using the longest available streamflow record in the upper Clark Fork basin (U.S. Geological Survey, issued annually). On the basis of long-term streamflow records for the Clark Fork above Missoula, streamflow during 1985-95 was substantially less than normal (fig. 13). Sediment-rating curves were developed for the Clark Fork at Deer Lodge and at Turah Bridge using log-log regressions of daily mean streamflow and daily suspended-sediment discharge computed by the USGS from daily or near-daily sediment samples (U.S. Geological Survey, issued annually). The sediment rating curves for these two stations were applied to the streamflow-duration curves to develop sediment-discharge duration curves for the 1985-95 and 1930-95 periods. Sediment-discharge duration curves for the other three control points on the Clark Fork mainstem (Galen, Goldcreek, and Drummond) were developed by applying a drainage basin relation to the duration curves for Deer Lodge and Turah Bridge. The resulting sediment-discharge-duration curves for the 1985-95 period for the five control points are shown in figure 14.

Average annual sediment loads were estimated at each control point along the Clark Fork by integrating the sediment-discharge- and streamflow-duration curves (table 14). Estimates of average annual sediment load at each gaging station using this methodology are presented in table 14 along with estimates from monitoring data for 1985-95. With the exception of the Clark Fork near Galen, the duration-curve estimates are reasonably close to monitoring-data estimates of annual suspended-sediment loads. The duration-curve estimate for Galen is double that of the monitoring-data estimate, which may affect some of the mass balance of

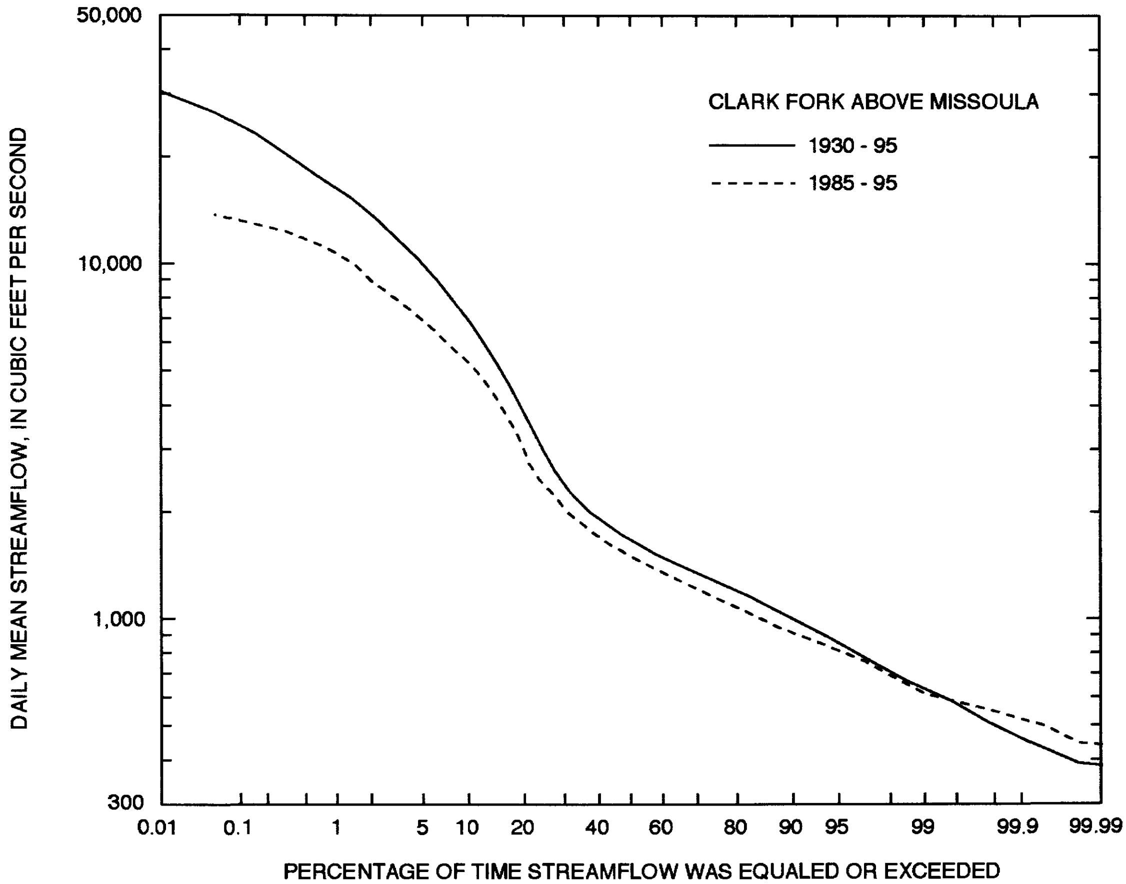

Figure 13. Streamflow-duration curves for the Clark Fork above Missoula (station 12340500), Montana, for the period of record (water years 1930-95) and the period of USGS sampling (water years 1985-95).

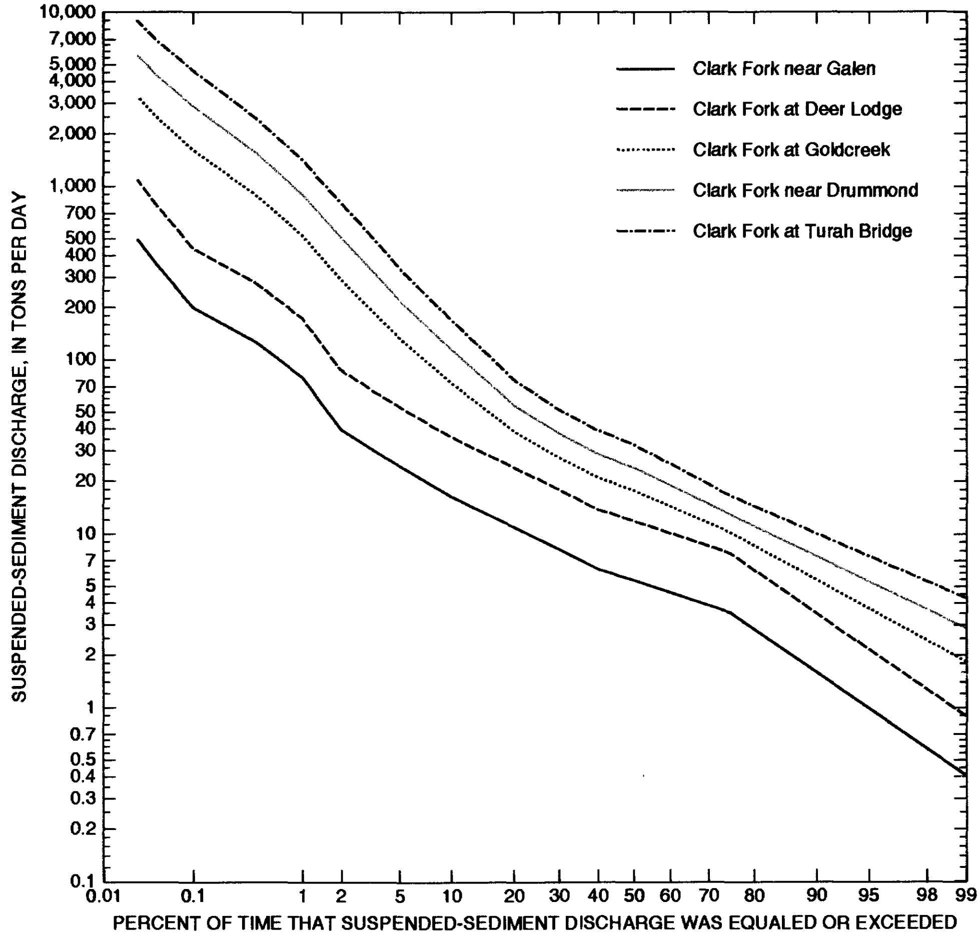

Figure 14. Duration curves for suspended-sediment discharge at five streamflow-gaging stations on the Clark Fork between Galen and Turah Bridge, Montana, water years 1985-95 (modified from R2 Resource Consultants, 1998).

Table 14. Comparison of average annual suspended-sediment loads estimated from monitoring data and from sediment-discharge-duration curves incorporated into mass-balance estimates for five streamflow-gaging stations on the Clark Fork, Montana (modified from R2 Resource Consultants, 1998)

Streamflow-gaging station (fig. 1)	Station number	Average annual suspended-sediment load (tons/year)		
		1985-95 monitoring-data estimate	Mass-balance estimate using 1985-95 duration curve	Mass-balance estimate using 1930-95 duration curve
Clark Fork near Galen	12323800	1,680	3,400	9,200
Clark Fork at Deer Lodge[1]	12324200	7,970	7,500	20,200
Clark Fork at Goldcreek[2]	12324680	15,100	16,200	49,900
Clark Fork near Drummond[2]	12331800	24,900	25,700	81,800
Clark Fork at Turah Bridge[1]	12334550	38,500	38,700	126,000

[1]Daily sediment station where daily or near-daily suspended-sediment samples were collected.
[2]Monitoring data available only for 1991-95.

source inputs apportioned in the reach from Galen to Deer Lodge.

Bank erosion

Copper loads introduced through bank erosion in Reach A were determined as a function of river mile by combining estimated meander-migration rates ("Bank Erosion" section) and average streambank copper concentrations for the left and right banks ("Estimated Metal Concentration in Banks" section, table 6). In Reaches B and C, migration rates and bank copper concentrations were roughly estimated based on limited available data.

Bank-erosion rates in Reach A were estimated from available aerial photographs for the period between 1960 and 1989 (R2 Resource Consultants, 1997). Because bank erosion rates are dependent on streamflow conditions and because the sediment-sampling period of 1985-95 was relatively dry compared to long-term conditions (fig. 13), the measured erosion rates for 1960-89 were adjusted downward to better represent 1985-95 hydrologic conditions. The adjustment was based on an integration of the flow-duration curves with the erosion rate scaled with water velocity in excess of a mobilization threshold (R2 Resource Consultants, 1998). Using this scaling technique, the average annual erosion rates for the period 1985-95 were estimated to be only 15 percent of rates measured for the 1960-89 period. Likewise, streamflow for the long-term period (1930-95) was slightly lower than during 1960-89, and the long-term erosion rates were estimated to be 84 percent of the erosion rates for 1960-89. For the mass-balance calculation, measured migration rates at each location along the Clark Fork were adjusted using the scaling factors computed in this manner.

Streambed sediment

To account for copper loading from sediment mobilized from below the armor layer of the streambed, information was needed to describe the copper concentration in the bed and the mechanism for sediment exchange. During development of the mass-balance algorithm, it became apparent that the initial copper concentrations assigned to streambed sediment had a significant effect on copper loads for the first few simulated years. Because monitoring data for copper concentrations in bed sediment collected above the armor layer have considerable scatter (fig. 15) and because no metal-concentration data exist for sediment below the armor layer, an alternative approach was used to derive initial streambed copper concentrations for the mass balance. The algorithm simulated 100 years of sediment exchange using estimated historical (elevated over current) copper loads, thus achieving a steady-state condition with copper concentrations in streambed sediment in equilibrium with the current (post-1990) copper loads transported (Hornberger and others, 1997). These steady-state streambed copper concentrations were then used as the initial conditions for the calculation of current mass balance and future conditions.

Sediment exchange between the streambed and sediment in suspension was calculated utilizing a depth-dependent sediment-availability function, because sediment lying deeper beneath the armor layer is less available for mixing than sediment immediately beneath the layer. The thickness of the streambed layer involved in sediment exchange was assumed to increase with increasing streamflow. For streamflow less than that needed to mobilize the armor layer, the thickness of the exchanging layer was assumed to be one-half of the 90th percentile diameter (d_{90}) of the particles in the armor layer. For higher streamflows, the thickness of the exchanging layer was increased to maintain the same shear stress at the base of the exchanging layer. The depth of the exchanging layer was calculated separately for the hydrologic conditions represented by each of the 15 flow intervals derived from the flow-duration curves. At the flow magnitude for several of the intervals, the thickness of the exchanging layer was very small (one-half of the d_{90} of the armor layer) and the armor layer was essentially immobile. A depth-dependent availability function was then added which allowed full availability for exchange of sediment at the top of the layer, decreasing to zero availability at the bottom of the layer. Details of the calculation of sediment exchange with the streambed are in R2 Resource Consultants (1998).

Owing to the complexity of the actual mechanisms, parameter values used to describe the sediment-exchange process were estimated by assuming that exchange occurs everywhere on the streambed during every mobilizing flow condition and that the distance below the streambed to which this exchange occurs decays exponentially with a scale depth related to the water depth in the river during the flow of interest. In reality, the scale for the exponential decay of exchange

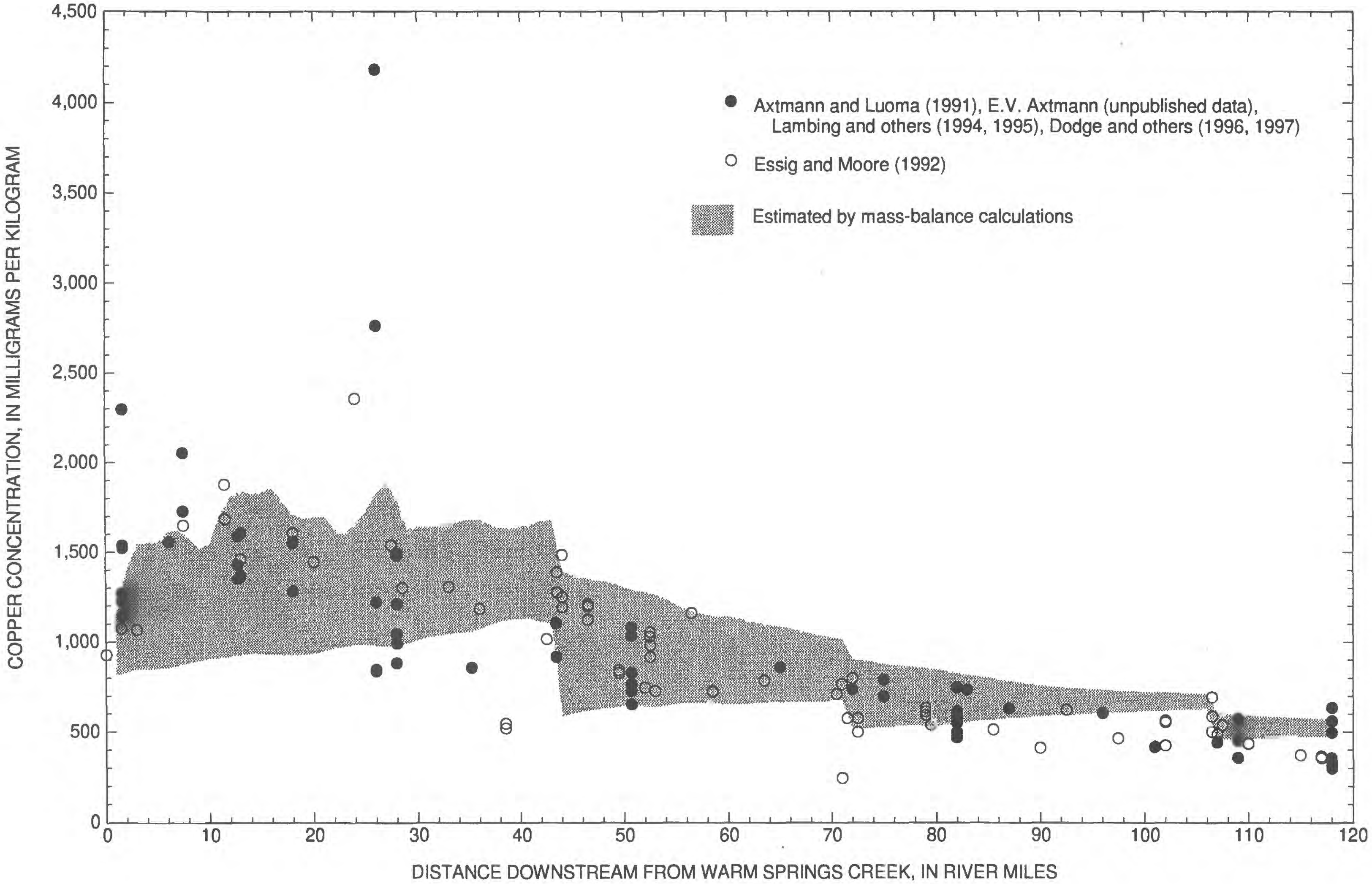

Figure 15. Downstream trend of copper concentrations in fine-grained bed sediment for the Clark Fork downstream from Warm Springs Creek, Montana. Circles represent concentrations measured in samples collected from surficial deposits located above the pebble and cobble armor layer. Shaded area represents the range in concentrations estimated by mass-balance calculations. (Modified from R2 Resource Consultants, 1998.)

depth is bounded between the armor particle size and the mean river depth. It is difficult, because of the non-physical nature of the algorithm, to calibrate the scale depth for the scour with any degree of precision, and the postulated exponential relation is neither very accurate nor generally valid. Nevertheless, when applied over a very large number of flows (that is, over a very long period of time) with a reasonably estimated scale depth, this parameterization is assumed to be satisfactory for providing gross estimates to evaluate relative magnitudes of sediment exchange.

Copper concentrations measured in fine-grained bed-sediment samples and estimated copper concentrations determined by mass-balance calculations are compared to distance downstream from Warm Springs Creek (fig. 15). The estimated concentrations exhibit a range instead of a fixed value at each location because the concentration changes as the mass-balance algorithm accounts for varying inputs of steady (for example, ground-water inflow) and streamflow-dependent (for example, bank erosion) copper sources during the course of one computational cycle through the 15 streamflow duration intervals. Although the measured concentrations exhibit considerable scatter, the estimated concentrations generally fall within the range of measured values.

Tributaries

Tributary inflows serve primarily as dilution sources to the Clark Fork. Copper concentrations in the three main tributaries above Turah Bridge (Little Blackfoot River, Flint Creek, and Rock Creek) generally are lower than concentrations in the Clark Fork. Data summarized in Dodge and others (1997) and Hornberger and others (1997) for the three tributaries were used to estimate copper loading from both gaged and ungaged tributaries (R2 Resources Consultants, 1998).

Ground water and flood-plain runoff

The copper load contributed by surface runoff from flood-plain tailings (4 tons/year) and from ground-water inflow (1.46 tons/year) was assumed to be continuous and steady in each reach for calculation purposes. Annual loads from these sources were based on the evaluations presented in "Surface Runoff from the Clark Fork Flood Plain" and "Ground Water" sections. Unlike other sources of metals, contributions of copper from ground-water inflow and flood-plain runoff were assumed to be independent of river discharge. In addition, the dissolved copper from these sources was assumed to immediately adsorb to the available silt-clay fraction of sediment and to subsequently mix and be transported with this sediment. Except for this mechanism for handling dissolved copper from these two sources, the algorithm does not allow for the interchange of copper between water and sediment.

Assumptions and limitations of mass-balance calculations

The mass-balance calculations use greatly simplified assumptions for the complex physical and chemical processes governing transport of metals in the Clark Fork. The primary purpose of the calculations is to provide a tool for evaluating the relative magnitude of metals contributions to the river from various sources. The following assumptions were used for the mass-balance calculations:

- All copper is attached to stream sediment. Dissolved copper contained in flood-plain runoff and ground water is immediately adsorbed to fine-grained sediment. Copper does not exchange between solid and dissolved phases.
- Sediment transport in the river is in equilibrium; consequently, the Clark Fork channel is not aggrading, degrading, or changing width over time. There is no net sediment gain or loss by bank erosion and deposition.
- Individual hydrologic events are not simulated. Instead, temporal changes in flow and sediment discharge are simulated using the duration of multiple flow ranges that are repeated for each year. Thus, flows are highly organized in the mass-balance algorithm, unlike the variability of natural streamflow. Seasonal effects are not calculated.
- Exchange of streambed sediment with suspended sediment is greatly simplified and only represents a rough approximation of actual processes.
- Copper concentrations and erosion rates for banks in Reach B and C were roughly approximated on the basis of limited data.

Mass-balance calibration

The physical processes that govern sediment transport, bank erosion, and streambed mobilization are dependent on streamflow conditions. In particular, the magnitude and duration of high streamflows are important. Owing to natural variability, streamflow conditions in one multi-year period can be significantly different than in another multi-year period. In order to calibrate and evaluate the representativeness of the sediment and copper mass balance, streamflow records for three hydrologic periods were analyzed: 1985-95, a water-quality monitoring period for which substantial sediment- and metals-transport data are available; 1960-89, the period for which bank-erosion rates were determined using aerial photographs; and 1930-95, the period representing the longest streamflow record available for a Clark Fork gaging station.

Calibration success was evaluated primarily by comparing the average annual copper loads estimated from monitoring data for 1991-95 (Hornberger and others, 1997) at the five control sites along the Clark Fork with the copper loads calculated by the mass-balance algorithm. After a number of sensitivity runs with the algorithm, the best calibration was achieved after making modifications to the magnitudes initially assigned (typically the mean of available data) to several of the copper sources. Copper concentrations in the streambed were increased to reflect historical copper loading, which was assumed to be higher than levels measured during 1985-90. After 1990, copper loading in the upper Deer Lodge valley presumably decreased as a result of remediation efforts such as the renovation of the Warm Springs Ponds, excavation of contaminated materials from the Mill-Willow Bypass (channel adjacent to Warm Springs Ponds), lime amendment and revegetation of flood-plain tailings along the upper 3 miles of the Clark Fork, and construction of berms to control flood-plain runoff in portions of the Deer Lodge valley. These pre-1990 sources were estimated to provide an additional 8 tons of copper annually to the river prior to the completion of remediation efforts. Thus, preceding the actual calibration run, the algorithm was run to an equilibrium condition with these historical copper sources present to represent conditions in 1990. Then, the supplemental 8 tons of copper were eliminated, and the algorithm was run for an additional 5 years through 1995 to simulate current (post-1990) source conditions.

Following the establishment of an initial equilibrium condition in the streambed, additional adjustments were made to other values in order to obtain close agreement with loads estimated from monitoring data. First, copper concentrations in the streambanks were increased by 30 percent compared to the values estimated from field data. This increase is reasonable because the thickness of tailings typically is greater in more erosive banks where protective vegetation may be suppressed; thus, the banks contributing the most sediment are also the most enriched in copper. Second, the bank erosion rate for 1985-95 was increased from 15 to 30 percent of the measured rate for 1960-89 to provide sufficient sediment and copper to achieve monitoring estimates of transport. Third, the proportion of sand in the sediment deposited on point bars was increased slightly to better represent natural sediment-transport processes which preferentially move fine-grained sediment farther downstream than sand-size sediment prior to deposition. This change resulted in additional downstream transport of metals because fine-grained sediment is more metal rich than sand-size sediment. Finally, the combined copper input from ground water and flood-plain runoff was increased from 6 to 10 tons/year, the upper limit of estimated current inputs for these poorly quantified sources. Results of the calibration are presented in table 15. For further details about the calibration process, the reader is referred to R2 Resource Consultants (1998).

Quantification of source contributions

The mass-balance algorithm provides a tool that can aid in understanding the relative magnitude of copper loading to the Clark Fork from various sources. The mass-balance algorithm was calibrated with streamflow and suspended-sediment data for 1985-95 and copper-transport data primarily for 1991-95. The mass loading of copper and percent of total input contributed from each source are presented in table 16 for the calibration period, which simulates post-1990 source conditions. The results indicate that streambank erosion is the largest source of copper to the river, comprising 56 percent of the total copper input. The calculations also indicate that 47 percent of the copper contributed to the river is deposited on point bars rather than transported past Turah Bridge.

Hydrologic conditions in 1985-95 were considerably drier than long-term (1930-95) conditions (fig. 13). Therefore, the magnitude of metals inputs and

Table 15. Average annual copper loads at five streamflow-gaging stations on the Clark Fork, Montana, estimated from monitoring data and calculated with the calibrated mass balance under current (post-1990) source conditions and 1985-95 hydrology (modified from R2 Resource Consultants, 1998)

[Symbol: --, no data]

Station	Station number	Average annual copper load (tons/year)		
		1985-90 monitoring-data estimate	1991-95 monitoring-data estimate	Calculated with mass balance
Clark Fork near Galen	12323800	4.5	3.9	3.3
Clark Fork at Deer Lodge	12324200	11.7	11.8	11.2
Clark Fork at Goldcreek	12324680	--	13.8	17.2
Clark Fork near Drummond	12331800	--	17.8	20.0
Clark Fork at Turah Bridge	12334550	37.2	22.0	22.4

Table 16. Summary of mass-balance estimates for copper loading from various sources upstream from the Clark Fork at Turah Bridge, Montana, based on the calibration period simulating current (post-1990) source conditions and utilizing 1985-95 hydrology (modified from R2 Resource Consultants, 1998)

[Rounding effects result in percentages not adding exactly to 100]

Copper source	Load (tons/year)	Percent of total input
Upstream input	2.2	5
Bank erosion	23.6	56
Tributary input	3.2	8
Flood-plain runoff and ground water	10.0	24
Streambed exchange	3.3	8
TOTAL INPUT	42.3	100
Loss to point-bar deposition	-19.9	-47
Total load transported at Turah Bridge	22.4	53

metal-transport characteristics in the river determined for the 1985-95 calibration period probably underestimate long-term averages. In comparison to hydrologic conditions for the long-term period, conditions during 1985-95 would be expected to have the following features:

- decreased metal loading from bank erosion and meander migration;
- decreased input of streamflow, sediment, and metals from upstream and tributary sources; and
- decreased mixing and exchange with bed sediment.

As a result of these decreased inputs during the low flows of 1985-95, the metal loads estimated from ground water and flood-plain runoff likely represent larger percentages of the total load than they would during a higher-flow period. Consequently, after calibration of the algorithm with the data for 1985-95, the system behavior under long-term hydrologic conditions was analyzed using streamflow data for 1930-95, the longest available streamflow record in the upper Clark Fork basin.

In addition to the hydrologic conditions of the 1985-95 calibration period, two scenarios representing long-term hydrologic conditions were investigated with the mass-balance algorithm. These three scenarios (fig. 16) provide a range in the relative magnitude of estimated average annual copper loads along the

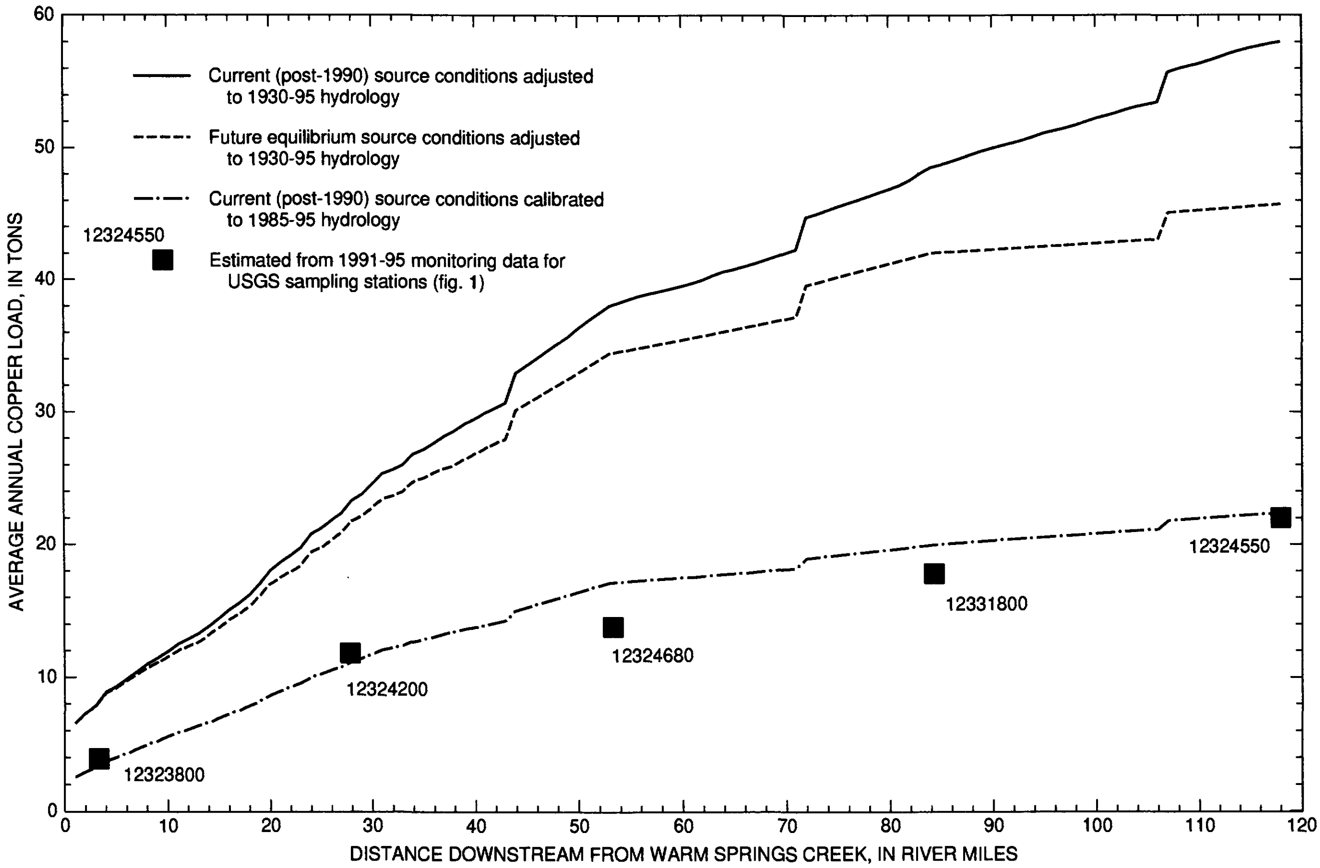

Figure 16. Average annual copper loads in the Clark Fork downstream from Warm Springs Creek, Montana, estimated from 1991-95 monitoring data for USGS sampling stations and from mass-balance simulations for three scenarios of metal-source conditions and hydrology. (Estimated copper loads between sampling stations interpolated from a drainage-area relation to streamflow. Modified from R2 Resource Consultants, 1998.)

Clark Fork for three combinations of hydrologic and source conditions: (1) current (post-1990) source conditions calibrated to 1985-95 hydrology, (2) current source conditions adjusted to long-term (1930-95) hydrology, and (3) future source conditions adjusted to long-term (1930-95) hydrology. This third scenario is the same as the second scenario except that the streambed is no longer a net source of metal to the river. This scenario represents expected conditions after the historical (pre-1990) metal enrichment in the bed is depleted by sediment exchange and metal concentrations in the bed are in equilibrium with metal concentrations in suspended sediment.

The relative magnitude and percent of total input contributed from each source for both current and future equilibrium conditions utilizing long-term hydrology (1930-95) are presented in table 17. Under current source conditions, about 60 percent of all copper input into the river upstream from Turah Bridge originates from bank erosion. Tributaries and the combined input from flood-plain runoff and ground-water inflow account for about 10 percent each, and upstream sources account for 6 percent of the total. The streambed accounts for about 14 percent of the total input. The mass balance also indicates that under current conditions, only about 56 percent of the average annual copper input to the river is transported past Turah Bridge. The remaining copper is deposited on point bars along the Clark Fork.

When compared to the 1985-95 calibration period (table 16), the magnitude of all sources except flood-plain runoff and ground water increases with the greater streamflow represented by the 1930-95 hydrology. Thus, copper sources from flood-plain runoff and

Table 17. Summary of mass-balance estimates for copper loading from various sources upstream from the Clark Fork at Deer Lodge and the Clark Fork at Turah Bridge, Montana, based on current (post-1990) and future equilibrium source conditions adjusted to long-term (1930-95) hydrology (modified from R2 Resource Consultants, 1998).

[Rounding effects may result in percentages not adding exactly to 100]

Copper source	Clark Fork at Deer Lodge				Clark Fork at Turah Bridge			
	Current condition		Future equilibrium		Current condition		Future equilibrium	
	(tons/ year)	(percent of total input)	(tons/ year)	(percent of total input)	(tons/ year)	(percent of total input)	(tons/ year)	(percent of total input)
Upstream input	6.0	15	6.0	16	6.0	6	6.0	7
Bank erosion	26.5	65	26.5	69	62.3	60	62.3	70
Tributary input	1.1	3	1.1	3	10.5	10	10.5	12
Flood-plain runoff and ground water	5.0	12	5.0	13	10.0	10	10.0	11
Streambed exchange	2.1	5	0	0	14.9	14	0	0
TOTAL INPUT	40.7	100	38.6	100	103.7	100	88.8	100
Loss to point-bar deposition	-17.4	-43	-16.8	-44	-45.7	-44	-43.1	-48
Total load transported at gage	23.3	57	21.8	56	58.0	56	45.8	52

ground water play a smaller role in the overall copper balance for the river under more representative long-term hydrologic conditions. The average annual copper load for the Clark Fork at Turah Bridge increases from about 22 tons/year for the 1985-95 hydrology (calibration case) to 58 tons/year under current source conditions after adjusting for long-term hydrology. The mass balance indicates that the average annual copper load at Turah Bridge under long-term hydrology will decrease from 58 tons/year to about 46 tons/year as the streambed comes to equilibrium with the existing sources of copper.

SEDIMENT AND METALS TRANSPORT IN 1991-97

Streamflow in 1996-97 was higher than in 1991-95 (fig. 3), the primary period for which metals transport was evaluated. Higher streamflow likely would result in increased bank erosion and tributary inputs, thus increasing annual sediment and metals loads. If different reaches of the river respond differently to increased flows, then the amount and proportion of sediment and metals transported may be different than in the low-streamflow period of 1991-95. Estimates of suspended-sediment and metal loads for water years 1996-97 and average annual loads in the Clark Fork for the extended averaging period of water years 1991-97 are presented in Lambing (1998). Hydrologic conditions during 1991-97 were similar to the long-term average hydrology, as indicated by the similarity in flow-duration curves for 1991-97 and 1930-97 for the Clark Fork above Missoula (fig. 17). Consequently, average annual suspended-sediment and metals loads for the 1991-97 period provide data useful for evaluating the mass-balance estimates of transport in the river under long-term hydrologic conditions.

Sediment and metals loads from intervening reaches in 1991-97

To provide some perspective on the importance of high streamflow to sediment and metals transport, a comparison of unit-length yields, in tons per river mile, is presented for the 1991-95 and 1991-97 periods (table 18). The 1991-95 period represents five consecutive years of below-normal flows, whereas the 1991-97 period includes both above- and below-normal years of flow (fig. 3). The yields are useful for representing hydrologically induced differences in input because the data were obtained in a consistent manner from a common network of sites and during a common source condition (post-1990) following completion of several remedial treatments in the upper basin.

The average annual yields for the 1991-97 period exceeded those of the 1991-95 period in almost all instances. Notably, however, there was a decrease in sediment yield for 1991-97 in the short reach between Warm Springs and Galen, possibly as a result of flood-plain deposition of sediment during May and June 1997 when high streamflow topped the banks in this area of dense riparian vegetation. This sediment deposition also would have removed particulate metals from the

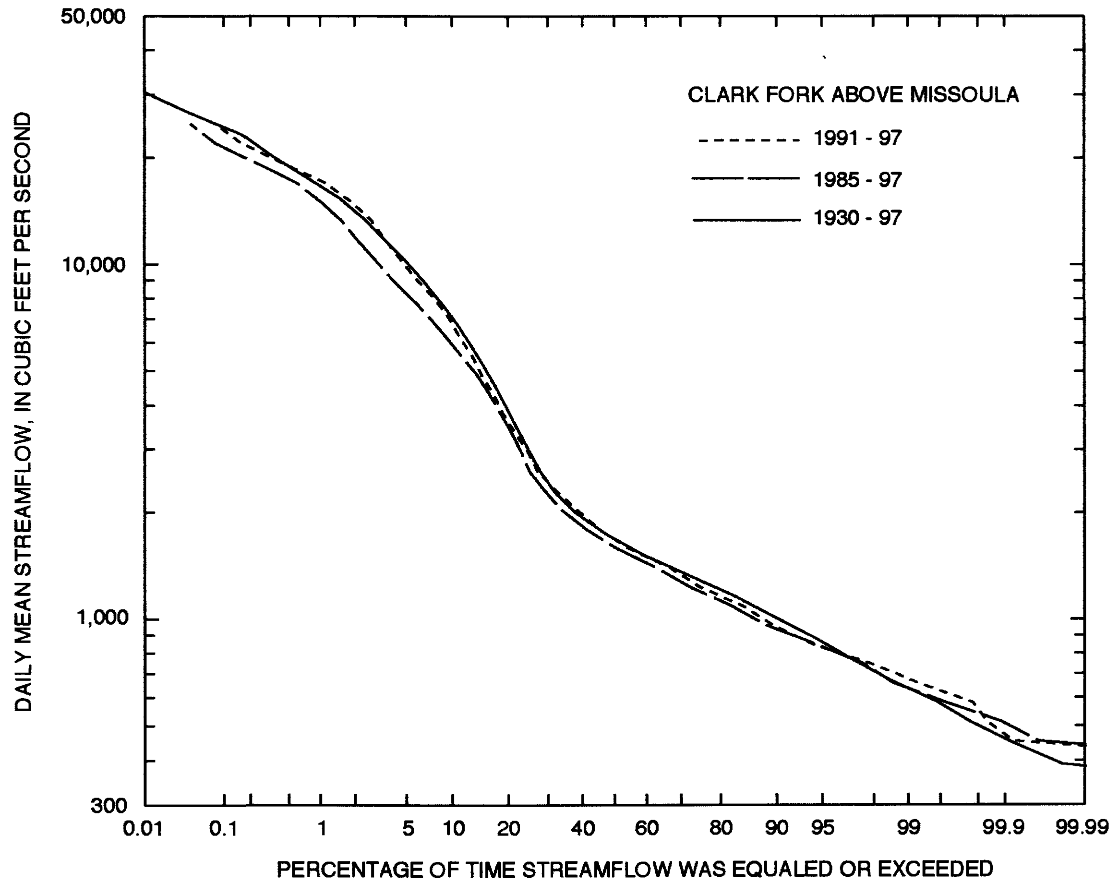

Figure 17. Streamflow-duration curves for the Clark Fork above Missoula (station 12340500), Montana, for the period of record (water years 1930-97) and recent study periods (water years 1985-97 and 1991-97).

Table 18. Estimated average annual suspended-sediment and total-recoverable metal yields, in tons per river mile, transported in the Clark Fork, Montana, water years 1991-95 and 1991-97 (modified from Hornberger and others,1997, and Lambing, 1998)

Intervening reach between mainstem stations	Average annual yield (tons per river mile)[1]							
	Suspended sediment		Copper		Lead		Zinc	
	1991-95	1991-97	1991-95	1991-97	1991-95	1991-97	1991-95	1991-97
Silver Bow Creek at Warm Springs to Clark Fork near Galen (4.2 miles)	129	93	0.29	0.29	0.02	0.03	0.24	0.38
Clark Fork near Galen to Clark Fork at Deer Lodge (24.8 miles)	219	382	.32	.51	.04	.06	.33	.49
Clark Fork at Deer Lodge to Clark Fork at Goldcreek (25.5 miles)	170	552	.07	.22	.02	.05	.18	.41
Clark Fork at Goldcreek to Clark Fork near Drummond (31.3 miles)	220	480	.12	.28	.02	.05	.28	.62
Clark Fork near Drummond to Clark Fork at Turah Bridge (33.4 miles)	103	336	.10	.27	.01	.03	.12	.30

[1]Yields from intervening reaches represent a unit-length input expressed as the average annual load originating from the reach, in tons, divided by the reach length, in miles. Expressing yields in this manner assumes that sediment and metals are derived primarily from channel and flood-plain sources.

river and may be the cause of a corresponding pattern of little or no change in the copper and lead yields between the two time periods. Zinc yield during 1991-97 increased in this reach, however, possibly because zinc tends to originate from ground-water sources to a greater degree than copper or lead (table 12).

The greatest increases in yield for suspended sediment occurred in the reaches from Deer Lodge to Goldcreek and from Drummond to Turah Bridge, where yields during 1991-97 were about three times higher than during 1991-95. The increase in sediment yield for 1991-97 was about double the yield of 1991-95 in the intermediate reach of the lower river from Goldcreek to Drummond. Increases in copper, lead, and zinc yields in these reaches for 1991-97 generally were proportional to that of sediment.

When viewed in a longitudinal (downstream) manner, suspended-sediment and metal yields during 1991-97, which included the ice breakup and high-flow years of 1996 and 1997, increased to a proportionally greater extent in the lower reaches (below Deer Lodge) than in the upper reaches. A fairly consistent downstream increase in yield occurred relative to 1991-95, ranging from essentially no change at the upstream end of the study reach to about a three-fold increase at Turah Bridge. This new information obtained from a hydrologic condition previously absent from the monitoring period illustrates the importance of both high flows and the lower river in the overall geomorphic process of sediment and metals transport in the Clark Fork.

Test of mass-balance results using 1991-97 data

Suspended-sediment and copper loads estimated for water years 1991-97 from monitoring data for the Clark Fork at Deer Lodge and Turah Bridge are presented in table 19 along with loads predicted from mass-balance calculations using long-term hydrology under current (post-1990) source conditions. Both sites are operated as daily sediment stations and provide the most accurate record of suspended-sediment loads available for comparison to loads predicted from mass-balance calculations.

The high natural variability in annual suspended-sediment transport is apparent, with annual loads at Turah Bridge varying more than 20-fold between 9,300 tons/year in 1992 and 211,000 tons/year in 1997. Similarly, the copper loads at Turah Bridge determined from monitoring data for 1991-97 varied 13-fold from 8.5 tons/year in 1992 to 109 tons/year in 1997. The mass-balance estimates for the long-term (1930-95) average annual sediment loads are approximately 60 percent higher than the average observed for the period 1991-97 at both Deer Lodge and Turah Bridge (table 19). The long-term mass-balance overestimate of sediment transport results in an overestimate of copper loading in the Clark Fork. The long-term mass-balance estimate for copper at Turah Bridge under current source conditions is approximately 30 percent higher than the average annual loads estimated from monitoring data for 1991-97. The predicted average annual copper loading at Turah Bridge was 58 tons/year for current source conditions under long-term hydrology, whereas the 1991-97 monitoring data estimate indicates an average annual load of about 44 tons/year.

Table 19. Suspended-sediment and total-recoverable copper loads for the Clark Fork at Deer Lodge and Clark Fork at Turah Bridge, Montana, estimated from monitoring data for water years 1991-1997 compared to mass-balance predictions for long-term (1930-95) hydrologic conditions (modified from R2 Resource Consultants, 1998)

Station	Annual suspended-sediment load (tons/year)				Annual copper load (tons/year)				
	1991-97 monitoring-data estimate			Mass balance, long-term hydrology	1991-97 monitoring-data estimate			Mass balance, current conditions, long-term hydrology	Mass balance, equilibrium conditions, long-term hydrology
	Minimum (1992)	Maximum (1997)	Average		Minimum (1992)	Maximum (1997)	Average		
Clark Fork at Deer Lodge	3,360	31,200	12,600	20,200	6.0	40	18	23	22
Clark Fork at Turah Bridge	9,300	211,000	76,700	126,000	8.5	109	44	58	46

The difference in the average annual 1991-97 loads determined from water-quality and streamflow data and the predicted long-term averages calculated by mass balance is caused primarily by the overestimation of transport during the two high-flow years, 1996-97. As shown in figure 18, the amount of sediment transported by the high sustained streamflow of 1997 and the post-ice-breakup streamflow of 1996 was significantly less than the transport predicted by the rating curve developed from 1985-95 data. This underestimation indicates the difficulty in extrapolating long-term estimates from data collected during a base period with non-representative hydrologic conditions. Apparently, during years when streamflow remains high for an extended period, sediment loads are not sustained at the high levels predicted by the rating curve, suggesting that sediment-supply limitations affect transport, the long-term flow adjustment was too large, or that the upper range of the rating curve was poorly defined. Whether the lower-than-predicted transport observed for 1991-97 is typical of the long-term average relation between flow and sediment transport is unknown. Thus, the 1991-97 data suggest that the mass-balance algorithm calibrated to 1985-95 data overestimates suspended-sediment (and associated metal) transport at high discharges. Few transport data from other high-

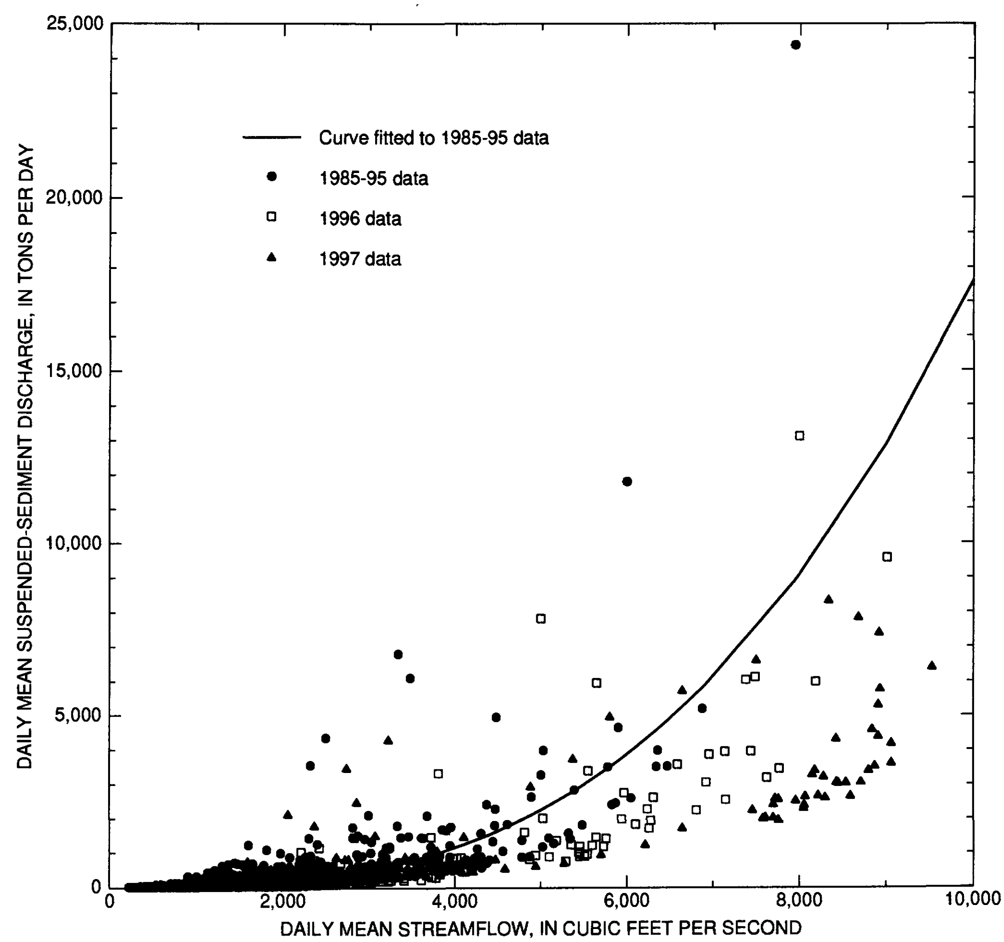

Figure 18. Comparison of 1996 and 1997 daily mean streamflow and daily mean suspended-sediment discharge to the 1985-95 suspended-sediment rating curve for Clark Fork at Turah Bridge (station 12334550), Montana.

streamflow years are available to evaluate how the relation between streamflow and sediment transport varies during different runoff conditions.

The potential effect of overestimation of sediment and copper loading on the relative proportions of copper contributed from various sources under current (post-1990) conditions can be seen by comparing tables 16 and 17. Table 16 shows the relative contribution of copper from each source calibrated with the available sediment- and copper-transport data for 1985-95. With a 1991-95 average load of 22.4 tons/year of copper transported past the Clark Fork at Turah Bridge, about 56 percent of the total input originates from bank erosion (table 16). For a long-term, flow-adjusted average annual estimate of 58 tons/year of copper transported past Turah Bridge, bank erosion constitutes about 60 percent of the total input from all sources (table 17). Thus, the relative percentage of total load contributed from various sources is not highly sensitive to the actual magnitude of long-term average annual copper loads.

SUMMARY AND CONCLUSIONS

Trace-element concentrations in water, sediment, and biota in the Clark Fork are elevated as a result of tailings introduced during a century of extensive mining and smelting in the headwaters and selected tributaries of the upper basin. Flood-deposited tailings rich in arsenic, cadmium, copper, iron, lead, and zinc are distributed over the upper Clark Fork flood plain. Most of these tailings were deposited during several large floods that occurred between the late 1800's and 1908. Metal enrichment extends for over a hundred miles of the Clark Fork mainstem, posing a potential risk of toxicity to aquatic biota. Because the erosion and transport of metals from the extensive flood-plain sources is a continuing public concern, remediation planning and initial cleanup efforts were begun in the 1980's as part of the U.S. Environmental Protection Agency's Superfund process.

To support remediation planning efforts, a study of metals transport and associated geomorphic processes in the Clark Fork valley between the Warm Springs Ponds and Milltown Reservoir, Montana, was conducted during 1995-98. The goal of the study was to synthesize existing and new data in order to provide an overview of interrelated metals-transport processes in the Clark Fork fluvial system. This assessment required quantifying the loads coming into the river from all important sources and then tracking the transport and accumulation of metals through the 120-mile reach of river.

Available data on metal distribution and inputs were compiled and incorporated into a mass-balance algorithm to account for metals inputs from specific sources, transport down the river, and deposition in the channel. Copper data were used to estimate metals mass balance because copper concentrations in the Clark Fork occur in measurable concentrations and exceed aquatic-life criteria more frequently than concentrations of other trace elements. Sources considered were the basin headwaters, tributaries, material eroded from streambanks, flood-plain runoff, groundwater inflow, seasonal bank-storage inflow, and metal stored in the streambed. Water-quality and continuous-streamflow data collected as part of a USGS long-term monitoring program were used to quantify the transport rates of suspended sediment and metals and to provide calibration values for the mass-balance calculations.

The upstream input from Silver Bow and Warm Springs Creeks during 1991-95 collectively accounted for about 4 percent of the suspended-sediment load passing Turah Bridge and about 12, 5, and 14 percent, respectively, of the total-recoverable copper, lead, and zinc. The three major tributaries above Turah Bridge (Little Blackfoot River, Flint Creek, and Rock Creek) collectively contributed one-third of the sediment load at Turah Bridge, but only a minor amount (6 percent) of the copper. Their combined contribution of lead and zinc (29 and 15 percent, respectively) was about 2-5 times greater than that of copper. The largest single tributary contribution of metal (lead) was from Flint Creek (17 percent of the total at Turah Bridge).

Loads originating from the five intervening reaches between mainstem stations represent the combined input from ungaged tributaries, flood-plain runoff, ground water, and channel sediments. The intervening reaches contributed a large proportion (63 percent) of the suspended-sediment load at Turah Bridge during 1991-95. Similarly, metal loads from these reaches accounted for a large proportion, representing 81, 66, and 71 percent of the copper, lead, and zinc loads, respectively, at Turah Bridge. Average annual yield, in tons per river mile, indicated that sediment yields were highest in the three middle reaches. Zinc yields generally varied in a manner similar to that of suspended sediment. In contrast, the copper yield from upstream reaches between Warm Springs and Deer Lodge was 3-5 times greater than in downstream reaches from Deer Lodge to Turah Bridge. Lead yields varied the least, with the highest lead yield occurring between Galen and Deer Lodge.

The proportion of load derived from specific sources within intervening reaches cannot be determined from the stream monitoring data; therefore, a mass-balance evaluation required that estimates of inputs from individual sources be developed. Inputs from individual sources within the intervening reaches were estimated from available data on flood-plain tailings distribution, bank-erosion rates, flood-plain runoff, and ground-water data.

A tailings and soils map was produced during this study for selected areas of the100-year flood plain to identify the areal and vertical extent of tailings and impacted soils, the range of trace-element concentrations, and the location of affected soils relative to the Clark Fork channel. In the 43-mile reach of the Clark Fork between Warm Springs Creek and the confluence with the Little Blackfoot River (Reach A, Deer Lodge valley), approximately one-third of the flood plain contains tailings or mixed soil/tailings layers. The information compiled from this mapping and sampling effort was used to estimate average metals concentrations in streambanks. Sampling of flood-plain tailings and soils was very limited in the lower 75 miles of the study reach (Reaches B and C, Clark Fork between the Little Blackfoot River and Turah Bridge) and, therefore, metals concentrations for flood-plain deposits in this area were generalized from sparse local data and data from the Deer Lodge valley.

Calculations of the volume of bank material eroded and the average copper concentrations in the banks were used to estimate the copper loads from bank erosion. Average annual meander-migration rates for the Deer Lodge valley were quantified by comparing the change in channel position using aerial photographs taken in 1960 and 1989. During this period, migration rates ranged from 0.0 to 5.8 ft/year, with an average rate of 0.6 ft/year over the 43-mile reach. Streamflow during the 1960-89 period was slightly higher than during the longest available gaging record of 1930-95; therefore, bank-erosion rates for 1960-89 were adjusted downward slightly to better reflect long-term bank erosion.

Input data were incorporated into a mass-balance algorithm that simulates copper transport during variable flow conditions over time as source conditions change. The resulting mass balance was used to estimate the relative contribution from various sources in the upper Clark Fork basin. The mass-balance estimates were calibrated with 1985-95 monitoring data on suspended-sediment and copper transport.

Copper loads in surface runoff from the Clark Fork flood plain were predicted separately for areas of exposed tailings (slickens) and vegetated tailings areas using runoff volumes and average soil copper concentrations. The estimated copper load from slickens represented 18 percent of the average annual copper load passing Turah Bridge during 1991-95, whereas that from vegetated tailings was negligible.

Copper loads from the shallow ground-water system were estimated using flow rates and copper data collected from monitoring wells completed in gravel underlying flood-plain deposits. The copper supplied from ground water discharging to the Clark Fork along the 120-mile study reach represented only about 7 percent of the copper loads at Turah Bridge. Seasonal copper loading from bank storage is probably small based on limited data that indicated minimal change in chemistry and hydraulic gradients during changes in river stage.

The gross inputs of sediment and copper were coupled with estimates of transport to determine the percentage of material delivered to the river that is subsequently deposited within the channel. Suspended-sediment transport was simulated for various flow conditions and duration during 1985-95 and compared to estimates obtained from monitoring data to assess the accuracy. The algorithm is based on the assumption that copper predominantly is transported attached to sediment; therefore, the copper concentrations determined for each of the sediment sources were used to calculate the corresponding copper transport.

The flux of copper into and out of the streambed beneath the armor layer affects transport because copper concentrations in the bed presumably are elevated as a result of historical inputs prior to the recent cleanup efforts in parts of the upper basin and enhancement of retention capabilities in the Warm Springs Ponds. Thus, the streambed is expected to act as a copper source by releasing historically stored copper to downstream transport until the bed comes to equilibrium with current (post-1990) copper inputs. At equilibrium, the bed is expected to be neither a source nor a sink for copper. Copper-concentration data for surficial bed sediment available from several studies were used in conjunction with estimated shear stress to simulate exchange of copper from the bed during high-flow conditions, when there is sufficient energy to mobilize the armor layer of pebble and cobble that covers the Clark Fork streambed. Under such conditions, fine sediments and associated copper underlying the armor layer can exchange with less concentrated material in suspension and become progressively diluted over time. The mass-balance algorithm was first run using initial streambed copper concentrations that were elevated with historical copper sources (pre-1990). The algorithm then was run without these sources for five years to simulate the removal and treatment of tailings in portions of the upstream reach that were completed around 1990. The equilibrium condition after five years then was used to represent current (post-1990) conditions of copper concentration in the streambed. Copper exchange with the streambed was grossly estimated to be 8 percent of the load at Turah Bridge.

Copper transport through intervening reaches was calibrated by modifying the initially assigned magnitude of various input concentrations or rates to produce output values similar to the average copper loads estimated from the 1991-95 monitoring data. The resulting distribution of mass inputs then was used to evaluate the relative contribution of copper from different sources. Under current source conditions and 1985-95 hydrology, the mass-balance calculations indicate that streambank erosion is the largest source of copper to the river, comprising approximately 56 percent of the total copper input within the 120-mile reach. Upstream input accounts for about 5 percent, whereas tributary and streambed exchange each account for about 8 percent. Flood-plain runoff and ground water together account for about 24 percent of the total copper input. Not all of the copper entering the river is transported past Turah Bridge. Instead, about 47 percent of the copper input is deposited on point bars.

After mass-balance calibration with data collected from the 1985-95 monitoring period, long-term transport rates were simulated by adjusting rates to streamflow conditions representative of 1930-95 hydrology. This long-term mass-balance simulation of loads was done for two scenarios: (1) current (post-1990) source conditions adjusted to long-term hydrology, and (2) future source conditions adjusted to long-term hydrology. Future source conditions represent expected conditions after the historical (pre-1990) metal enrichment in the bed is depleted by sediment exchange and metal concentrations in the bed are in equilibrium with metal concentrations in suspended sediment.

Under current source conditions and with 1985-95 transport rates adjusted to 1930-95 hydrology, the average annual copper load at Turah Bridge estimated by mass balance increases from 22.4 to 58.0 tons/year. About 60 percent of all copper input to the river under current source conditions and long-term hydrology originates from bank erosion, with tributaries and the combined input from ground water and flood-plain runoff accounting for about 10 percent each. Upstream input represents 6 percent and streambed exchange provides about 14 percent. About 56 percent of this input reaches Turah Bridge, with 44 percent being deposited in channel features such as point bars.

Because upstream inputs of metals have been greatly reduced by the Warm Springs Ponds and recent cleanup efforts, the mass-balance estimates also predict changes in copper transport after the metals that were historically deposited in the streambed become depleted over time through bed-scour sediment exchange to the point where the streambed is no longer acting as a source or sink for metals. The long-term copper load at Turah Bridge under future streambed equilibrium conditions decreases from 58 to 46 tons/year. The proportion of bank input increases to about 70 percent while the streambed input goes to 0 percent. The other inputs increase by only about 1 or 2 percent. About 52 percent of the input reaches Turah Bridge, with the remaining 48 percent being deposited within the 120-mile reach.

High streamflows in 1996 and 1997 exceeded those of the 1985-95 calibration period. The additional data for the two high-streamflow years results in flow-duration statistics for 1991-97 that are similar to those for the long-term 1930-97 period. Under a hydrologic regime that includes high streamflows, inputs to the river from intervening reaches increase disproportionately in the lower reaches of the river compared to the upper reaches. This results in nearly equivalent copper yields along the 120-mile length, with the exception of the Galen to Deer Lodge reach, which provides about double the input per mile compared to the other reaches.

Loads estimated by the mass-balance algorithm that was calibrated to 1985-95 data and adjusted to long-term (1930-95) hydrology were compared to the 1991-97 average annual loads estimated from monitoring data to evaluate the mass-balance load estimates for the higher streamflow conditions of the long-term period. The long-term suspended-sediment transport at Turah Bridge predicted by mass-balance calculations for current source conditions are about 60 percent higher than the 1991-97 average annual load determined from monitoring data. The difference results primarily from overestimation of transport during the high-flow range, which is a consequence of the sediment rating being developed from data collected during a period absent of such high flows and then extrapolated to conditions outside the measured flow range. The long-term prediction of copper transport under current source conditions was 58 tons per year at Turah Bridge, whereas the 1991-97 monitoring data indicated an average annual copper load of 44 tons per year. However, regardless of the difference in loads predicted by the mass-balance algorithm and those determined from the 1991-97 monitoring data, the relative percentage of total load contributed from various sources remains similar.

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