A combined flood surface and geochemical analysis of metal fluxes in a historically mined region: a case study from the New World Mining District, Montana

M.T. Hren · C.P. Chamberlain · F.J. Magilligan

Abstract Remediation of environmental damage due to mining activities requires distinguishing anthropogenic alteration from natural baseline conditions. Through ICP-OES analyses of the <63 μm fraction of overbank sediments dating from ~8,000 years to the present, the development of a regional flood probability model, traditional topographic surveying, and the use of flood surface modeling, it is shown that the combination of hydraulic modeling and geochemical analysis of sediments is an effective tool for determining remediation strategies. This combination provides a means of distinguishing natural from anthropogenic sediments in a naturally metal-rich region, delineating zones of sediments with elevated metal concentrations, and creating an accurate estimate for appropriate remediation. Specifically, the distribution of metals in Fisher Creek of the New World Mining District, Montana, suggests the following: (1) The Glengarry adit is currently a point source of metal contamination (the present surface distribution of metals in the <63 μm fraction of overbank deposits is related to the probability of a surface being covered by water during a flood of a given recurrence probability); (2) sediments with elevated metal concentrations pre-date mining activity; (3) pre-mining overbank sediments contain metal concentrations as great or greater than post-mining sediments; (4) remediation of sediments with the highest concentration of metals requires assessment of sediments deposited above the 100-year flood surface.

Keywords Mine waters · Sedimentation · Hydraulic modeling · Rocky Mountains

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Introduction

Geochemical analyses of the spatial distribution of metals in overbank alluvium are useful techniques to distinguish natural baseline conditions from anthropogenic alteration (Macklin 1985; Leenaers and Schouten 1988; Boult 1996; Taylor 1996). In addition, streamflow modeling can effectively approximate flood inundation (Feldman 1981; Hoggan 1989). At present, however, few studies exist that couple both geochemical analyses and flood surface modeling to assess the impact of mining on floodplain surfaces of differing ages, elevations, and inundation histories. As such, this study uses these two techniques to determine whether such a combined approach is a viable method for the examination of the impact of mining within a catchment.

Metal transport by both dissolved and suspended load profoundly affects the distribution of metals within a stream system. Acid mine drainage and the fluvial transport of mine tailings alters stream chemistry and metal accumulation in overbank alluvium (Leenaers and Schouten 1988; Mcknight and Bencala 1989; Boult 1996; Miller 1997), and the increased transport of fine-grained sediments from mining-related deforestation, road construction, and crushing and milling processes may alter stream channel morphology through meander-belt-narrowing and overbank deposition (James 1991, 1999; Lecce and Pavlowsky 1997). In fact, in regions with a history of mining, overbank deposits may serve as semi-permanent sinks for metals and record temporal changes in mining-related sedimentation (Knox 1987; Graf and others 1991; Marron 1992; Macklin and others 1994; Graf 1996; Taylor 1996; Lecce and Pavlowsky 1997; Marcus

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and others 2001). However, Macklin and others (1994) suggest that without dating control or fluvial geomorphological information, overbank sediments may fail to provide an accurate assessment of natural variations and anthropogenic influences. Thus, a combined geochemical and numerical modeling approach should significantly enhance the ability to understand the transport of metals within a historically mined drainage.

To test whether such a combined approach is feasible, it is necessary to study an area where a sufficient record exists of both stream geomorphic development and mining activity. The Fisher Creek drainage of the New World Mining District was selected to test this application because: (1) recent work has demonstrated that well-dated Fe-oxide deposits in Fisher Creek record metal deposition for the past ~8,000 years (Furniss and others 1999); and (2) several stream terraces evidenced within this drainage can be dated and correlated with terraces in nearby drainages in Yellowstone National Park (Meyer and others 1995).

Past work in Fisher Creek, a small acid mine stream that drains a portion of the New World Mining District, Montana (Fig. 1), has indicated that stream-waters, stream sediments, and near-stream vegetation currently contain elevated concentrations of metals that may be linked to mining activity (Barnhorst 1995; Manske 1998; Horton and others 1999). However, recent examination of 8,000-year-old Fe-oxide deposits (Furniss and others 1999) in the Fisher Creek drainage suggests a long history natural acid rock drainage, with metal deposition occurring during the past 8,000 years. Because the Fisher Creek drainage displays evidence of both historic and active metal deposition it is well suited for a combined geochemical and numerical model approach to assess the impact of mining. Therefore, through the combination of HEC-RAS flood surface modeling (Brunner and others 1996) and geochemical analyses of metal concentrations, the spatial and temporal distribution of metals in the overbank alluvium of the Fisher Creek drainage was examined in an effort to develop a means of distinguishing natural metal transport and accumulation from anthropogenically influenced alteration. This approach assumes that the distribution of post-mining fluvial sediments is limited by stream migration and flood frequency during that time period. At present, there are no geochemical studies of overbank deposits in Fisher Creek. If these deposits can be dated, geochemically characterized, and assessed using flood frequency models, then it may be possible to separate anthropogenic from natural sources.

By combining flood surface models of the Fisher Creek drainage with geochemical analysis of the <63 μm fraction of sediments, it is possible to determine the areal extent of mining-related sediments and distinguish them from naturally metal-rich ones. The results from this study suggest that while mining-related sediments contain elevated concentrations of iron and copper, these concentrations are no greater than those found in deposits that pre-date mining activity. Herein, it is shown that: (1) in the last 100 years the Glengarry adit at the headwaters of Fisher Creek has served as a point source of metals within this catchment; but (2) pre-mining sediments also have elevated metal concentrations, suggesting that this stream has been naturally metal-rich for the last 8,000 years, in support of the Fe-oxide study of Furniss and others (1999).

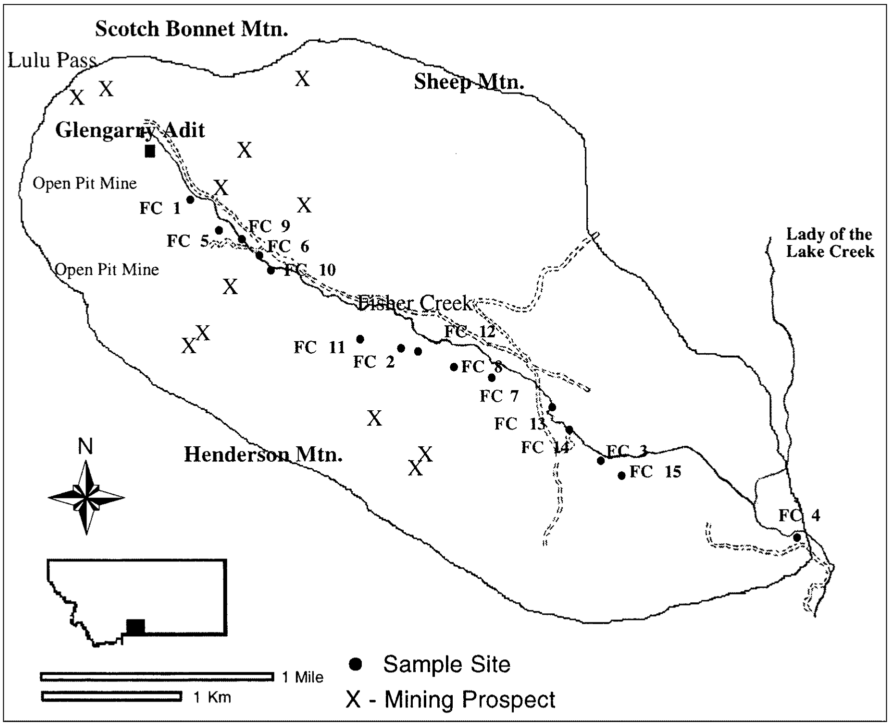


Fig. 1
Map of the Fisher Creek drainage, New World Mining District, Montana. *Black circles* indicate survey sites, while *crosses* indicate mining prospects. The *large black line* circling Fisher Creek indicates the boundaries of the Fisher Creek drainage

Study area

The Fisher Creek basin is located in the New World Mining District near Cooke City, in southwestern Montana (Fig. 1). It has a drainage area of ~6.5 km^2 over a distance of 7 km. Located only a few kilometers from Yellowstone National Park, this metal-rich mining district is bounded on all sides by National Forest and National Park lands, and is host to rich deposits of copper, gold, and silver (Elliot 1979; Kirk and Johnson 1993). Fisher Creek, the focus of this study, is an alpine stream in a glacial hanging valley. Elevations range from nearly 2,900 m at the headwaters to 2,500 m near the junction of Fisher and Lady of the Lake Creeks. The uppermost and bottom 1.5 km of the stream are characterized by heavily wooded, steep valley sides and bouldered stream channels. The middle portion of Fisher Creek is characterized by a shallow, cobbled, meandering stream, and a broad grass, willow, and pine-covered floodplain.

The headwaters of the stream currently drain directly from the Glengarry mining adit on the southeastern end of Fisher Mountain, over small piles of tailings, and into a sediment containment pond. During low-flow conditions, the waters draining the mine may have a pH as low as 2.5–2.9 and total dissolved solids and Cu concentrations of 800 ppm and 4 ppm, respectively (Barnhorst 1995; Fantle 1997). Little or no vegetation is visible by the stream channel or the small tailings piles at the headwaters; however, within 250 m grasses and trees are found bordering the stream. By 1 km from the source the low-flow pH increases from ~2.5 to ~4 (Barnhorst 1995; Fantle 1997). Within 3 km from the source, the low-flow pH of the stream is above 6 (Fantle 1997).

Over the ~8,000-year history of sedimentation in Fisher Creek, long- and short-term climatic variations have resulted in episodic terrace formation. Work by Meyer and others (1995) has suggested five major periods of terrace construction in the Yellowstone region dating from before 8,000 B.P., 7,000–5,600, 3,100–2,600, 2,000–1,300, and post 800 years B.P., but only three distinct terraces have been identified in Fisher Creek in this study, two of which date from 8,220 and 860 years B.P. These former floodplains record sediment transport and storage in Fisher Creek, and typically evidence baseline historic metal concentrations, while surface deposits and young terraces are more likely to represent active metal deposition due to mining activity (Leenaers and Schouten 1988; Macklin and others 1994; Taylor 1996).

The Fisher Creek basin lies in the Beartooth Uplift, a large N–S fault block of uplifted sequences of Cambrian to Ordovician shales and limestones and Precambrian granites and gneisses (Elliot 1979; Wooden and others 1982; Kirk and Johnson 1993). Felsic to intermediate Tertiary intrusives of dominantly rhyodacitic composition ring the Fisher Creek valley, and are thought to be the heat source responsible for the metal deposits of the New World Mining District (Elliot 1979; Wooden and others 1982, Kirk and Johnson 1993).

▶

Fig. 2
Iron concentrations and flood surfaces for Fisher Creek transects FC 1, 5, 6, 2, 7, 3, and 4. Each cross section displays iron concentrations (ppm) in the <63 μm fraction of sediments, and HEC-RAS estimated flood surfaces for the 2.33, 33, and 100-year floods. *Black circles* indicate position of dated organic material

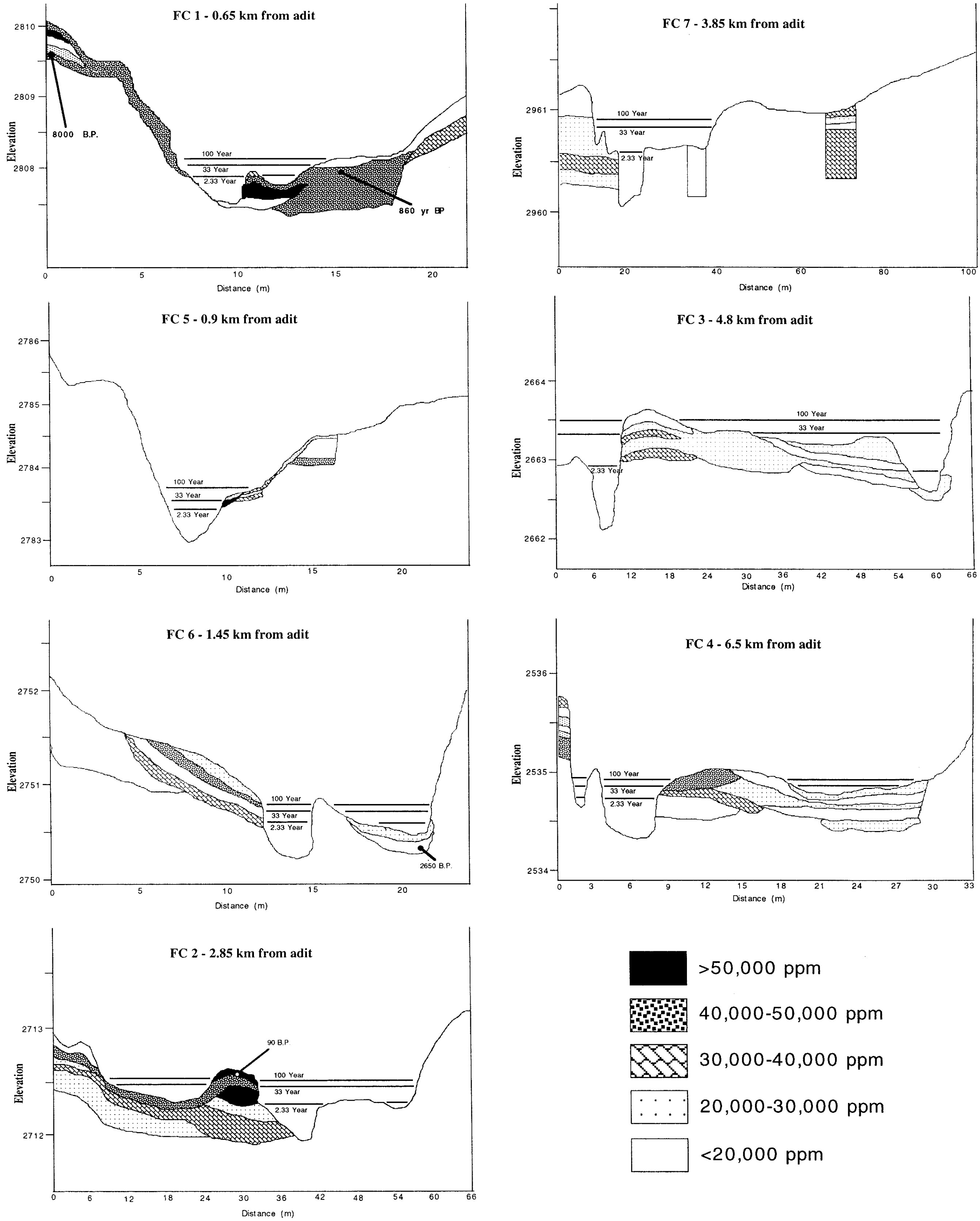
Mining history

Mineral resources were first discovered by trappers in the Cooke City area in 1869. Mining operations on Fisher and Henderson Mountains began with small-scale gold and silver mines in 1888, but large-scale development of mines along the sides of Fisher and Henderson mountains did not begin until the early part of the twentieth century (Elliot 1979; Nelson and Williams 1984). These mines operated until 1930, producing numerous small piles of tailings and crushed ore material. Large-scale gold production in the New World Mining District commenced in 1938 with the opening of an open pit mine on the back side of Fisher Mountain, and continued operating until the mill fire of 1953 put an end to mining activities (Elliot 1979). During the period of operation, however, ore crushing and milling processes yielded sand-size and finer particles. Much of these tailings were used as backfill for removed rock, but today large piles of finely ground rock and coarse gravels can be found near the headwaters of Fisher Creek.

Field and laboratory methods

To examine the spatial and temporal distribution of metals in the overbank sediments of Fisher Creek, a total of 15 transects were surveyed from 0.35 to 6.5 km from the Glengarry adit over the course of 3 years. Seven transects (FC 1–7) were selected with distinct floodplain and terrace features as sample locations for sediment analyses for metals (Fig. 2). At each sampling site, four pits were spaced and dug from 0 to 70 m from the present-day stream channel in an attempt to understand the spatial controls of metal deposition in overbank alluvium (pits were used rather than sediment cores due to the gravelly nature of the deposits), and to sample both modern and ancient overbank alluvium. Each pit was dug to a minimum depth of 0.4 m with a stainless-steel shovel, with the exception of seven pits where large cobbles or the water table impeded further penetration. A total of 191 sediment samples were taken at regular depth intervals of 5 cm, but, in some instances, were sampled on smaller increments. All sediment samples were stored in plastic Ziploc bags and shipped to Dartmouth College, where they were stored at 4 °C until sample preparation.

Each sample was dried at 65 °C for 24 h and sieved to separate the <63 μm fraction. One gram of the <63 μm fraction was place in an acid-washed vial and filled with 10 mL of 1 M HNO_3 and shaken for 1 h. The tubes were



then heated in an 85 °C hot bath for 6 h, and shaken again for 1 h. The solution was separated from the sediment through centrifugation and filtration and brought to 12.5 mL with 1 M HNO_3. The concentrations of iron, copper, and base metals were determined through ICP-OES analysis; reproducibility of the results was within 10%.

It is important to note that this technique is designed to analyze only leachable metals bound to the clay and silt-size fraction of the sediment rather than determine the total metal content of the mineral components of the sediment itself (Herr and Gray 1997). This method leaches metals primarily from the sulfide, organic, and carbonate fractions of sediments. However, in this application most metals dissolved in the leachate are derived from the sulfide and carbonate fractions, as overbank sediments contain low organic contents. As a result, organic matter–metal relationships are not likely to significantly affect the spatial distribution of Fe and Cu in sediments. Organic material collected for ^{14}C analysis was analyzed using standard radiometric dating and accelerated mass-spectrographic dating by Beta-Analytic, Inc. Organic content was determined by LOI. Stream cobbles were statistically sampled to estimate the amount of ore-rock as a percentage of total stream cobbles using the methods devised by Wolman (1954).

Flood frequency analysis

HEC-RAS (Brunner and others 1996) water surface profile analysis provides a useful model for estimating the geomorphological impacts of floods of varying magnitude on streams such as Fisher Creek (Feldman 1981; Hoggan 1989). HEC-RAS calculates channel flood stage and other hydraulic variables (e.g., shear stress, velocity, etc.) for a given design discharge (e.g., 2–100-year floods) from field-derived channel data by using a standard-step iterative process to reconstruct water surface profiles (cf. Hoggan 1989). However, the development of accurate HEC-RAS flood surface models requires accurate streamflow inputs.

No historical records of stream discharge are available for Fisher Creek; therefore flood discharges were estimated through the development of a regional flood frequency model. Because Fisher Creek is a small alpine drainage and large floods are primarily driven by spring snowmelt, 11 streamflow gauges were selected from streams within a 100 km radius of Fisher Creek to develop the localized flood frequency model. These gauges were chosen because of similarities to Fisher Creek in climate, altitude, and drainage size. Several of the selected gauges contained shorter record lengths than normally desired; however, record homogeneity was evaluated using Dalrymple's homogeneity test (Dunne and Leopold 1978).

Each discharge record was independently analyzed based on the techniques described by Dunne and Leopold (1978) to determine the mean annual discharge (Fig. 3). This technique analyzes the annual-maximum series of discharges for a stream and estimates recurrence intervals for each discharge based on the formula $T=(n+1)/m$, where T is flood recurrence interval, n the number of discharge events, and m the rank of a given discharge in the series (Dunne and Leopold 1978). Because 11 stream records were used from various elevations, the graph was divided into elevation isograds to more accurately predict the discharge of the mean annual flood for varying drainage sizes and elevations (Fig. 3).

The discharges of floods of decreasing recurrence (for a given drainage area) were estimated by multiplying the mean annual flood discharge with the median $Q_T/Q_{2.33}$ ratio for a flood of a given recurrence for the regional data set (Fig. 4) where Q_T is the discharge of a given recurrence interval T, and $Q_{2.33}$ is the mean annual flood. This technique compares the discharge (m^3/s) of floods of varying probabilities to the discharge (m^3/s) of the mean annual flood to develop a regional modeling relating flood discharge and the mean annual discharge (Dunne and Leopold 1978). This regional model was used to estimate Fisher Creek stream discharges for floods with a recurrence interval greater than the 2.33-year flood.

Carter and Green (1963) and Patterson (1966) previously estimated the mean annual discharge for streams in northwestern Wyoming and the upper Clark's Fork River.

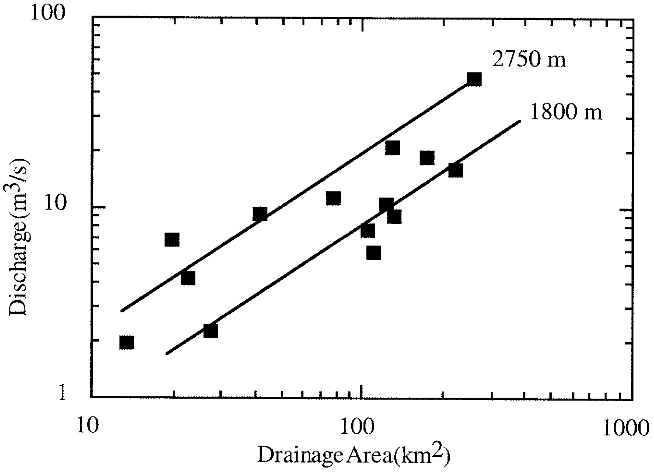


Fig. 3
Regional flood model: mean annual discharge and drainage area. *Black squares* indicate mean annual discharge (m^3/s) and drainage area (km^2) for each stream used in the model. *Black lines* (2,750 and 1,800 m) separate streams by elevation

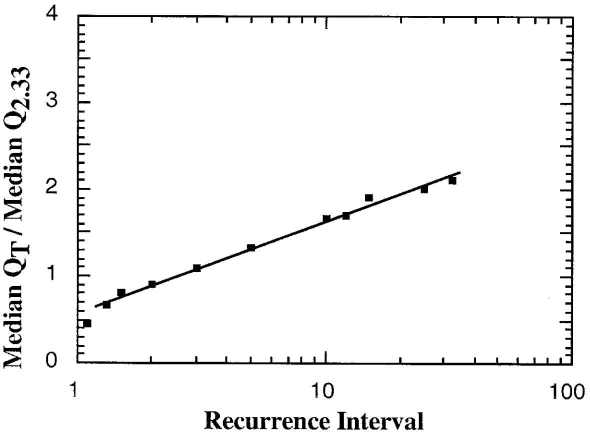


Fig. 4
Regional flood model: ratio of median discharge for floods of varying recurrence intervals (years) to median discharge of mean annual flood

The regional flood model used in this paper attempts to more specifically select streams with characteristics similar to Fisher Creek. However, it is important to note that there was agreement to within 5–10% between our model and those previously published (Carter and Green 1963; Patterson 1966). The discharges ultimately used as inputs in the HEC-RAS flood surface modeling were a combination of our regional flood model and the two previously published, and based on the following equation plus 10%:

$$Q_{2.33} = [0.183(A)^{85} H^{2.43}] \tag{1}$$

where A is drainage area in square miles; H is elevation in thousands of feet; and Q is in cfs (Patterson 1966). The estimated discharges for floods of varying recurrences at each surveyed transect are shown in Table 1.

The HEC-RAS flood surface modeling program calculates water surface profiles for various discharges based on the known channel geometry, calculated flood frequency, and estimated channel roughness and slope (Feldman 1981; Hoggan 1989). Channel geometry, reach length, and slope were determined through topographic surveys of Fisher Creek, while Manning's roughness coefficient was estimated for each transect based on the work of Barnes (1967), Limerinos (1969, 1970), and Jarrett (1985). Because portions of Fisher Creek have a slope of nearly 10%, and the reach lengths between Fisher Creek transects were near the limits of the ability of HEC-RAS to accurately describe water surface profiles, the model may have less than the typical 95% accuracy for a given flow on a stream profile. However, sensitivity analysis of variables such as the Manning's roughness coefficient, starting water elevation, and flow regime showed low sensitivity for the generation of modeled water surface elevations for a given discharge. The dominant source of error in the HEC-RAS flood surface model occurs in the flow inputs and channel geometry. Both dendrochronologic dating of modern trees (>75 years old) directly bordering Fisher Creek and the regional stream discharge records from the Yellowstone region indicate that Fisher Creek has not experienced a flood greater than the 100-year event during or after the initiation of mining activity. Therefore, this paper classified surface sediments (<10 cm) inundated by the 100-year flood as "active" in the post-mining period, and all other sediments above the 100-year flood surface as "non-active" in the post-mining period.

Site descriptions

This paper used sampled overbank sediments at seven sites along Fisher Creek over the course of 2 years. These sites ranged from narrow wooded stream valleys to broad floodplains and are given the names FC 1, FC 2, FC 3, FC 4, FC 5, FC 6, and FC 7. Because sampling took place over a period of 2 years, site numbers do not follow numerically, but rather are listed in order of distance from the Glengarry adit and described in Table 2.

Results

Several results follow from the geochemical and flood modeling studies of the Fisher Creek basin. These results are as follows:

1. Sediments in the Fisher Creek drainage range in composition from coarse gravel to silts and fine clays. The deposits vary locally, and sediment variations may be used to interpret stream channel migration. Radiocarbon dating of organic material in overbank sediments suggests minimal channel migration in the upper reaches of Fisher Creek in at least the past ~2,700 years B.P. (Fig. 2), and an extensive history of metal transport and deposition.
2. At least three distinct terraces are present in Fisher Creek at sites FC 1 and FC 2 (Fig. 2), and at least two terraces at each other site. The lowest and highest terraces at site FC 1 date to ~860 and ~8,220 years B.P., respectively. In addition, a preserved charcoal layer in site FC 6 dates to 2,650 years B.P. These two dated

Table 1

Stream discharges for floods of varying recurrences for each site in Fisher Creek. Recurrence intervals is in years and discharge is in m^3

Site	Recurrence interval (years)							
	2.33	5	10	12	15	25	33	100
FC 1	0.70	0.93	1.18	1.20	1.34	1.41	1.47	2.1
PC 5	1.00	1.33	1.68	1.71	1.91	2.01	2.10	3.00
FC 9	1.10	1.46	1.85	1.88	2.10	2.21	2.31	3.30
FC 6	1.30	1.73	2.18	2.22	2.48	2.61	2.73	3.90
FC 10	1.45	1.93	2.44	2.48	2.77	2.92	3.05	4.35
FC 11	1.70	2.26	2.86	2.91	3.25	3.42	3.57	5.10
FC 2	1.90	2.53	3.19	3.25	3.63	3.82	3.99	5.70
FC 12	1.95	2.59	3.28	3.33	3.72	3.92	4.10	5.85
FC 8	2.05	2.73	3.44	3.51	3.92	4.12	4.31	6.15
FC 7	2.25	2.99	3.78	3.85	4.30	4.52	4.73	6.75
FC 13	2.37	3.15	3.98	4.05	4.53	4.76	4.98	7.11
FC 14	2.45	3.26	4.11	4.19	4.68	4.92	5.15	7.35
FC 3	2.55	3.39	4.28	4.36	4.87	5.13	5.36	7.65
FC 15	2.71	3.60	4.55	4.63	5.18	5.45	5.69	8.13
FC 4	2.40	3.19	4.03	4.10	4.58	4.82	5.04	7.20

Table 2
Site descriptions for FC 1, 5, 6, 2, 7, 3, and 4, listed in order of distance from the Glengarry adit (km) and elevation above sea level (m)

Site	Distance	Elevation	Comments
FC 1	0.65	2,800	Sand and gravel close to the stream channel, dark silts and organics on upper surfaces; west bank steep and covered by sparse grass and shrubs; marked by small terrace bordering base of an avalanche chute; east bank marked by a low grassy floodplain and higher grassy terrace; surface is covered by grass and 5–10 year old spruce trees; samples run perpendicular to point bar and floodplain at distances of 0, 11, 16, and 22 m; flat charcoal layer at 42 cm in the 0 m pit dates 8,220 years B.P., spruce tree at 15 cm deep in 16 m pit dates 860 years B.P.; ancient and modern Fe-oxide deposits present
FC 5	0.9	2,770	Area surveyed approximately 30 m wide; current stream channel roughly 2.5 m wide and bordered by steep dirt slope on the west, and a low grass covered slope on the east; stream channel filled with cobbles and small boulders. No dates exist for sediments at this location; massive ferricrete outcrop perched several meters above the present stream channel; modern Fe-oxide deposits present
FC 6	1.45	2,740	45 m transect, main channel ~5 m wide; between 22 and 39 m, channel, cobble, and gravel bar, and former meander evidenced; west side of stream is broad, low sloping surface covered by grass; east bank comprised of steep muddy slope with few trees >40 years old; charcoal layer at 18 cm deep in 22 m pit dates to 2,650 years B.P.; ancient Fe-oxide deposits present
FC 2	2.85	2,700	100–200-m-wide floodplain, bounded by Henderson and Sheep Mtns to SW and NE, respectively; transect cuts across long point bar covered by spruce and pine of varying ages; three terraces evidenced, spruce and pine on highest terrace (~100 years old), and young (~20–30-year-old) trees on lower terrace; east overbank covered with gravelly sand and thick willow; distinct charcoal layers in 30 m pit at depths of 30 and 38 cm; stream channel full of large cobbles stained by metals; no evidence of modern or ancient Fe-oxides
FC 7	3.85	2,680	Wide, grassy floodplain and wet meadow; area surveyed over 100 m wide, and current channel ~5 m wide; gravel and cobble covered floodplain sits 50 cm above base of the active channel, and old cut bank evidenced near 40 m mark; above this cut bank is long, flat floodplain surface with small drainages running through it; no dates are available for this site
FC 3	4.8	2,660	Thickly wooded on east bank, bounded by heavily cobbled west bank; transect cuts across infilling meander and point bar; site displays lateral migration of stream channel and provides obvious age differences by sampling location along the meander bend; sediment variation in pits evidences point migration; west overbank area of main channel extends for 30 m on long sloping grassy area; eastern overbank of old meander rises sharply up a wooded hillslope
FC 4	6.5	2,540	Several hundred meters above confluence of Fisher Creek and Lady of the Lake Creek; flow divided into two channels; transect cuts wide, low, point bar bounded by steep valley walls: bar covered with short, young vegetation, and is comprised primarily of river sands and gravels; two raised, heavily vegetated terraces on west bank; stream channel somewhat stained by Fe- and Mn-oxide precipitation, but coloration slighter than at any previous site

terraces at site FC 1, and the dated charcoal unit at site FC 6, all correspond in ages to periods of overbank deposition and terrace formation found nearby in streams in Yellowstone National Park (Meyer and others 1995). This correlation between periods of sediment accumulation in Fisher Creek and in streams found in Yellowstone National Park suggests that undated terraces in Fisher Creek may serve as a proxy for estimating the minimum age of a sedimentary deposit.

3. Overbank deposits at Fisher Creek contain higher concentrations of Fe and Cu than would be expected from weathering of local bedrock alone. The highest metal concentrations evidenced are located in the uppermost 2.85 km of the Fisher Creek drainage, in the steep sloped FC 1, and the broad valley at FC 2 (Fig. 2). These two locations contain several sediment units with leachable Fe concentrations of >50,000 ppm, and, in some instances, up to 100,000 ppm (Table 3; Fig. 2). However, sediments with Fe concentrations ranging between 40,000 and 50,000 ppm are found throughout all examined cross sections, though are more common in the upper 2–3 km of the stream (Table 3; Fig. 2). Because Fe shows the greatest variation in concentration in the sediments, is present in high concentrations in ore rock, and is the dominant metal in Fisher Creek (Horton and others 1999), it is used as a primary indicator of metal contamination in sediments.
4. Both Fe and Cu exhibit a unique distribution of metals with distance from the mining adit. In sediments classified as "active" during the period of mining activity (those surface sediments impacted by floods of a recurrence of 100 years or less) Cu and Fe exhibit different trends (Fig. 5). Rather than a typical distance decay pattern, mean Cu concentrations tend to increase with distance from the current point source of metals, the Glengarry adit, to a peak concentration at 3–4 km. Iron, on the other hand, displays statistically equal concentrations 1 km from the adit and 6.5 km from the adit, and little variation with distance. However, similar to Cu, Fe exhibits peak concentrations 3 km from the mining adit.
5. Sediments classified as "non-active" during the period of mining activity (sediments that will not be covered by a flood of a recurrence interval less than once, on average, in 100 years) display a sharp increase in mean metal concentrations with distance from the mining adit, to a peak at 3–4 km (Fig. 5). Beyond this distance, both Fe and Cu concentrations are observed to decrease to their lowest mean concentrations in sediment.
6. Iron and copper are found in higher mean concentrations in "active" sediments 4–7 km from the adit than "non-active" sediments of the same distance. However, "active" and "non-active" sediments contain similar mean concentrations of Fe and Cu in the uppermost 3 km of the stream.

Table 3
Geochemical data for sites FC 1, 5, 6, 2, 7, 3, and 4. Numbers above each site's details indicate sample pits position for each transect. Depth is in cm below the surface, and iron and copper concentrations are listed in ppm

Site	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu
	0 m			11 m			13 m			16 m		
FC 1	0–5	46,606	340	0–5	35,097	117	0–5	15,138	641	0–5	3,482	988
	5–10	97,501	343	5–10	43,488	119	5–10	13,674	805	5–10	17,343	1,116
	20–28	17,065	1,375	15+	52,939	157	10–15	13,368	933	10–15	43,615	121
	35–40	28,588	763	10–15	8,214	786	15–20	14,148	1,638	–	–	–
	45–55	45,628	840	–	–	–	20–25	18,832	1,547	–	–	–
	72+	26,569	521	–	–	–	25–35	33,282	1,030	–	–	–
	–	–	–	–	–	–	35+	38,363	1,205	–	–	–
	9.8 m			11.7 m			16 m			20.6 m		
FC 5	0–6	23,511	650	0–2	27,660	813	0–2	21,548	1,150	0–2	11,153	503
	6–8	61,886	925	2–5	34,755	1,200	2–5	12,390	2,350	2–5	22,235	796
	–	–	–	5–10	36,113	3,063	5–10	29,610	2,775	5–10	13,909	1,110
	–	–	–	15–20	–	900	10–15	12,879	2,100	10–15	13,808	1,816
	–	–	–	–	–	–	15–20	7,827	2,000	15–20	8,529	2,071
	–	–	–	–	–	–	35–40	38,420	5,300	20–25	6,106	931
	–	–	–	–	–	–	–	–	–	25–30	22,515	1,950
	3 m			13 m			22 m			39 m		
FC 6	0–5	24,386	2,138	0–5	30,046	1,188	0–5	27,026	913	0–3	27,636	900
	5–10	5,523	3,163	5–10	30,078	1,738	5–10	39,432	–	3–10	24,045	263
	10–15	7,594	760	10–15	4,933	614	15–20	6,535	320	10–15	–	–
	15–20	6,963	823	15–20	9,295	695	20–25	14,734	756	15–20	9,379	216
	20–25	8,499	1,675	20–25	11,338	1,038	25–30	31,009	679	20–25	11,274	242
	25–30	8,485	1,017	25–30	13,386	699	–	–	–	25–30	9,635	263
	30–35	7,484	895	30–35	13,244	734	–	–	–	30–35	9,417	221
	35–45	7,869	861	–	–	–	–	–	–	35–40	11,054	335
	0 m			13 m			23 m			30 m		
FC 2	0–5	34,030	614	0–5	42,808	1,527	0–5	47,000	1,555	0–5	62,113	2,682
	5–10	36,545	1,975	5–10	29,661	1,407	5–10	32,469	1,733	5–10	48,305	1,826
	10–15	30,120	1,301	10–15	31,538	1,264	10–15	34,057	2,239	10–15	57,072	1,695
	15–10	18,780	62	15–20	33,074	1,845	15–20	36,034	2,377	15–20	63,281	1,896
	20–25	25,431	1,227	20–25	33,466	1,257	–	–	–	20–25	30,589	1,809
	25–30	19,090	1,349	25–30	22,869	1,170	–	–	–	25–30	27,855	1,839
	30–35	30,484	1,096	35–45	30,703	1,199	–	–	–	30–35	23,111	1,143
	35–45	33,925	1,205	–	–	–	–	–	–	40–45	31,442	1,445
	44–55	25,599	747	–	–	–	–	–	–	–	–	–
	3 m			16 m			38 m			71 m		
FC 7	0–5	3,139	235	0–5	19,958	–	0–5	2,828	1,953	0–5	33,485	496
	5–10	4,442	213	5–10	32,233	–	5–10	2,742	1,155	5–10	25,714	236
	10–15	4,720	175	10–12	36,439	1,814	10–15	7,282	904	10–15	12,534	110
	15–20	9,668	211	12–15	31,639	1,712	15–20	1,341	1,125	>68	34,793	661
	20–25	21,461	373	15–17.5	30,419	1,345	25–30	14,515	1,360	–	–	–
	30–35	24,016	750	17.5–20	20,524	987	–	–	–	–	–	–
	–	–	–	20–22	24,884	1,030	–	–	–	–	–	–
	–	–	–	25–27	28,625	1,128	–	–	–	–	–	–
	18 m			30 m			45 m			51 m		
FC 3	0–2	14,407	601	0–5	22,777	628	0–5	26,865	602	0–5	27,435	641
	2–5	3,087	36	5–10	30,951	708	5–10	21,709	651	–	–	–
	5–10	27,492	594	10–15	29,214	360	10–15	17,083	598	–	–	–
	10–15	22,169	911	15–20	28,955	455	15–20	22,743	850	–	–	–
	15–20	32,133	770	20–25	31,666	517	25+	17,561	718	–	–	–
	20–15	25,425	753	25–30	27,212	697	–	–	–	–	–	–
	25–30	22,470	580	30–35	18,027	762	–	–	–	–	–	–
	30–35	27,034	715	–	–	–	–	–	–	–	–	–
	35–45	26,358	813	–	–	–	–	–	–	–	–	–
	65+	38,696	1,502	–	–	–	–	–	–	–	–	–
	0 m			10 m			16 m			22 m		
FC 4	0–5	15,448	316	0–5	30,849	1,315	5–10	17,378	757	0–5	29,879	788
	5–10	11,510	397	5–10	32,027	1,370	10–15	19,115	882	5–10	15,285	698
	10–15	22,264	535	10–15	20,151	841	15–20	21,148	1,506	10–15	20,229	842
	15–20	20,179	668	15– 20	30,808	1,663	20–25	21,092	1,545	15–20	7,215	344

Table 3
(Continued)

Site	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu	Depth (cm)	Fe	Cu
		0 m			11 m			13 m			16 m	
	20–25	12,263	–	20–25	18,121	393	35–45	22,611	1,516	20–25	13,143	902
	25–30	20,625	689	–	–	–	–	–	–	35–45	23,390	1,041
	35–45	29,394	643	–	–	–	–	–	–	–	–	–
	50–60	30,979	557	–	–	–	–	–	–	–	–	–

7. HEC-RAS flood surface modeling and geochemical analyses of overbank deposits indicate a correlation between Fe, and, to a lesser extent, Cu concentration in the upper 10 cm of sediment and the frequency with which a surface is flooded (Fig. 6). If mine tailings and sediments at the headwaters of the creek are the current dominant source of Fe and Cu, this relationship suggests that Fisher Creek is currently in a period of deposition of sediments with elevated Fe and Cu concentrations, and that flood recurrence probabilities control the distribution of these fluvial sediments over the Fisher Creek valley.

Discussion

The results of the study of the overbank alluvium of Fisher Creek, New World Mining District, Montana, have important implications to the understanding of the distribution of metals in these sediments, and the ability to distinguish mining related sedimentation from naturally metal-rich sediments. Three important conclusions may be drawn from this study: (1) elevated Fe and Cu concentrations in overbank deposits in Fisher Creek result from both natural and anthropogenic processes; (2) mining activity resulted in the transport and deposition of sediments with high concentrations of Fe and Cu; and (3) sediments pre-dating mining activity contain Fe and Cu concentrations as great as those found in modern sediments. These conclusions are discussed below.

Mining-related sedimentation

Despite the difficulties in distinguishing natural from anthropogenically influenced sedimentation in a naturally metal-rich region, the results from this study indicate that post-mining sediments in general contain Fe and Cu at concentrations greater than most of the pre-mining sediments, and their distribution reflects the frequency with which a surface is flooded and the distance from the adit. These findings suggest that mining activity has increased the input of Fe and Cu to Fisher Creek, resulting in the transport and deposition of metal-rich sediments. Several

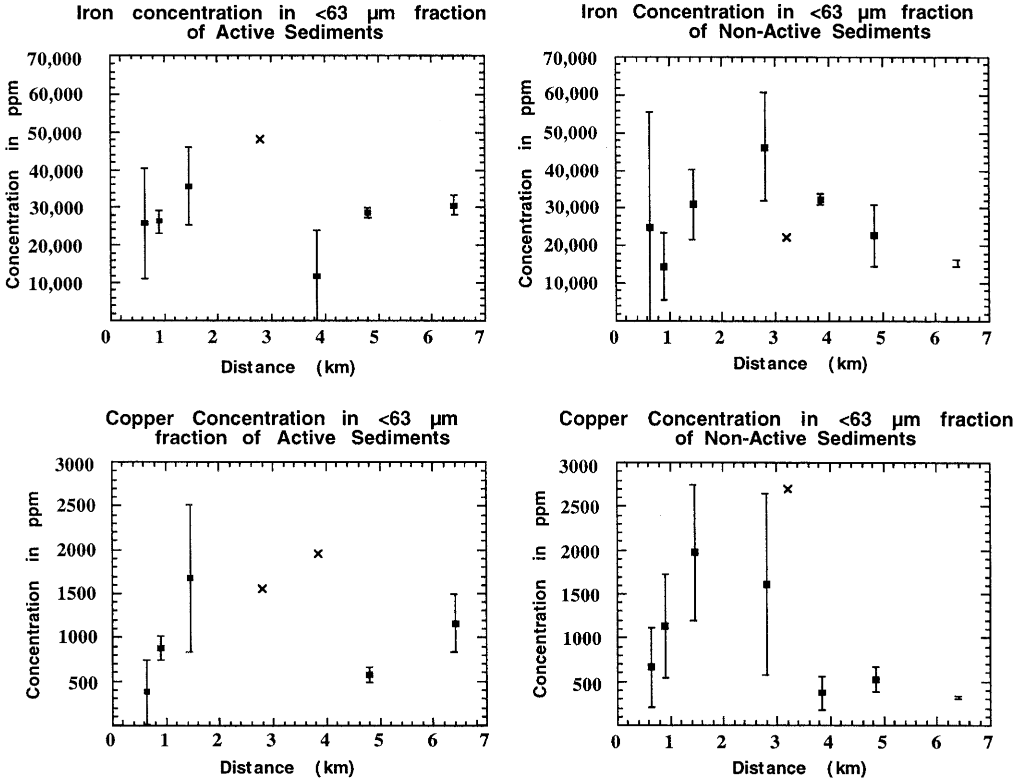


Fig. 5
Iron and copper concentrations in the <63 μm fraction of active (below the 100-year flood surface), and non-active (above the 100-year flood surface) sediments and the distance from the Glengarry adit. *Black squares* indicate mean iron and copper concentrations, *black lines* indicate 1 standard deviation from the mean. *Crosses* indicate metal concentration for sites with only one data point

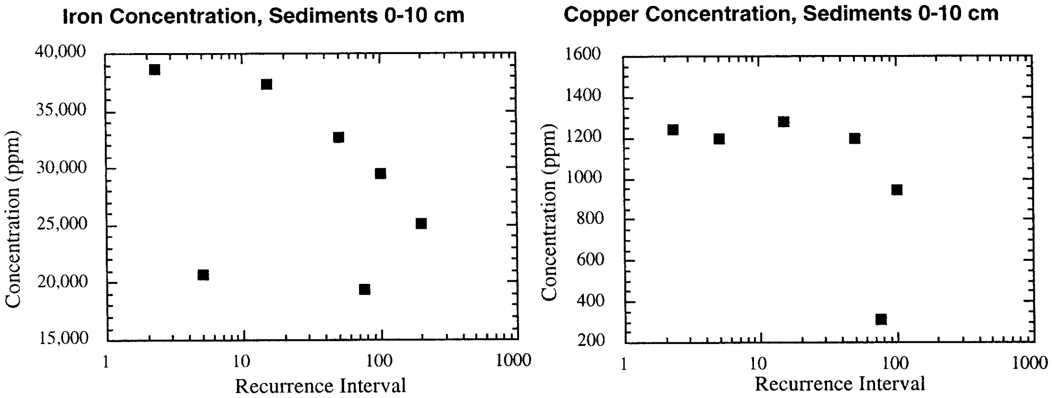


Fig. 6
Mean iron and copper concentrations in the <63 μm fraction of surface sediments and the recurrence interval (years) of the flood magnitude needed to inundate that surface

results support these findings. First, Fe and Cu display a logarithmic relationship between metal concentrations in surface sediments and the recurrence interval with which the surface is flooded (Fig. 6). Surfaces that are flooded more frequently display greater concentrations of Fe and Cu than surfaces that have been flooded only once or twice in the post-mining period. Second, in the floodplain of Fisher Creek, approximately 2.85 km from the Glengarry adit, post-mining sediments have high Fe and Cu concentrations. Here (site FC 2) approximately 20 cm of sediments have accumulated in the past 90 years, with Fe concentrations of up to 60,000 ppm and Cu up to 2,600 ppm (Fig. 2). Third, surface sediments 4–7 km from the Glengarry adit, that have been "active" during the period of mining activity, display greater concentrations of Fe and Cu than "non-active" sediments of the same distance (Fig. 5).

These results suggest that mining activity near the headwaters of Fisher Creek and in the Glengarry adit has increased metal deposition by changing the degree of interaction of water with exposed sulfidic minerals. One of the major inputs of Fe and Cu to streams in metal-rich regions is the mechanical and chemical weathering of sulfides through acid rock drainage. In the metal-rich rocks found at the headwaters of Fisher Creek, Fe- and Cu-bearing sulfides naturally react with oxygen and water (Garrels and Christ 1965) to produce sulfuric acid and liberated Fe and Cu ions. As these metals are transported in solution, changes in the chemical conditions of the stream can cause the Fe to precipitate out of solution in the form of Fe-hydroxides in the stream channel or in overbank sediments, as evidenced by the numerous iron oxide (ferricrete) deposits in Fisher Creek. However, the rate of transport and deposition of the metals is limited by: (1) the chemical and physical conditions of the stream, (2) the supply of metals, and (3) the rate of weathering and erosion. Clearly mining activity at the headwaters of Fisher Creek has increased both the volume of sulfide-rich material introduced to the stream and the exposed surface area of sulfidic material, resulting in greater mobilization of Fe and Cu and visible accumulation of these metals in mining-related sediments. However, the geochemical and modeling analyses of overbank sediments from Fisher Creek allows assessment of the controls of distribution of metals downstream.

Based on the flood modeling and geochemical analyses, the distribution of metals in mining-related sediments in Fisher Creek is controlled by three important factors. These are: (1) a current point source input of metals; (2) the distance from the source of metals and the hydraulic conditions and trap efficiency of the depositional sites; and (3) the frequency with which sediments are deposited or eroded from a surface. Evidence for a point source comes from studies of stream waters which suggest that waters draining the Glengarry adit are the primary source of metals (Nelson and Williams 1984; Fantle 1997). The chemical analyses of overbank sediments partially support this, as evidenced in the longitudinal distribution of Cu in "active" sediments along the length of Fisher Creek (Fig. 5). Cu is found in low concentrations close to the adit, where the stream slope is steep and trap efficiency low, and peaks in the broad floodplain 2–4 km from the adit (site FC 2; Fig. 5). Beyond site FC 2, where stream slope is relatively constant, mean Cu concentrations decrease with distance from the point source. Iron concentrations in "active" sediments do not show a similar longitudinal distribution. However, Fe and Cu show greater concentrations in "active" than in "non-active" sediments 4 to 7 km downstream of the adit, which suggests that mining has increased deposition of these metals in the stream. It is unclear why Fe does not show a similar longitudinal profile as Cu in "active" sediments, but it is interesting to note that Fe does show a similar distribution to Cu in "non-active" sediments.

The analysis further suggests that Cu and Fe concentrations in "active" sediments are controlled by the frequency with which sediments are deposited or eroded from a surface. This paper shows that surface Fe and Cu concentrations are logarithmically correlated to flood frequency (Fig. 6). This relationship suggests that surfaces that have been inundated more frequently since the onset of mining activity have greater concentrations of Fe and Cu in sediments. This finding is consistent with the expected distribution from a point source of contamination at the headwaters of Fisher Creek. Two data points fail to fit the Fe and Cu concentration and flood frequency relationship; however, these outliers are an expected result due to varying sediment trap efficiency and modern erosion of mining-related depositional surfaces.

Although HEC-RAS (Brunner and others 1996) provides a unique means of distinguishing the potential zone of impact of mining-related sedimentation on a drainage, this method is complicated by: (1) channel migration and (2) aggradation during the mining and post-mining period. The increased sediment loads often associated with the initiation of mining activity may cause the channel bed to aggrade, ultimately altering the frequency with which surfaces are inundated. In addition, the remobilization of sediments through the lateral migration of stream channels may result in the transport and deposition of older sediments on younger surfaces. However, channel migration and aggradation are not significant factors in the control of metal distribution in Fisher Creek for the following reasons. First, several meters from the active stream channel, sediments at 15, 22, and 42 cm depths are dated at 860, 2,650, and 8,220 years B.P., respectively (Fig. 2; see sites FC 1 and FC 6). These dates are believed to be accurate, as the dated charcoal is from several discrete layers found throughout the drainage, and the wood from fragments of complete, buried trees. Thus, Fisher Creek has experienced minimal channel migration, at least in these two sites, during the post-mining period, which supports the hypothesis that metal-rich sediments are controlled by overbank deposition rather than lateral migration of the stream channel.

In addition, any aggradation of the Fisher Creek stream channel during post-mining activity has not significantly influenced deposition of metal-rich sediments over channel banks. There is some evidence that the stream channel may have aggraded in the last 100 years. This is evidenced by gravel deposits on overbank surfaces at site FC 6 and 10–20-cm-thick modern sediments near the 100-year flood surface at site FC 2. However, any significant aggradation is limited to these two sites and may not be a direct result of mining. Here, stream cobbles and overbank gravel are large, subrounded fragments of ferricrete and felsic igneous rocks, rather than fine-grained mine tailings, suggesting no direct link to mining activity. Furthermore, site FC 1, the site closest to the adit, indicates no aggradation, as there is only 15 cm of overlying sediment on a tree dating to 860 years (Fig. 2). However, even with minor aggradation the general relationships between flood frequency and metal deposition should not change significantly.

Pre-mining sediments

Previous studies (Macklin 1985; Leenaers and Schouten 1988; Macklin and others 1994; Taylor 1996) have shown that sediments pre-dating mining activity display uniform background metal concentrations, while the initiation of mining activity is frequently marked by a sudden increase in metals in young sediments. Unlike these studies, however, this paper shows that metal concentrations in pre-mining sediments are commonly as great as in post-mining sediments. As such, the analysis of Fisher Creek demonstrates that overbank sediments can serve both as a record of mining history and pre-mining metal transport. As shown here, sediments from Fisher Creek display elevated metal concentrations in sediments post-dating mining activity. However, the results also suggest that Fisher Creek sediments that pre-date mining activity naturally contain concentrations of Fe and Cu, in some cases as great as those found in modern, mining-related sediments. This conclusion is supported by the following evidence: (1) ~8,000-year-old Fe-oxide deposits are found in the uppermost 1.5 km of Fisher Creek (Furniss and others 1999); (2) radiocarbon dating of organic material in Fe- and Cu-rich layers indicates ages of up to 8,220 years B.P. (site FC 1); and (3) metal-rich sediments are found above the 100-year flood surface. These three lines of evidence are discussed below.

1. Recent work by Furniss and others (1999) indicates that Fe-oxide deposits, some of which are over 8,000 years old, are found in the uppermost 2 km of Fisher Creek. This result suggests that Fisher Creek had relatively high Fe concentrations before mining activity (Furniss and others 1999). Thus, erosion of these ancient Fe-oxide deposits could have provided a major input of sediments with high concentrations of Fe and Cu to the stream. This suggestion is supported by a Wolman (1954) pebble analysis of stream cobbles in Fisher Creek, which indicates that Fe-oxides currently comprise a large portion of the stream bed load in the uppermost 2.85 km (~ 30% of the bed load), and are found as far as 7 km from the Glengarry adit, and rounded ferricrete pebbles are found in hand samples of pre-mining sediments, those above the 100-year flood surface.
2. Further evidence for natural deposition of metal-rich sediments comes from radiocarbon dating of organic material in overbank deposits. Sediments in several of the transects show evidence of elevated Fe and Cu concentrations in sediments that pre-date mining activity. For example, FC 1, the site closest to the Glengarry adit and the sulfide-rich rocks of Fisher and Henderson Mountains, contains wood and charcoal in sediments dated at 860 and 8,220 B.P. (Fig. 2). At this site, modern sediments taken from point bars and overbank deposits closest to the stream channel show Fe concentrations of <20,000 ppm. However, at this same site samples from sediments dating 860 years B.P. display Fe concentrations of 40,000–50,000 ppm. In addition, sediments in a terrace with charcoal dating to 8,220 years B.P. show Fe concentrations of >60,000 ppm.

   Furthermore, at sites FC 3 and FC 4, sediments with relatively high Fe concentrations (~39,000 and 31,000 ppm) are found in 65- and 50-cm-deep sediments below trees aged 100 and 125 years, respectively. In addition, both the sites are above the 100-year flood surface, which further supports the hypothesis that these are relatively old metal-rich sediments. Further evidence for pre-mining deposition of metal-rich sediments comes from site FC 2 located in the floodplain of Fisher Creek (Fig. 2). Pit samples from the highest terraces have Fe concentrations ranging from 20,000 to 40,000 ppm. The minimum age of this surface is at least 90 years, based on dendrochronology. However, the terrace is more likely older than 800 years B.P., based on the fact that: (1) the Yellowstone region has undergone several periods of terrace formation in the last 8,000 years (Meyer and others 1995); (2) Fisher Creek contains terraces from at least three distinct depositional periods, the youngest dating to 860 years B.P.; and (3) site FC 2 indicates at least two terraces in the transect, the lowest of which likely corresponds to the most recent period of overbank deposition (~800 years to present) in the Yellowstone region.

The geochemical analyses of overbank sediments also indicate that mean Fe and Cu concentrations in "active" and "non-active" sediments are similar in the uppermost 4 km of Fisher Creek (Fig. 5). Because "non-active" sediments are defined as those not impacted by a flow less than the 100-year flood, if only mining activity contributed to the metal load in Fisher Creek, these "non-active" sediments should have relatively lower Fe and Cu concentrations, which they do not.

3. HEC-RAS flood models indicate that the 100-year flood fails to inundate all surfaces with high Fe and Cu concentrations. Dating of modern trees (>70 years old) bordering the stream, stream discharge data for the Clark's Fork of the Yellowstone, and regional stream discharge records support the hypothesis that Fisher Creek has not experienced a flood greater than the 100-year magnitude during or after the initiation of mining activity. Therefore, fluvial deposits at sites FC 1, 5, 6, and 4, which contain sediments above the 100-year flood surface with iron concentrations >40,000 ppm, must be a result of natural transport and sedimentation processes (Fig. 2). While there is no firm evidence that Fisher Creek has experienced a flood event exceeding the 100-year flood during the period of mining activity, a flood event of the magnitude necessary to reach the FC 1, 8,220 year B.P. terrace is unrealistic for the modern hydrologic regime and no geomorphic evidence exists in the basin demonstrating that a catastrophic flood has occurred.

Taken together, these three lines of evidence suggest that Fisher Creek has experienced periods of deposition of metal-rich sediments for the past 8,220 years. However, lateral and vertical movement of metals within sedimentary sequences after deposition, and changes in the water table could all possibly complicate the interpretation that many of the metal-rich sediments pre-date mining activity. This research, however, suggests that these factors have minimal impact on the distribution of metals in Fisher Creek sediments for the following reasons. First, comparison of the concentrations of Fe and Cu in a nitric leach of sediments and sediment depth suggests minimal migration of these metals from mining-related sediments to non-mining sediments. Geochemical analyses of sediments indicate no consistent relationship between sediment depth, type, and metal concentrations. These findings suggest that Fe and Cu concentrations are independent of sediment permeability and composition, and are more likely a result of variations in the metal content of sediment at the time of deposition. Second, geochemical analyses of sediments taken from above and below the spring water table indicate no significant variation as a result of changes in this water surface. For example, sediments with elevated iron concentrations below the spring water table are only found at site FC 1, the site closest to the Glengarry adit. At this site, water from the stream may leach out into sediments and mix with more dilute waters, increasing pH and decreasing the solubility of metals such as Fe, thereby precipitating metals out of solution. However, if this were the case at all sites, metal concentrations in sediments adjacent to the stream would be greater than those found further away from the stream. The results show that there is no trend between metal concentration and distance to the stream, indicating that changes in the position of the water table do not significantly affect metal concentrations in the seven sites analyzed.

Conclusions

The main conclusions drawn from this paper, based on geochemical analyses of overbank sediments and HEC-RAS flood surface modeling of Fisher Creek of the New World Mining District, are: (1) sediments contain an ~8,000-year record of metal deposition indicating both modern, point source, and natural deposition of metal-rich sediments; (2) pre-mining sediments have concentrations of metals as large as post-mining sediments; and (3) natural, metal-rich sediments are found throughout overbank alluvium in Fisher Creek, independent of flood recurrence.

These results support an earlier study of this stream which suggests that Fisher Creek has been the site of high metal concentration for the last ~8,000 years (Furniss and others 1999). The results from this paper, along with those of Furniss and others (1999), suggest that data from both overbank deposits (this study) and Fe-oxide deposits should be used to assess realistic remediation strategies. Specifically, setting realistic goals on water quality requires knowledge of pre-mining concentrations and the results presented in this paper show that metal concentrations have been naturally elevated in Fisher Creek. In addition, the removal of the most contaminated sediments from the Fisher Creek basin requires removing ancient sediments well above the 100-year flood surface, which were deposited prior to mining activity.

In addition, this paper shows that the combination of geochemical analyses of overbank sediments and HEC-RAS flood surface modeling provides a powerful method for assessing the relative impact of anthropogenic and natural sources of metals within a stream system. Such an approach, as demonstrated here, enhances the understanding of the spatial and temporal distribution of metals in stream alluvium, and allows for the development of more accurate remediation strategies.

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