Hazardous Wastes from Large-scale Metal Extraction: The Clark Fork Waste Complex, MT

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Abstract

Large-scale metal extraction has generated extensive deposits of hazardous waste worldwide. Mining began more than 125 years ago in the Clark Fork drainage basin, western Montana, and contributed to primary, secondary and tertiary contamination over an area 115 the size of Rhode Island and along hundreds of kilometers of riparian habitat. This complex of waste deposits provides numerous examples of technically difficult problems in geochemistry I hydrology, ecology and epidemiology associated with characterizing, understanding and managing hazardous mine wastes.

Introduction

The "Superfund Act. (CERCLA) of 1980 signed into Federal law the first comprehensive authority to respond to and pay for the cost of releases of hazardous materials to the environment Coping with the magnitude and the diversity of the hazardous waste problems in the United States is an immense challenge, the ultimate cost of which is unknown. Others have reviewed the managerial and political challenges of hazardous waste clean up. (Freeze and Cherry. 1989) but the technical difficulties posed by the inherently complicated nature of some contaminated sites often are not adequately considered. A complex of waste deposits in the Clark Fork River basin of western Montana (Fig. I) is discussed here to illustrate the number of spatially extensive, complicated problems that can develop in association with large-scale metal extraction. We describe the historic activities in the Clark Fork complex and how modern contamination is a legacy of many of those activities. An analysis of existing understanding of the contamination is accompanied by a discussion of the processes that must be better understood for effective remediation. Finally we consider whether contamination in soils. Air, groundwater and surface water threaten human and ecological health. Our conclusions point out the difficulties in remediating large-scale hazardous waste problems and thus the importance and ultimate cost effectiveness of careful waste management reduction during production.

Discovery and Development

In 1805, Meriwether Lewis and William Clark began exploration of what is now Montana. Near the Clark Fork River basin, they described a “unique landscape of primitive beauty” filled with vast resources (Lang, 1988). Extraction of these resources to feed the developing new nation began several decades later, and the Clark Fork River basin has supported a variety of mineral extraction activities for more than 125 years.

Placer mining for gold in the headwaters of the Clark Fork River started in 1864. Prospectors and miners pouring into Montana depleted most of the gold-bearing gravel by 1869, but discovered silver-and gold bearing veins at Butte. Hard-rock mining of these ores climaxed in 1887 when 450 metric tons (MT)/day were processed by stamp mills. When the price of silver fell in 1892, production waned and the last of the large silver smelters closed in 1896. Copper was first located in 1864. By 1896, over 4,500 MT of ore per day was being smelted, and construction of one of the world's largest smelting plants had begun 40 km west of the mining operations at Anaconda (fig. 1). By the early 1910's the new smelter was processing 11,500 MT of ore per day. Depressed copper prices forced closure of that smelter in 1980. In 1955, underground mining of high-grade ores in Butte was superseded by large-scale open-pit mining. Underground operations ceased in 1976. Mining of the largest open pit stopped in 1983, but has resumed in recent years along with limited underground operations.

When the smelter at Anaconda stopped production, over 1 billion MT of ore and waste rock had been produced from the Butte district. From 1880 to 1964, 297 million MT of ore was removed from an unrecorded amount of total material (Johnson and Schmidt, 1988). Total ore production through 1972 was 411 million MT, with 715 million MT of material removed from the Berkley Pit between 1955 to 1973 (Miller, 1973). In 1973 approximately 225,000 MT of rock and 43,000 MT ore was produced per day from the pit alone. That level of production continued until 1983 when major production stopped, accounting for an additional 675 million MT of waste rock and ore.

Touted as the "richest hill on Earth", Butte produced more metals than the Leadville district in Colorado or the Comstock Lode in Nevada (Lang, 1988). The mining and smelting operations that produced this vast wealth left behind massive deposits of waste covering an area 1/5 the size of Rhode Island. The Clark Fork waste complex encompasses four Superfund sites, including 35 km of tailings ponds, more than 300 km of soil contaminated by air pollution, over 50 km unproductive agricultural land and hundreds of km of contaminated river bed a of riparian floodplain habitat along the largest tributary of the Columbia River.

Characteristics or Contamination

Ultimately the hazardous waste problems associated with mineral extraction are determined by the characteristics of the ore and the specific processes employed to extract metals from it. The original geological studies showed that the ore body at Butte consisted of high-grade metal sulfide veins enclosed in lower-grade altered rock (Meyer et al, 1968). The predominant copper minerals were chalcocite (Cu S) bornite (Cu FeS), chalcopyrite (CoFeS), enargite (Cu AsS) and tennantite-tetrahedrite (Cu (As, Sb) S). Other associated metal sulfides included sphalerite (ZnS), pyrite (FeS), acanthite (Ag S), galena (PbS), arsenopyrite (FeAsS) and greenockite (CdS) (Weed, 1912). The richest vein deposits contained up to 80% copper and the lowest-grade, altered-rock ores, 0.2% copper. Ores contained up to 4% arsenic, with some containing as much as 18%. Sulfur commonly exceeded 30%, with pyrite the most common sulfide in the ores and a primary component (0.5 to 4%) of the wall rock that enclosed the ores. CdS is rare in Butte ores, but Cd commonly replaces other metals in sulfides (especially in sphalerite), so it is a common contaminant in Clark Fork waste deposits. These characteristics suggest antimony, arsenic, cadmium, copper, lead and zinc should be the significant contaminants in the Clark Fork complex. Their fate also could re affected by the abundance of sulfur, especially through its role in complicated oxidation-reduction reactions.

In this paper we characterize waste products from mineral extraction as primary, secondary or tertiary contamination. The variety of wastes produced during mining, milling and smelting (Table 1; Fig. 2) are the sources of primary contamination. As these contaminants are transported away from the site by water or wind, they generate secondary contamination in soils, ground water, rivers and the atmosphere. Deposits of these byproducts can be distributed over vast areas (Hutchinson, 1979) and. if remobilized, can result in tertiary contamination (Loxham, 1988).

Primary Contamination

The first studies of hazardous wastes in the Clark Fork Complex focused on the primary contamination spread in an ill-defined patchwork of deposits over the countryside near the modern and historic centers of mining and smelting (Johnson and Schmidt. 1988). These primary deposits contain waste rock, mill tailings, furnace slag or flue dust. Analyses from the Clark Fork and other mineral extraction areas indicate that the different types of waste have vastly different contaminant concentrations and different compositions (Table 1).

Separated from ore and dumped near the mines, waste rock is the probably the least contaminated material, although few analyses have been conducted. The 300 million m of rock removed from the Berkeley pit and tens of millions m from underground workings covers approximately 10 km of land. Waste rock disposal visibly affected the countryside as early as 1912 (Weed, 1912):

> *To one approaching the city the general appearance is most desolate. Bare, brown slopes, burnt and forbidding, from which all vegetation was long ago driven by the fumes from the smellers, rise from an almost equally barren valley. The city lies toward the base of the slopes. Within it and dolling all the hills about rise red mine buildings, which with the great heaps of gray waste rock from the mines form the most conspicuous feature of the landscape. ...Heaps of waste are everywhere prominent, attesting by their great size the extent of the underground working.*

As the ore was separated by milling and flotation, about 98% of it was discarded as fine-grained tailings. When the concentrate was further refined by smelting, flue dust and slag were produced. Such residues contain 100 to 1000 times natural levels of arsenic, cadmium, copper, lead and zinc (Table 1). Site characterization is a fundamental early step in contaminant remediation (McKay and Cherry, 1989), but locating and identifying specific deposits of these heavily contaminated wastes has been difficult because of the lack of historic records. The largest and best understood deposits occur in tailings ponds, constructed between the early 1900's and the 1950' s to restrict the movement of wastes. The ponds cover at least 35 km and hold more than 200 million m of mill and smelter tailings. Based on average concentrations of metals in the tailings, approximately 9,000 MT arsenic, 200 MT cadmium, 90,000 MT copper, 20,000 MT lead, 200 MT silver and 50,000 MT zinc could be present in the ponds.

Atmospheric Dispersion of Secondary Contamination

Smelter operations resulted in widespread dispersion of secondary contamination. The oldest smelting process, "heap roasting" (burning large piles of intermixed ore and timbers) released massive amounts of sulfur dioxide and metals to the atmosphere (Hutchinson, 1979). When heap roasting was prevalent in Butte in the late 1880's, the resulting fumes were quite noxious (Davis, 1921):

...ore was being roasted outside in the grounds of the reduction works , the fumes rising in clouds of cobalt blue, fading into gray, as it settled over the town like a pall. ...The driver reined his horse as we entered the cloud of stifling sulfur and cautiously guided them up the hill. A policeman, with a sponge over his mouth and nose, to protect him from the fumes, led us to a little hotel in Broadway, for we could not see across the street.

When smelting operations were transferred to Anaconda, contamination followed. Within months of beginning production in the new smelter in 1902, outbreaks of arsenic poisoning occurred in cattle, sheep and horses over an area of 260 km (Harkins and Swain, 1908). One ranch, 20 km downwind of the smelter, lost 1000 cattle, 800 sheep and 20 horses during the first year of smelter operation. To reduce the damage, a flue system was constructed to settle the solids in the smoke. Even after the construction, releases of 27 ,000 kg/day arsenic, 2300 kg/day copper , 2200 kg/day lead, 2500 kg/day zinc and 2000 kg/day antimony from the stack were documented (Harkins and Swain, 1907). The contamination of soils by deposition of these air pollutants was worsened when farmers were forced to irrigate with contaminated river water during dry years (Bateman and Wells, 1917; Haywood, 1917). Although the extent of contamination is not completely characterized, recent estimates based upon photo reconnaissance suggest soil contamination visible affects vegetation cover over an area of at least 300 km (Johnson and Schmidt 1988). Thus transport processes appear to have left a legacy of secondary contamination that affects cropland, soils and farm animals (see also Munshower, 1977).

Secondary Contamination or Ground Waters

Complicated reactions of the sulfur -rich Butte ores with oxygen play an important role in determining the fate of contaminants that contact water. Facilitated by bacterial decomposition, acidic waters are produced when metal sulfides react with oxygen-rich water. Through several steps, metal ions, sulfate and hydrogen ions are produced (Nordstrom, 1982). This process mobilizes metals and metalloids previously bound in sulfide and degrades waste rock, releasing more metals to solution.

During underground and surface mining in Butte, ground water was pumped from the workings to eliminate flooding. When open-pit mining ended in 1983, pumping was discontinued and oxygenated water began filling underground shafts and tunnels and the 390 m deep Berkeley pit These waters soon turned acidic, with pH from 2 to 3, and now concentrations of sulfate and some metals are as much as thousands of times those found in uncontaminated water. Estimates of groundwater movement suggest that 30 million 1/day of water flows into the pit, raising the water level 22 m per year. If mean concentrations of As, Cd, Cu and Zn are 7.1,0.54, 5.3 and 740 mg/l in mine-shaft waters adjacent to the pit and inflow is 30 million I/day (Johnson and Schmidt, 1988), 210 kg As, 15 kg Cd, 160 kg Cu, and 22,000 kg Zn would be transported into the pit each day. The hydrology of this system is sufficiently complex that the ultimate fate of the contaminated water is uncertain. Resumed pumping, water treatment and metal extraction may be possible, but specific economic, engineering and waste disposal strategies remain to be demonstrated. Otherwise, the simplest scenarios suggest that the contaminated water will ultimately flow into the adjacent Butte Valley alluvial aquifer (probably by the turn of the century) and from there into Silver Bow Creek and the Clark Fork River, compounding existing contamination problems.

Ground water contamination in a diverse expanse of tailings ponds is affected by a mix of complicated processes, mostly governed by reduction and oxidation of sulfur. The most recently constructed ponds are full of water, pH is near neutral, and. sufficient organic matter is available to establish anaerobic conditions. Sulfides produced in these sediments would be expected to immobilize cadmium, copper, lead and zinc, but contaminants with more soluble reduced forms, such as arsenic, might be released into ground water. Such conditions occur in a contaminated reservoir at Milltown (Fig. 1; Moore et al, 1988), but have not been verified in the ponds. In older ponds organic material is limited and small inputs of water oxidize sulfides. pH is reduced and thus most metals could be carried into the underlying alluvial aquifer. In a pond in Butte the metals appear to re-precipitate where they el1counter a subsurface anaerobic zone rich in organic material (Johnson and Schmidt, 1988), Analyses of ground water below the ponds at, Anaconda (Fig. 1), suggest contaminant penetration is occurring there. Contaminants are found in ground water at depths of 10 to 25 m, and as much as 1 km down gradient. If the 9 oxidized zone extends through the entire thickness of these tailings or there is not sufficient organic material available for reduction, arsenic, cadmium, copper and zinc could infiltrate into the underlying aquifer. The processes affecting groundwater contamination are understood in only the most general sense in the Clark Fork Complex, thus prediction of distribution, fate or movement of contamination has been difficult.

Secondary and Tertiary Contamination by River Transport

Because of the long-term deposition of contaminants in the system, riverine transport of secondary and tertiary contamination may be much more extensive than previously thought. Recent studies show that metals can be transported away from the primary sources as either particulates or as solutes of secondary origin. One source of the solutes is metal sulfate in the upstream floodplain soils (Moore unpublished data). The sulfates form as acid waters evaporate in the summer. When mixed with water, these compounds readily dissolve, pH drops to low values within seconds, and solute metal values reach many hundreds of mg/l (Nimick and Moore, in press). Thus intense rainstorms can transport large amounts of dissolved metals and acid into the river.

Contaminated particulates are widely dispersed in the river system. Fine-grained sediments in the river and its reservoirs are contaminated for more, than 560 km downstream from the smeller (Johns and Moore, 1985; Andrews, 1987; Brook and Moore, 1988; Axtmann and Luoma, 1991). The contamination follows a simple exponential decline that fits both riverbed and reservoir sediments through this distance (Figure 3). Concentrations of metals in river sediment near Anaconda (at the confluence of the headwater tributaries) are twenty to more than one-hundred times higher than those in uncontaminated tributaries. At 380 km, concentrations still exceed those in the least enriched tributaries by ten times or more. If the exponential function is extrapolated downstream it suggests that detectable enrichment of most metals would extend into Pend Orielle Lake.

Much of the particulate contamination probably originated from historic mineral extraction activities that until the 1950’s did not efficiently trap particulates before they entered the river. Until the early 1900' s, much of the particulate waste material from milling and smelting in the Clark Fork Complex was sluiced onto surrounding land surfaces or directly into local streams. The two tributaries in the headwaters, Silver Bow and Warm Springs creeks, transported the bulk of these wastes away from the mines and smelters. These streams, although only 0.4% of the total discharge of the Clark Fork River (Fig. 4A), have supplied the majority of the metallic contaminants to the drainage. Early observers noted that discharges of contaminated particulate material kept the Clark Fork River turbid over 200 km downstream (Averett, 1961) at least periodically into the 1950's, until completion of the last tailings ponds. The addition of huge amounts of sediment to the river system plugged streambeds causing extensive flooding (Meinzer, 1914) and deposition of contaminants on the surrounding floodplain. Vast areas of the floodplain became contaminated wastelands (slickens) first described in 1917 (Baleman and Wells, 1917).

C) Concentration or copper in bed sediment (as B). a) Average value reported by Tetra Tech, 1987 cited in (Johnson and Schmidt, 1988); b) Average value reported by (Johnson and Schmidt, 1988); c) Only two values, no standard deviation reported.

A trip through the region affected by the tailings presents interesting picture. Before their advent the soil supported the characteristic flora of this district which is still seen outside the tailing areas...flourishing willows line the little streams while grasses of various kinds, the wild rose, and clover among other things grow abundantly ...altogether a typical mountain valley. In contrast, among the tailings the willows in places stand back and dead for thousands of yards at a stretch while at others they have an unhealthy appearance… Over extensive areas no plant life at all is to be seen. The soil is gradually covered by the tailing solids which impart to it a variety of colors in some cases gray, in others yellow or bright red from ferric oxide. For miles along the streams where the water is evaporated away the ground is encrusted with masses of bright blue and green deposits...the blue a basic copper sulfate, and the green a mixture of copper and iron sulfate…The water in many of the rivulets is decidedly acid with sulfuric acid while the rocks in the bed of the streams are mostly changed...into velvety pebbles of various shades of green, the color again being due to compounds of copper. Even the bones of perished stock, instead of being bleached, are dyed a vivid green.

Not much has changed in seventy years. Slickens with malachite-colored bones can still be seen along the banks of the Clark Fork River for over 100 km from its origin.

Floodplain sediments in the uppermost Clark Fork contain arsenic a few hundred times, copper a thousand times and zinc a few thousand times background values found in uncontaminated tributaries (Fig. 4B). Highly contaminated cutbanks have been found 200 km downstream (Moore et. al. 1989; Axtmann and Luoma, 1991). Johnson and Schmidt (1988) suggest that approximately I million m or tailings reside on the floodplain between Warm Springs and Deer Lodge. However, 1.2- 2.5 million m of tailings have been identified along Silver Bow Creek alone (Hydrometrics. 1983) and visible patches of tailing materials also cover tens or hectares as far as 60 km below Deer Lodge; These data suggest a minimum of 2 million and likely more than 3 million m of contaminated sediments in the floodplain. This type of secondary contamination can provide a huge non-point source of metals as a river meanders through its floodplain. Continuous inputs from such a source might extend the downstream penetration of the contamination.)

The distribution of metal enrichment in the floodplain is highly variable downstream (Moore et at, 1989; Axtmann and Luoma, 1990). Processes that contribute to the variability appear to include historically variable sediment transport; spatially and temporally variable geochemical mobility from soils; highway and railroad construction that isolated patches of old floodplain or moved the river a banks unaffected by historic deposition of wastes; and perhaps, historic variability in mining and smelting processes. Because of this patchiness, quantitatively 1 valuating the importance of bank inputs may require understanding, which cutbanks specifically contribute to sediment loads or how metals are distributed among banks with differing geomorphological activity.)

Dams may trap sediments in the Clark Fork, but they do not necessarily prevent downstream transport. Four dams occur on the river. The oldest was built in 1907 at Milltown 190 km downstream from the origin of the Clark Fork River. Additional reservoirs were built at 452 km in 1915, at 556 km in 1952 and at 516 km in 1959. Elevated concentrations of at least some contaminants have been determined in all the reservoirs (Johns and Moore, 1985) (Fig. 5). Furthermore, the presence of the dams does not appear to affect the downstream trend of contamination (Fig. 3). The specific effects of the dams on the long-term fate of metal contaminated sediments in the river clearly needs more study.

Reservoir sediments also may act as a toxicant sink, and a source of tertiary contamination of local ground waters. A tertiary contamination problem of this type was discovered in Milltown Reservoir (Fig. 1). (Moore et al, 1988). Although it is over 200 km from the mines and smelters at Butte and Anaconda, this reservoir filled with sediments apparently released during me early stages of mining and smelling. Today it retains approximately 100 MT cadmium, 1600 MT each arsenic and lead, 13,000 MT copper and 25,000 MT Zinc.

Tertiary contamination of ground water was discovered in November 1981, I when commW1ity water wells adjacent to Milltown Reservoir were found to contain arsenic levels well above the EPA drinking water standards. Oxidation-reduction processes released arsenic from the reservoir sediments contaminating the adjacent alluvial aquifer. The plume of contamination extended only a few hundred meters from the reservoir but covered an area of nearly 3 km, beneath and adjacent to the reservoir. When evidence showed that the health-threatening contamination originated from the adjacent reservoir sediments, the site was placed on the original Superfund National Priorities List. The aquifer was abandoned in 1981 and a new water supply for the community developed.

Effects on Ecosystems

The risk of adverse ecological effects associated with metal extraction is high because of the high concentrations in the waste of potential toxicants such as Copper, zinc, cadmium, lead and arsenic. Trout are one of the most valuable ecological resources affected by metals in the Clark Fork. Trout densities in most of the Clark Fork are only one-tenth or less of those in nearby streams of similar size and comparable habitat (Fig. 6) (Phillips, 1985; Berg, 1986). Only brown trout occur in the most contaminated reaches, in contrast to diverse assemblages of trout species found in uncontaminated waters. However, Clark Fork fish populations are not related to contaminant distributions in a simple fashion. High densities of brown trout occur in one small area in the uppermost river in the presence of some of the highest contaminant concentrations (Fig. 6), suggesting complex processes may affect the bioavailability of the metal toxicants and trout success in different reaches of the river.

In addition to the continuous contaminant exposures indicated by persistent sediment contamination, biota of the Clark Fork are exposed to periodic episodes of much higher contamination during some high-flow events. Acute toxicities of river water to caged trout were first demonstrated by Averctt (1961) during an episode in March 1960. The toxicities coincided with "red", high iron content", "discolored" water that occurred as far as 380 km downstream from Anaconda. In more recent years, fish kills have coincided with summer storms in the upper 100 km of the Clark Fork (Phillips, 1985, Phillips and Spoon, this volume). It remains unclear which water quality factors cause the fish to die so rapidly in these episodes (low pH, Fe-AI coagulates, high Cd, Cu or Zn?). Fish also seem to return quickly in the upper river, suggesting immigration from uncontaminated tributaries might be an important process.

One initial step in assessing ecological effects of persistent contamination of the bed sediments is to determine metal concentrations in the tissues of animals that live on the riverbed, many of which are crucial in the food web of fish. Recent studies show high concentrations of copper and cadmium in benthic invertebrates, especially in the Upper Clark Fork (above the Blackfoot) where fish populations are most severely reduced. In web- spinning caddis flies (Hydropsyche sp.), at three stations between Anaconda and Deer Lodge, Cu concentration was 186+ 36 ug/g dry wt., Cd 2.8+ 1.1 ug/g. and Pb 12.8+2.6 ug/g. AL three downstream stations, between Alberton and the Flathead Confluence, Cu averaged 27+8 ug/g dry wt., Cd 0.7+0 ug/g, and Pb 3.1+1.5 ug/g. In the least contaminated tributaries in the watershed mean concentrations in this species were 15+1 ug/g for Cu, <0.2 ug/g for Cd, and 1.0 ug/g for Pb. These results demonstrate that downstream as far as 380 km contamination of sediments is passed on to biota. An extensive area of river is contaminated with biologically available metals, an observation that previous studies of effects on benthic communities and fish have not always considered (Canton and Chadwick, 1985; Chadwick et al, 1986).

It should be recognized that the effects of contamination on trout and associated organisms in a river are typically expressed within the context of poorly understood environmental and ecological relationships; and conclusively demonstrating the causes of problems manifested as chronic ecological change can be difficult Long term, sophisticated manipulation studies have demonstrated the naivety of employing simple, single factor analyses to explain the disappearance of large, upper trophic level species (Schindler, 1987). Flow, temperature, and food web Characteristics, among other biological and environmental processes, interact with contaminants to determine the well-being of species. We can expect that a complete understanding of how contaminants affect trout in the Clark Fork will require careful, systematic, multi-year studies of such interacting processes. If solutions to the loss of the trout resource are possible, understanding the processes that control and affect the toxicity will be their source.

Effects on Human Health

Elevated death rates from disease are, in general, associated with active and historic mineral extraction areas (Sauer and Reed, 1978). One possible reason is that several of the contaminants typically associated with metal extraction activities are hazards to human health. Arsenic is a carcinogen (Lederer and Fensterheim, 1983); Cd is associated with high blood pressure and kidney disease (Nat'l. Res. Council, 1979); and Pb is associated with behavioral anomalies in children and high blood pressure (Wessel and Dominski, 1977). Radon, another carcinogen, has not been studied in the complex, but is a possible contaminant because of the high uranium content in the ore body.

Several national data bases on mortality from disease include cities or counties from the Clark Fork complex, and can be employed in comparative assessments of risk of disease in the area. The national health statistics were established specifically to identify high risk localities, and to identify localities that need more detailed study (Riggan et al, 1983). Cause and effect are difficult to determine from such statistics, although methods such as comparing rates among men and women can be employed to help separate occupational from environmental risks. Available statistical data of relevance 10 the Clark Fork complex include the National Cancer Institute/EPA 's U. S. cancer mortality trends comparing more than 3000counties from 195010 1979 (Mason et.al, 1975; Mason and McKay, 1974; Riggan et.al, 1983), and the National Institute of Health's comparison of mortality from cardiovascular and non-cardio- vascular disease in 480 U. S. cities including Butte, Great Falls and Billings in Montana {Feinleib et al, 1979).

The above data sources all indicate that the incidence of mortality from serious disease has been unusually high in the Clark Fork complex, especially in the areas where primary contamination occurs. Between 1959 and 1972, Silver Bow County was among the 100 counties in the nation with the highest mortality rates from disease for people aged 35- 74 (Sauer and Reed, 1978). The death rate in Butte from disease was the highest, or among the highest, of any city in the nation between 1949 and 1971, when adjusted for population (Feinleib et al, 1979; Table 2). High rates of death from heart and kidney disease in Butte contributed to the elevated mortality ratio for all diseases; but the city ranked even higher for incidence of mortality from diseases other than cardiovascular and kidney.

Comparisons of cancer rates by county also showed elevated incidence of some cancers in the Clark Fork waste complex. Counties in the area of primary contamination were among the U.S. counties with the highest rates of mortality in males and females from all types of cancer (Mason et al, 1975; Table 3) and, more specifically from trachea, bronchus and lung cancer through 1979 (Table 4). Average age~ adjusted mortality rate due to the latter cancers among white males in Montana Idaho, Wyoming and North Dakota between 1950 and 1969 was 25+4 deaths per 100,000 people. Deaths from these diseases occurred at more than twice that rate in the counties containing primary contamination (Fig. 7; Mason and McKay, 1974), During this period, 20.5% of the total number of such cancer deaths in Montana occurred in these counties, among 6 -7% of the state's population. The risks of cancer did not appear to be purely occupational. In 1970- 79 death rates in women from a variety of cancers were statistically greater than the norm in the nation (Riggan et alt 1983; Table 5). Overall cancer rates in Butte women were in the highest 4 percent U.S. Counties during this period.

Some statistical data suggest the incidence of lung cancer was not increasing as rapidly in the Clark Fork complex as it was in the rest of the nation in the 1970's (e.g. Fig. 7); but in 1979 (the latest available national comparisons) risk of death from disease remained high, especially among women.

The ultimate challenge at a hazardous waste complex is to determine if the contamination in soils, air, ground water and surface water threaten human health. Comparisons with available national statistical data show elevated incidences of mortality from serious diseases have occurred in the areas of primary contamination in the Clark Fork complex. Detailed local studies should be undertaken immediately to determine if the risk of death from disease remained unusually high into the 1980's; if such risks are environmental, or related to confounding exposures such as smoking; if elevated incidence occurs outside the areas of primary contamination; and if relationships with specific types of contaminant exposure can be established.

Strategies for Solution

Much remains to be learned about the nature and effects of the hazardous wastes generated by metal extraction activities in the Clark Fork complex, but studies to date already are providing some important lessons.

1. The long history of mineral extraction in this area has resulted in contamination of soils, ground water and surface water on an immense spatial scale. Reduced availability of resources (fisheries, agricultural resources) and a high incidence of disease occur coincident with contamination, especially the most severe levels.
2. The area affected by primary contamination is large. The diversity of deposits, the scale of the deposition, poor historic documentation, and the number of analyses necessary call for a

systematic approach to site characterization, and careful documentation of the results of that characterization.

3. Environmental problems may extend far beyond the boundaries of primary contamination at metal extraction sites; extensive secondary and tertiary contamination is possible. The precise extent and location of contamination of soils, agricultural crops, livestock, fish or ground water in the Clark Fork Basin is not yet adequately documented; but the scale is hundreds of river km, hundreds of km of land and tens of km of ground water. Many studies have underestimated the extent of the problems. Perhaps because many of the secondary problems are historic, the present generation may view them as part of the "normal" terrain, failing to recognize their origin in activities as much as hundreds of km away.
4. The number of separate, significant contamination problems can easily confuse prioritization or systematic characterization and remediation processes. The problems requiring immediate attention in the Clark Fork Complex are numerous: identifying if risks to human health persist, identifying sources of human exposure from among the many localities of primary contamination, defining the causes of ecological problems in the Clark Fork so the fishery of the river can be improved, defining the extent and severity of contamination of soils and agricultural products, mapping pockets of contamination in the floodplain and their susceptibility to mobilization, determining what to do about the contaminated water rapidly filling the Berkeley Pit, determining if contaminated ground water under the older tailings ponds will spread, determining if ground water contamination occurs under floodplains and other unstudied deposits, to name a few. Some problems are interconnected. For example, removing contaminated sediments from downstream reservoirs is futile if contaminants are continually re- supplied from contaminated floodplains. Prioritizing efforts (Travis and Doty, 1989) is not a trivial problem where a number of interconnected, important problems compete for limited funds. The piecemeal contracting that is common at hazardous waste sites adds to the difficulty of establishing the integrated, prioritized, systematic strategy for problem management at seems critical.
5. Many individual problems are sufficiently complicated that solutions are not immediately obvious. In the Clark Fork many of the above problems fit this statement to some degree. The extent of the ground water problem, and the likely presence of sorbed phases will hinder solutions to inherently difficult ground Water clean-up efforts. Removal of primary wastes to containment areas carries unacceptable financial and ecologic costs where the area involved is 20% the size of Rhode Island. Restoring the river must involve dealing with hundreds of km of contaminated floodplain, and manipulating a poorly understood ecological system. Defining the significance of human exposures to contamination will be limited by the area's (statistically) small population. Resolution and remediation of all the problems of the Clark Fork complex by immediate application of "proven and effective technologies" (Travis and Doty, 1989) seems naive. Some such "fixes'. may merely relocate or even exacerbate poorly understood problems. Where mitigation of health risks (for example) appears to necessitate clean-up, but the best solutions are unclear, the efforts could be approached as full-scale, real-time experiments (Freeze and Cherry, 1989) accompanied by follow-up studies that monitor results and progressively improve approaches.
6. Developing additional process understanding may be cost effective in solving some problems. Creative solutions to local problems and to the problems of large-scale metal wastes in general will develop as understanding of these environments improves. Examples of important questions in the Clark Fork might include the following. What approaches are feasible for metal recovery from the water in the Berkeley Pit? How important is immigration in maintaining trout in the Clark Fork River, and is preservation of water quality in tributaries a critical first step in

preventing further loss of the fishery? What effects do existing or proposed ponds have in providing refuges of improved water quality for trout populations? Reducing human exposures to contaminants and metal movement into the river both depend upon understanding the processes that mobilize wastes in tailings ponds, floodplains, and from surface deposits. All such suggestions require careful rigorous scientific studies.

7. Some contamination problems, because of their scale, intensity or complexity, may not be amenable to remediation under foreseeable circumstances. Attaining pre-development status for the ground water, river ecosystem, and land surfaces in the Clark Fork complex is now extremely difficult Some problems might be improved (the fishery for example), but solutions for others, such as the extensive ground water contamination under the tailings ponds, may involve perpetual monitoring (Freeze and Cherry, 1989) until real solutions are found. It is important to accept that some of our environmental mistakes have been so serious that they cannot be repaired. Modem society remains capable of such irreparable environmental mistakes. A principal lesson from the Clark Fork experience is that careful waste management and reduction during production of metal reserves is imperative. Recognition and assessment of the potential for creating highly contaminated primary wastes deposits, secondary/tertiary contamination in soil, ground and surface water, and deleterious consequences for human health and ecosystems should be a part of our mineral extraction efforts. The immense costs associated with the historic contamination of the Clark Fork Basin clearly points out the benefits of avoiding such problems in the future.
8. The descriptors that might guide the successful approach to managing the contamination problems in the Clark Fork complex are more difficult to implement than to list. Management must be coordinated, systematic, carefully prioritized, integrated over a large area and staffed by technically qualified individuals dedicated to the complex for the entire program. Management must be supported by studies that are multi- disciplinary, rigorously peer reviewed, systematic in their accumulation of knowledge, aware of related work, and guaranteed some continuity in support. The challenge to existing institutions is clear.

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Figure 1: Location map showing the extent of the Clark Fork Superfund Complex and the location of individual sites mentioned in the text: 1) Silver Bow Creek Superfund Site; 2) Anaconda Smelter Superfund Site; 3) Milltown Reservoir Superfund Site; 4) Butte addition Superfund Site (this site ties together all the previously separate sites). The downstream distance in kilometers from the origin of the Clark Fork River at the junction of Warm Springs Creek and Silver Bow Creek (0 km) are indicated by the solid triangles and associated km designation. The irregular dashed line is the boundary of the Clark Fork River drainage basin.

Figure 2: Block diagram depicting types of contamination in an area affected by large-scale metal extraction. Primary contamination denoted by (1), secondary contamination by (2) and tertiary contamination by (3). Primary wastes include waste rock, smelter slag, ash and tailings. Secondary wastes include air-fall and irrigation contaminated soils, floodplain sediments, riverbed and reservoir sediment, and ground-water contamination originating from mines, waste rock piles, tailings ponds or contaminated floodplain sediment. Tertiary contamination includes remobilized contamination in the riverbed and ground-water contamination from contaminated reservoir sediment far removed from the primary sources. The scale of the diagram is variable, but the extent from mines to downstream reservoirs is over 550 km in the Clark Fork waste complex.

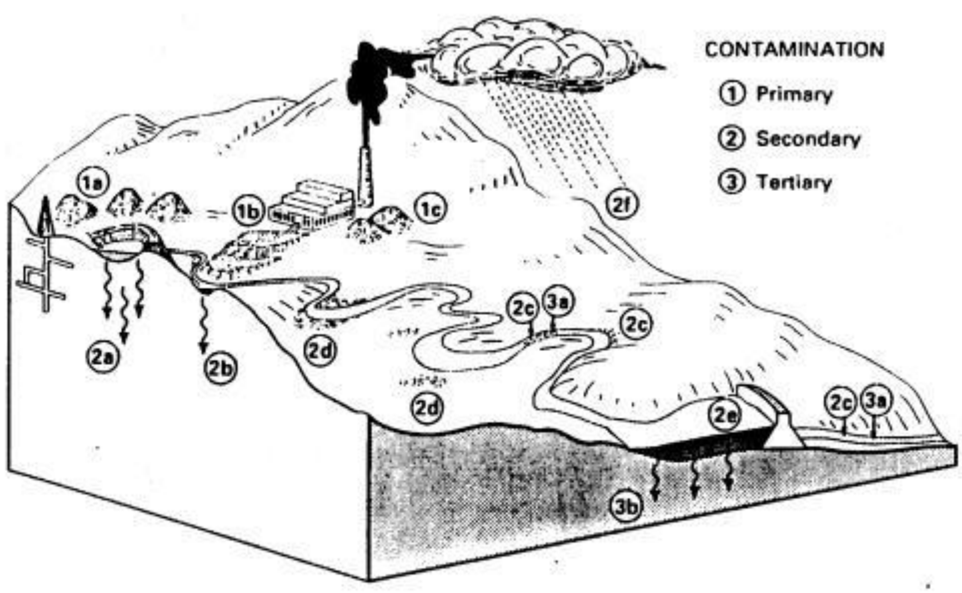

Table 1: Metal concentrations (ppm) in various waste deposits from copper mining. "Background" is taken from average shale values in Turekian and Wedepohl, 1977. Other data from Nordstrom, 1982; Hutchinson, 1979; Johnson and Schmidt, 1988.

	Heap-roasting slag	Mill tailings	Flue residue	Background
As	1,070	2,960	10,400	10.0
Cd	13.4	8.0	-----	0.22
Cu	7,000	6,730	37,100	45.0
Pb	1,030	2,740	-----	20.0
Zn	18,000	11,000	-----	95.0

Figure 3: Exponential fit to copper concentration in bed sediment versus distance downstream in the main stem of the Clark Fork River. Solid squares are data from bed sediment in river; open boxes are mean data from reservoir sediment. Fit to exponential equation: R = 0.94; function suggests copper concentrations will decline by 50% every 97 km (Axtmann and Luoma, in press). (Data combined from Axtmann and Luoma, in press; Moore et al, 1989); Brook and Moore, 1988; and Johns and Moore, 1985).

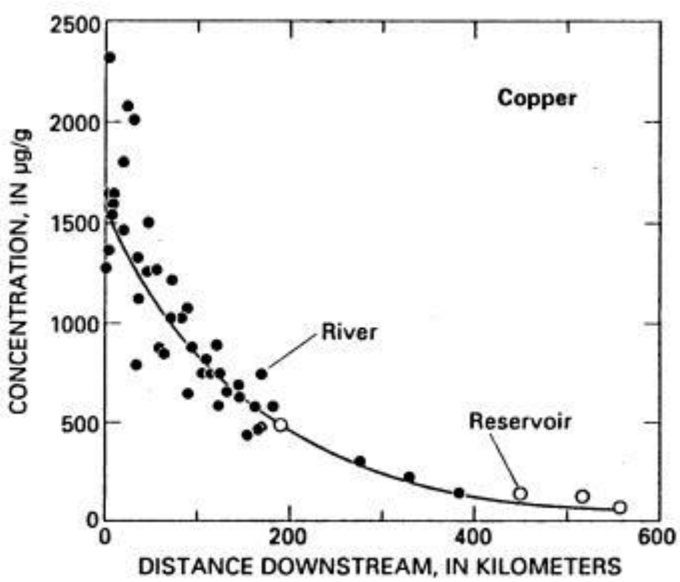

Figure 4: Manifold diagrams showing the relative components of flow and copper in the tributaries and main stem of the Clark Fork River:

A) Mean discharge in the Clark Fork River (to 1988) and its tributaries; numbers represent flow for those tributaries; width of arrow shanks scaled for relative comparison.
B) Concentration of copper in bank (floodplain) sediment of the Clark Fork River and its tributaries. Numbers are mean concentrations between tributaries (one standard deviation in parentheses) on the main stem and for samples for each tributary. Thickness of segments scaled for relative comparison.
C) Concentration of copper in bed sediment (as B). a) Average value reported by Tetra Tech, 1987 cited in (Johnson and Schmidt, 1988); b) Average value reported by (Johnson and Schmidt, 1988); c) Only two values, no standard deviation reported.

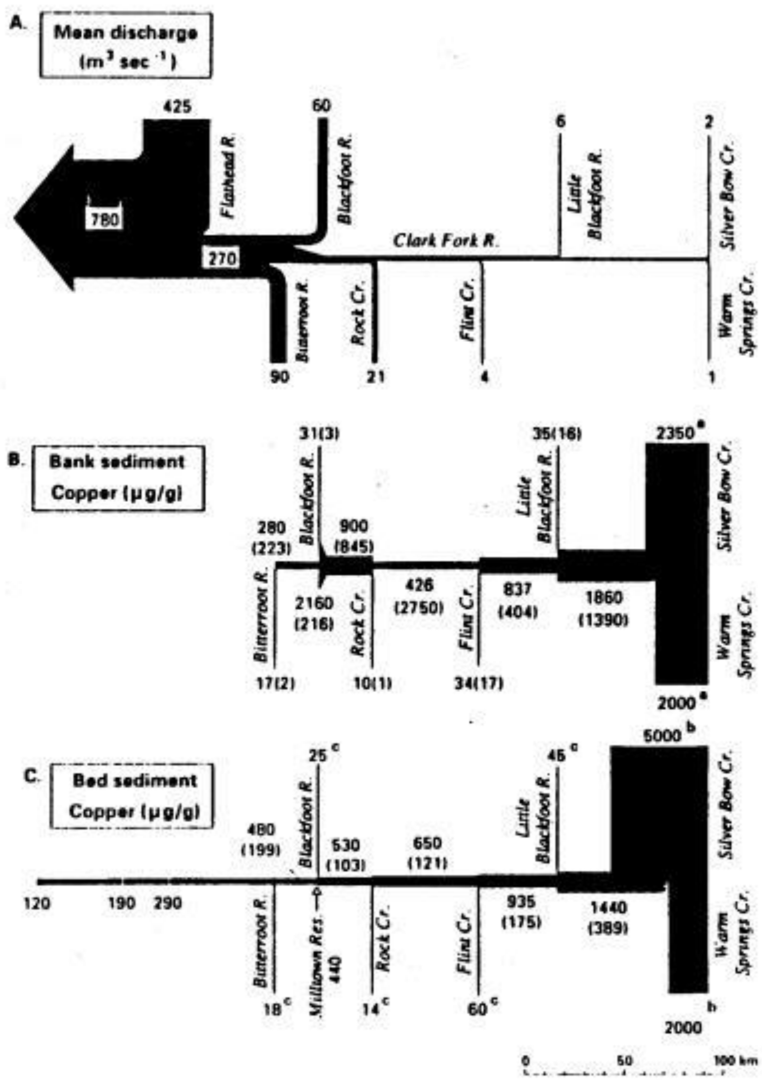

Figure 5: Enrichment factors (mean concentration in sediment divided by background concentration from uncontaminated tributaries) of sediment in the reservoirs on the Clark Fork River. See Figure 1 for names of reservoirs at specific kilometer.

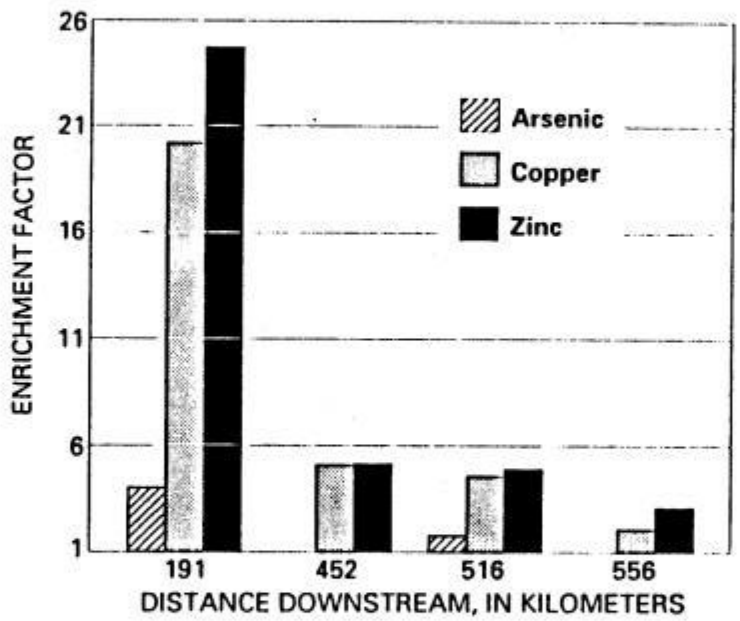

Figure 6: Number of trout per kilometer in the Clark Fork River from the origin (0 km, Fig. 2) to 380 km. Data from Montana Fish, Wildlife and Parks (Johnson and Schmidt, 1988 and D. Peters, personal communication).

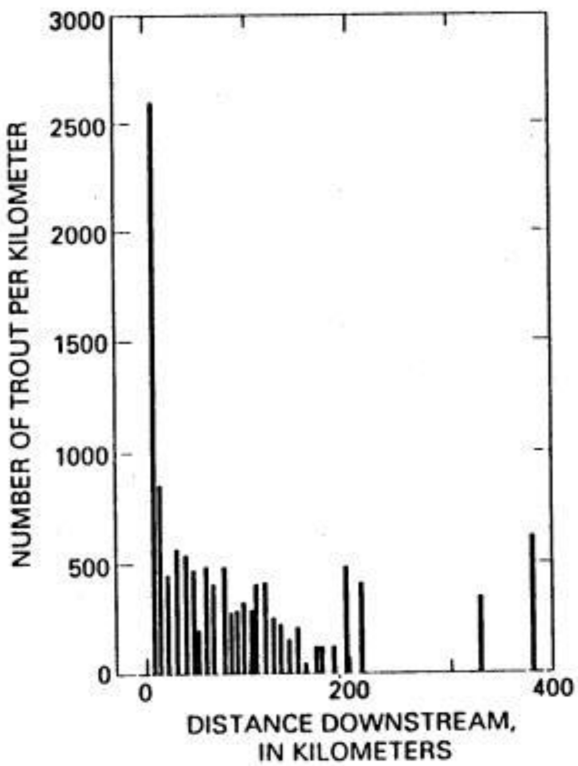

Table 2: Ranking of Butte, Montana, (relative to the 480 largest U.S. cities for disease-caused mortality (i.e. Butte has the highest mortality ratio in the nation from all types of disease and from heart + kidney disease in 1949-51). Mortality ratio is the per capita mortality rate relative to that expected for the nation. Data from Feinleib et al, 1979.

	1949-51	1959-61	1969-71
ALL DISEASES	1	1	5
HEART & KIDNEY	1	2	31
HEART DISEASE	2	18	94
OTHER THAN HEART & KIDNEY	3	1	1

GREAT FALLS AND BILLINGS RANK BETWEEN 350 - 450 IN ALL CATEGORIES.

Table 3: Mortality from all types of cancer (death rates per 100,000) compared between Silver Bow county and the state of Montana. Asterisks indicate cancer rates were significantly higher than expected from national data. Rank in percentile in 1970-1979 among the nation's >3000 counties also is shown. Data from Mason and McKay, 1974; Mason et al, 1975.

	1950-59	1969-69	1970-79	Rank in 1979 (Percentile)
MEN				
SILVER BOW	211*	202	204	70 (Top 30%)
MONTANA	156	170	180	
WOMEN				
SILVER BOW	163*	127	156*	97 (Top 3%)
MONTANA	129	121	119	

*Statistically significant: Greater than "expected" from national statistics.

Table 4: Mortality rates from lung, trachea and bronchial cancer in areas of primary contamination in the Clark Fork complex, compared with such cancer rates in Montana as a whole and adjacent states for the period 1970-1979. Note that Montana's statistics are biased upward by the Clark Fork data. Data from Riggan et al, 1983.

AREA	NUMBER DEATHS 1970 -1979	RATES PER 100,000
DEER LODGE COUNTY	140	65.2
SILVER BOW COUNTY	282	55.3
MONTANA	2062	31.1
NORTH DAKOTA	1257	20.5
IDAHO	1406	22.9
WYOMING	779	26.7

Figure 7: Age-adjusted mortality rates per 100,000 people from trachea, bronchus and lung cancer amound white males for the state of Montana, and Missoula, Granite, Deer Lodge and Silver Bow counties. Number on bars refer to number of deaths.

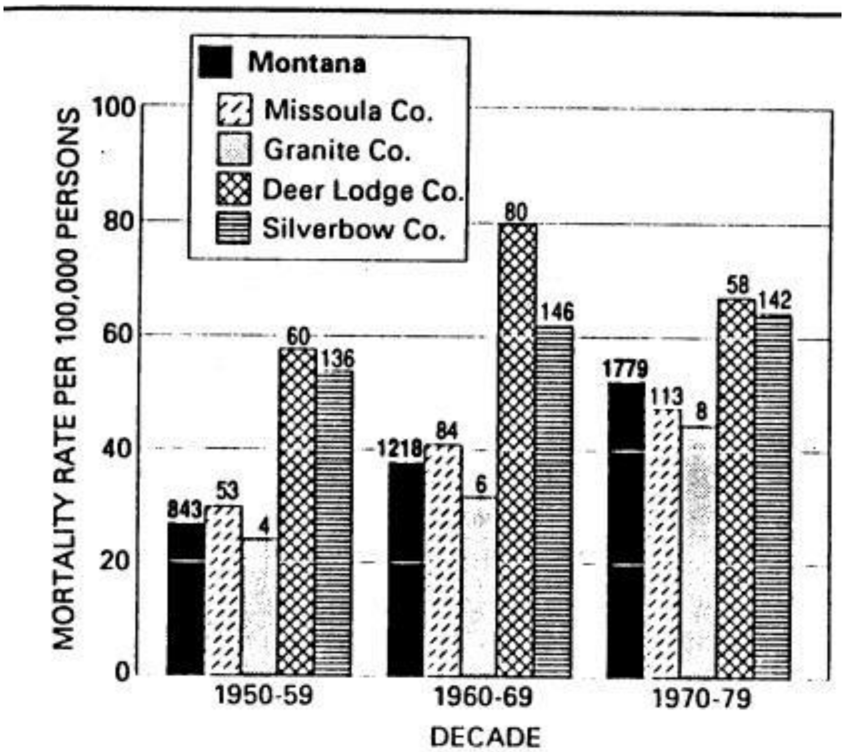

Table 5: Cancers that occurred in women from Silver Bow county at significantly greater rates than expected from national statistics for the period 1970-1979. Percentile in nation also is shown for Silver Bow county for selected cancers. Data from Riggan et al, 1983.

DISEASE	PERCENTILE RANKING
SALIVARY GLAND	
LARGE INTESTINE	
LIVER/GALL BLADDER	
PANCREAS	94
CHORION-UTERUS	91
HODGKINS DISEASE	90
LUNG, TRACHEA, BRONCHUS	96
SECONDARY, SITE UNSPECIFIED	