PHYTOSTABILIZATION OF FLUVIAL TAILINGS DEPOSITS IN THE CLARK FORK RIVER FLOODPLAIN[1]

Dennis R. Neuman,[2] and William M. Schafer

Abstract: Butte, Montana is the site of a world class copper deposit that has been mined nearly continuously since the 1870's. Tailings deposits, a legacy of early mining practices, are abundant in the floodplain of the Clark Fork River, which has its headwaters near Butte. Tailings released by large-scale flooding in the early 1900's form a patchwork in the floodplain. Waters that contact the pyrite-rich tailings are generally acidic and contain elevated copper, zinc, and arsenic levels.

Thinner tailings deposits (e.g. less than 15 cm) are fully oxidized and have become naturally re-vegetated. In areas with thicker tailings deposits, low pH (3 to 4.5) persists and tailings are devoid of vegetation. Evaporation from bare tailings concentrates metal sulfate salts at or near the surface. The bare tailings are susceptible to erosion and water flowing across the tailings dissolves metals and contributes metal loads to the Clark Fork River. In the middle and late 1980's, large fish kills occurred in the Clark Fork after thunderstorms rinsed soluble metals, especially copper, into the river.

In 1990 and 1991, 4 km of the Clark Fork River near Warm Springs, Montana, was reclaimed using liming and both deep and conventional tillage techniques to reduce the mobility of metals in the floodplain and to allow re-establishment of vegetation. Successful stabilization of the floodplain soils has been amply demonstrated and phytostabilization was proposed as a cornerstone of the remediation efforts for the Clark Fork River superfund site. Environmental monitoring of the Clark Fork Demonstration project over a 14 year period is described in this paper.

Additional Key Words: Reclamation, ARD, metals, mining, Superfund, CERCLA

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[2] Director of Reclamation Research Unit, Department of Land Resources and Environmental Sciences, Montana State University; and principal of Schafer Limited LLC, Bozeman, MT

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Introduction

Historic mining and ore processing activities in the Butte-Anaconda area have produced large quantities of acid-generating, metal-enriched mining waste (tailings). Release of historical tailings into Silver Bow Creek and the Clark Fork River and flooding in the early 1900's caused deposition of tailings in the floodplain of the Clark Fork River. Subsequent oxidation of sulfide-bearing tailings produced low pH conditions, which increased the solubility of metals contained in the tailings, including Cu and Zn. Arsenic is also elevated in tailings but is relatively immobile at pH ranging from 3.5 to 5.5.

Conceptual Model

The conceptual site model (Fig. 1) identifies several potential pathways for contaminant transport from tailings into the Clark Fork River. These pathways include (1) surface water runoff from tailings to the river, (2) percolation of meteoric water through the tailings into the vadose zone or groundwater, (3) wind transport of tailings as fugitive dust to adjacent areas, (4) erosion of streambank tailings into the river, and (5) bioaccumulation of metals in vegetation.

Clark Fork Demonstration Project

The Clark Fork Demonstration Project (Schafer 1991), implemented in 1990 and 1991, employed alkaline amendments and revegetation (Fig. 1). The goal was to achieve a long-term remedy to chemically neutralize and physically stabilize tailings deposits to improve water quality.

The project site is located along 4 km of the Clark Fork River between Warm Springs Ponds and Perkins Lane Bridge, near Warm Springs, Montana. Prior to project implementation, the site was characterized by large, nonvegetated tailings deposits within meander bends of the river (Fig. 2). Dead and decadent willow stands were common, as were areas covered by crusted salt deposits. Tailings deposit thickness ranged from 90 cm near the river to 10 cm near floodplain margins. The active stream channel was cutting into moderately thick tailings deposits in several locations. Streambank erosion was compounded by grazing pressure.

The methods used to reduce metal mobility and toxicity is termed "phytostabilization", which entailed addition of chemical amendments to facilitate establishment of a vegetative cover. Phytostabilization is defined as the use of metal tolerant plants to inhibit the mobility of metals, thus reducing the risk of further environmental degradation by leaching into groundwater or by airborne spread (Salt et al. 1995). In the Clark Fork Demonstration Project, perennial vegetation provided long-term reduction in surface runoff and reduced the quantity of deep percolation of water through the tailings. To facilitate plant establishment on previously barren soils, $CaCO_3$ and CaO were incorporated to depths ranging from 30 to 120 cm. The amounts of lime applied ranged from 7 to 150 t/ha. Reclaimed areas were seeded with mixes of grasses and alfalfa (Table 1). A limited amount of streambank stabilization and channel modification was also conducted.

The most significant challenges to successfully reclaiming this large scale mine waste site were;

- the spatial variability of the tailings thickness and their chemical characteristics and the means of calculating amendment application rates;
- physical constraints to mixing alkaline amendments to depths of 90 cm;

- the success of alkaline amendments in reducing the mobility of the three key constituents: Cu, Zn and As;
- and the permanence of the remedy.

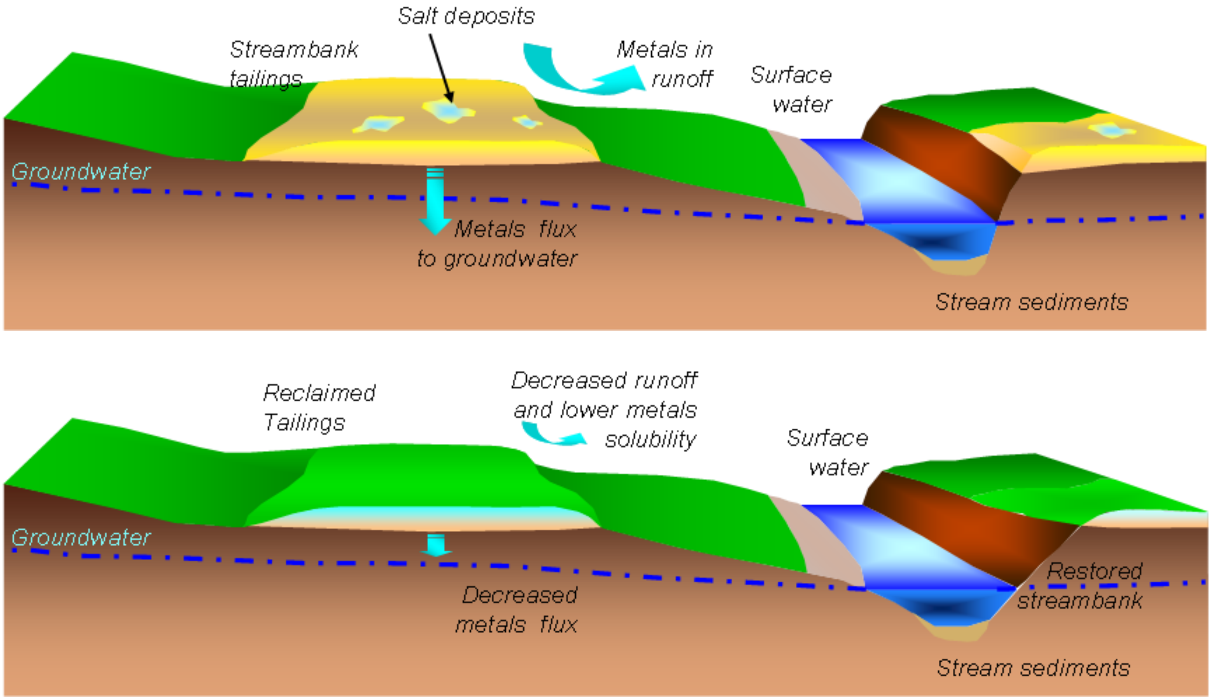


Figure 1. Conceptual model of Clark Fork River before reclamation (above) and after reclamation (below).

Figure 2. Dead and decadent willow stands and areas of bare soil are indicative of thick (>50 cm) tailings deposits in the Clark Fork River floodplain circa 1989.

Table 1. Vegetation seeded in the southern portion of the Clark Fork Demonstration project.

Scientific Name & Cultivar	Common Name	Seed Rate (kg pure live seed (PLS)/ha)
Agropyron trichophorum	Greenleaf Pubescent wheatgrass	4.5
Agropyron riparium	Sodar Streambank wheatgrass	3.4
Elymus junceus	Bozoisky Select Russian wildrye	4.5
Elymus cinereus	Basin wildrye	4.5
Medicago sativa	Spreader Alfalfa	1.75

Results and Discussion

The Clark Fork has been monitored periodically for 14 growing seasons. Extensive data was collected between 1993 and 1997 and results were incorporated into the Remedial Investigation and Feasibility Study for the Clark Fork Superfund Site.

Spatial Variability of Tailings and Lime Rates

Tailings deposits form a complex mosaic across the Clark Fork floodplain. The vertical sequence of tailings deposition (Fig. 3) was determined by fluvial events and depositional processes, which created thick tabular layers of tailings overlying natural soils on the inside of large meander loops. Deposits are in areas that would have had more quiescent conditions during a large flood. The flood (or floods) responsible for tailings deposition was thought to occur in or around 1908. Subsequent to tailings deposition, surface layers have been re-worked so that many tailings deposits are overlain by “cover-soil” consisting of re-worked tailings and other sediments. Similar coarse-textured mixed soil and tailings deposits were accreted on point bars subsequent to 1908.

In order to develop a strategy for adding alkaline amendments to tailings, a number of samples were collected in 1988 and 1989. The tailings depth and net neutralization potential (NNP) of each sample (Sobek et al. 1978) was determined (Fig. 4) (Schafer & Associates 1991, and Nimick 1990). Although the NNP values were variable, owing to the variable nature of tailings deposits, the NNP was generally between 0 and -25 t/1,000 t for tailings in the upper 30 cm and was between 0 and -45 t/1,000 t for deeper tailings. In order to insure that adequate alkalinity was added to all tailings, deposits were limed at this maximum rate. Consequently, most tailings areas were substantially over-limed. This strategy was deemed appropriate given that the consequence of under-liming is re-acidification and continued release of metal release, while the consequence of over-liming is mostly a cost issue. More intensive sampling, itself an expensive endeavor, could partially reduce the amount of over-liming.

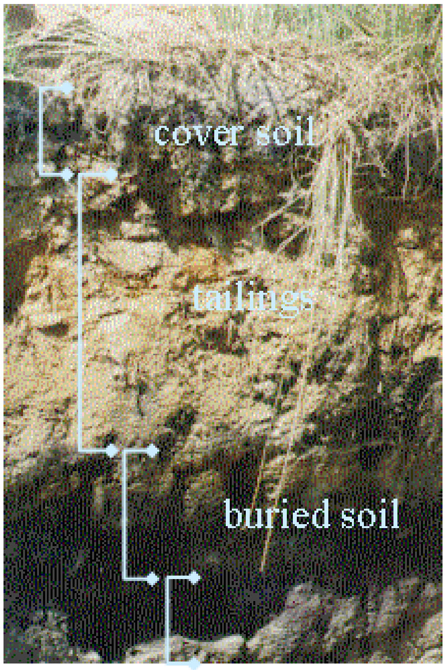
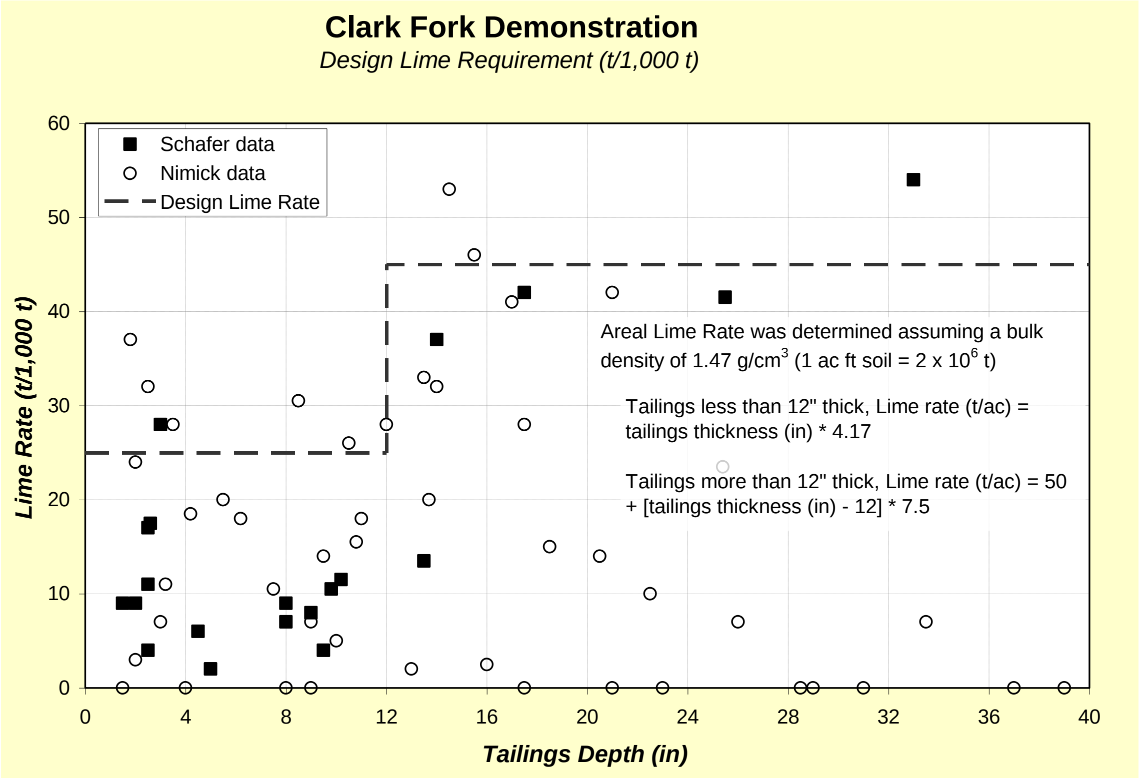


Figure 3. Typical sequence of soil layers in 18 inch thick tailings deposit within a meander bend of the Clark Fork River.



Areal Lime Rate was determined assuming a bulk density of 1.47 g/cm^3 (1 ac ft soil = 2 x 10^6 t)

Tailings less than 12" thick, Lime rate (t/ac) = tailings thickness (in) * 4.17

Tailings more than 12" thick, Lime rate (t/ac) = 50 + [tailings thickness (in) - 12] * 7.5

Figure 4. Net neutralization potential of tailings samples as a function of depth shown in relation to Clark Fork lime rate convention (25 to 45 t/1,000 t $CaCO_3$.

Samples collected after chemically amending tailings (Fig. 5) showed that most tailings had near neutral to alkaline pH and had a surplus of alkalinity of up to 130 t/1,000 t, an indication of localized over-liming. About 10 % of the tailings samples, however, were inadequately limed. These samples generally were found between furrows in deep-tilled areas. Due to the spatial scale of the amended furrows (about 30 to 60 cm spacing) and the ability of perennial vegetation to selectively exploit higher pH zones, the remaining zones of un-amended tailings did not seem to impair development of a nearly continuous vegetative stand.

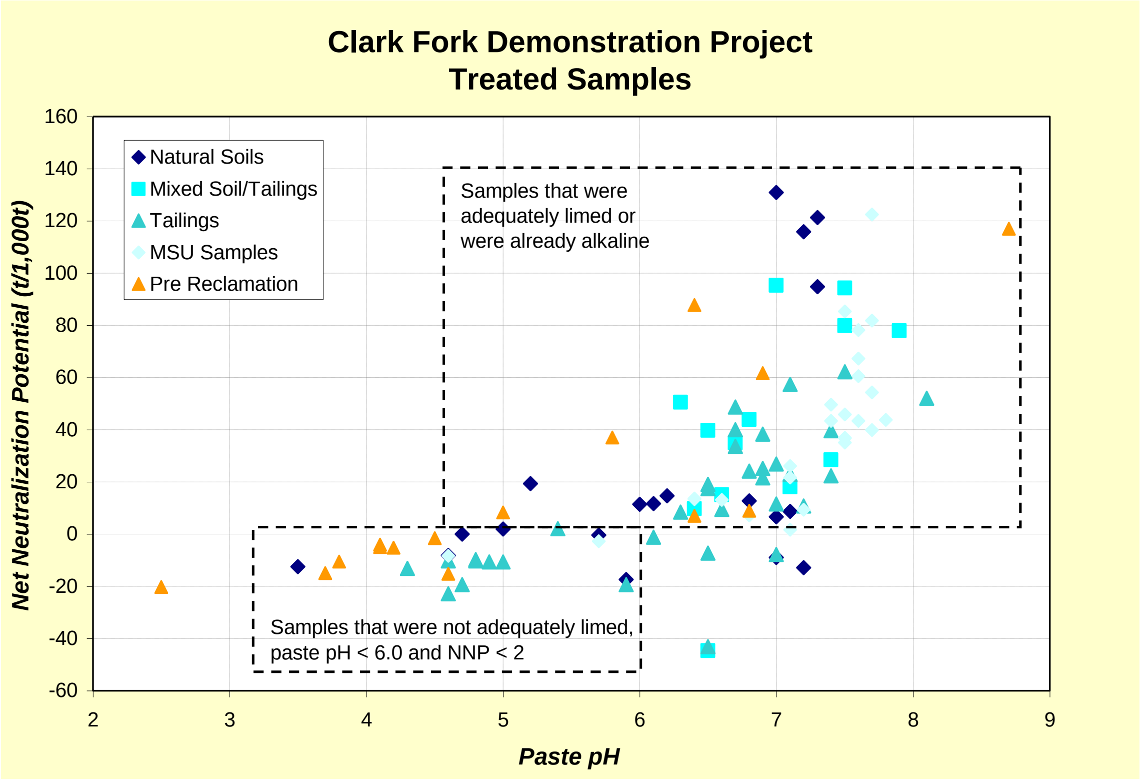


Figure 5. Net neutralization potential and paste pH of tailings collected prior to and after amendment addition to Clark Fork tailings.

Physical Incorporation of Chemical Amendments into Tailings

Chemical amendments used in the Clark Fork included a mixture of CaO and $CaCO_3$. The CaO ensured rapid pH control without the impediment of chemical coatings on $CaCO_3$ that has been found in previous studies to slow chemical dissolution. The amendments were spread using fertilizer spreaders. Agricultural implements can effectively mix surface applied material to depths of only 15 to 25 cm. Deep incorporation (to 1m) was accomplished using a specialized moldboard type deep plow with a blade nearly 1.2 m deep.

A visual field evaluation of the degree of mixing (Fig. 6) showed that pH in surface layers was uniformly increased to 7.5 to 8.0 (based on the blue color of the indicator dye added to soils in Fig. 6). Deeper layers (below 15 cm) were fully amended in slots that corresponded to the plow depth. An excavation oriented perpendicular to the plow (Fig. 6 left) shows that amendments were only mixed within the furrow. Additionally, roots grew only in amended soil and were absent from acidic soil zones. An excavation oriented parallel to the furrow (Fig. 6 right) shows complete mixing in the plowed zone.

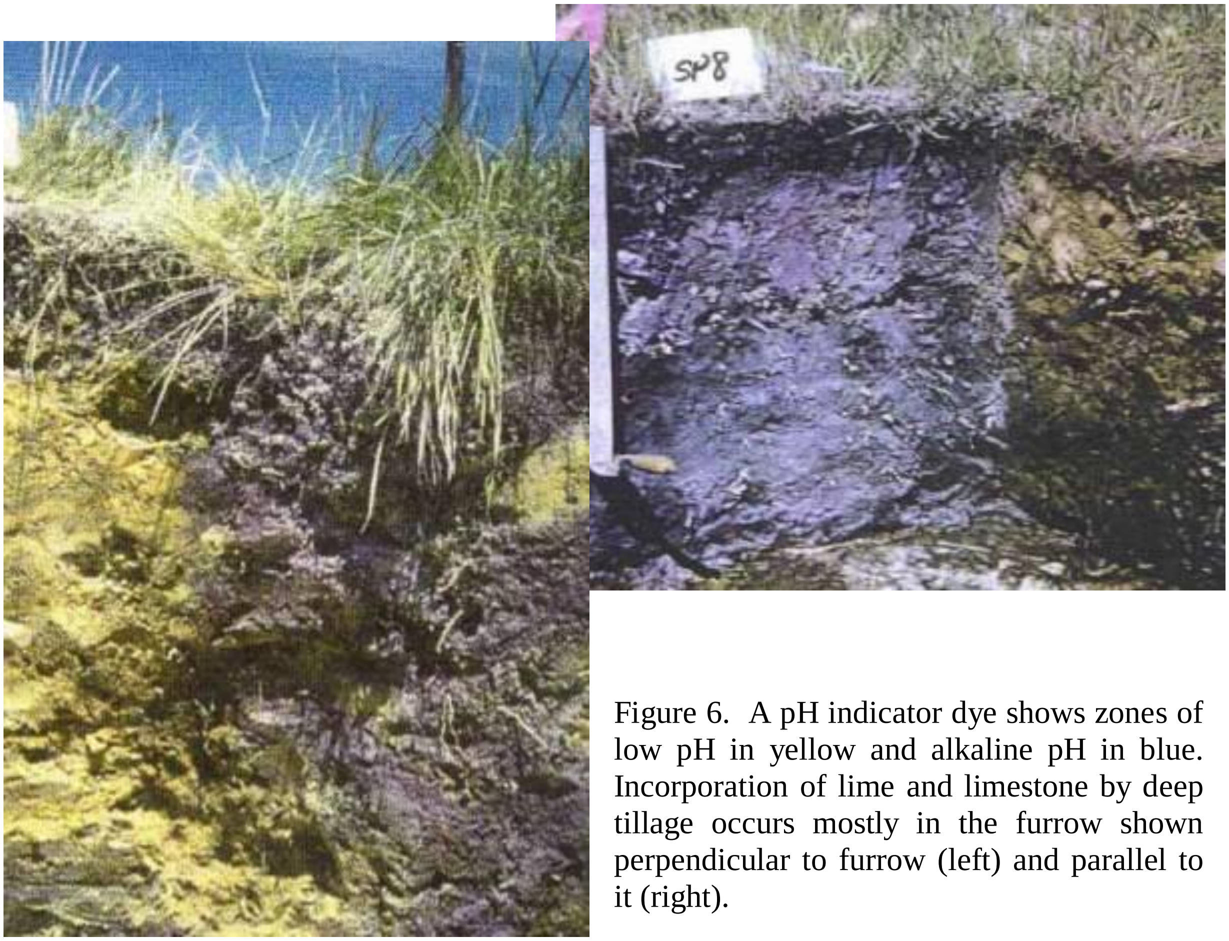


Figure 6. A pH indicator dye shows zones of low pH in yellow and alkaline pH in blue. Incorporation of lime and limestone by deep tillage occurs mostly in the furrow shown perpendicular to furrow (left) and parallel to it (right).

Reduction in Metal Mobility

Tailings and other floodplain soils varied both in total and soluble metal levels. Over a period of about 90 years, tailings acidified and metals were leached into underlying soils (Table 2). Buried soil layers typically had higher total Cu and Zn than tailings layers as a consequence of leaching. Only pure tailings materials had pH values of less than 5.5. As a result, soluble Cu and Zn were most pronounced in pure tailings (Fig. 7). Addition of chemical amendments was found to increase pH from a range of 3 to 5.5 to 6.5 to 8.5. Soluble Cu in pore waters (sampled with suction lysimeters) declined 2 to 4 orders of magnitude from a range of 200 to 1,000 mg/L to 0.1 to 10 mg/L. Similar reductions in Cu and Zn solubility were found for surface runoff from untreated and chemically treated areas (Schafer and Spotts 1996).

Arsenic solubility (Fig. 8) followed an inverse trend with lower concentrations (e.g. 0.01 mg/L) occurring in low pH zones and elevated concentrations 0.01 to 0.1 mg/L in lime-amended zones. From a terrestrial and aquatic toxicology perspective, the reduction in soluble Cu and Zn outweighed the increase in As.

Table 2. Average total metal concentrations in various kinds of natural soil, tailings and mixtures found in the Clark Fork River floodplain.

Soil Material	Total Arsenic (mg/kg)	Total Copper (mg/kg)	Total Zinc (mg/kg)
Exposed tailings	765	1,764	1,532
Cover soil	330	1,977	2,064
Buried soil	32	373	410
Mixed soil/tailings	419	2,364	2,323
Natural soil	63	303	400

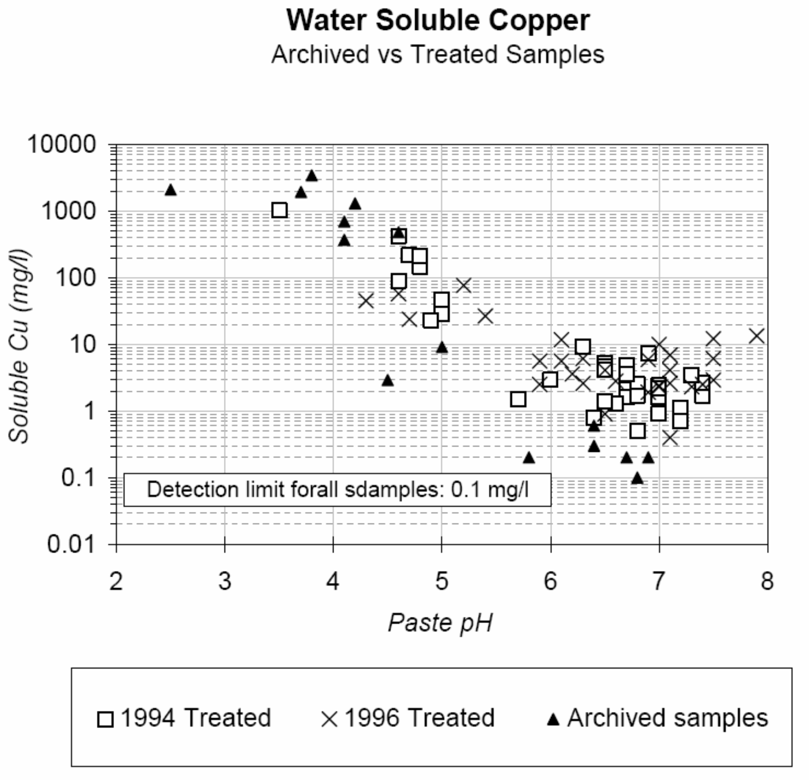


Figure 7. Solubility of Cu in untreated and limed tailings as a function of pH.

Permanence of Remedy

Vegetation performance and soil chemistry are two key indicators of the permanence of phytostabilization of the Clark Fork. During the first several years after seeding, the cover provided by perennial vegetation gradually improved (Fig. 9). The improvement in cover was most pronounced in deep (>60 cm) and moderately thick (30 to 60 cm thick) tailings. All tailings areas, regardless of thickness, achieved similar levels of cover of about 70 %.

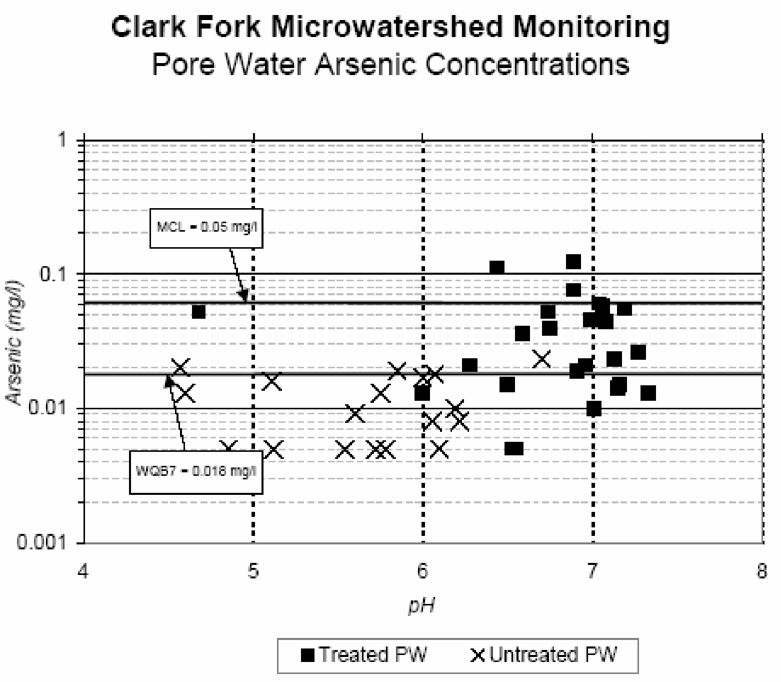


Figure 8. Solubility of arsenic in untreated and limed tailings as a function of pH.

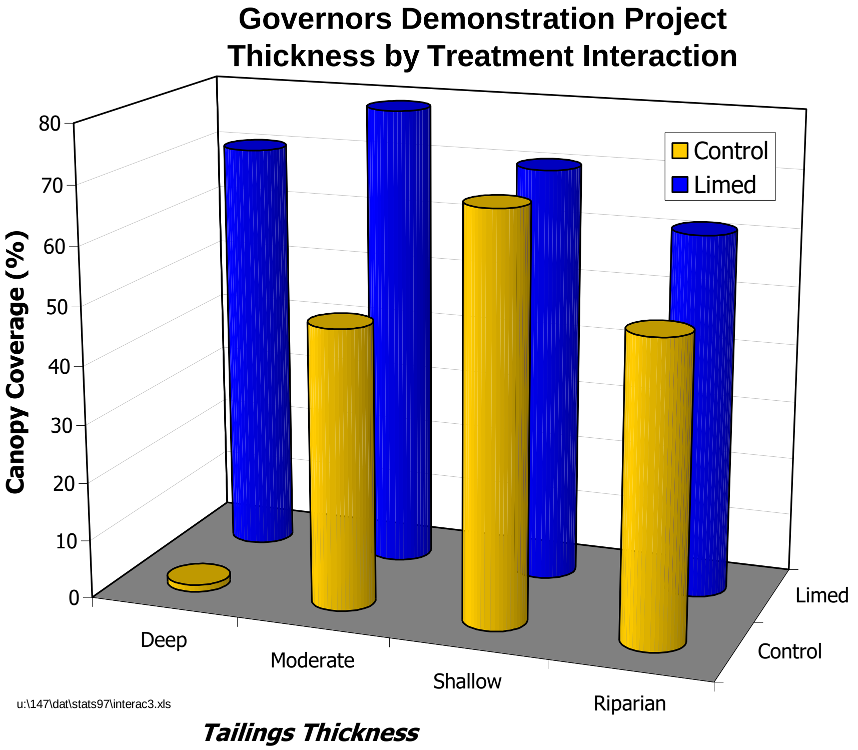


Figure 9. Average canopy cover as a function tailings depth for treated and untreated tailings, 1993 to 1996.

Vegetation at the site was evaluated after 12 growing seasons by Munshower et al. (2003). Their findings are summarized below.

> “Clark Fork River Governor’s Demonstration - Twelve Growing Seasons
>
> Soils at the study area yielded an averaged pH of 7.7 and EC of 6.4 dS/m. The conductivity was slightly elevated but vegetation was performing very well. Total soil levels at this site were measured at 939 mg/kg (As), 1880 mg/kg (Cu), 1280 mg/kg (Zn), 690 mg/kg (Pb), and < 3.8 mg/kg (Cd). Soluble Cu was elevated (3.1 mg/l), but not enough to impact vegetation at the pH of these materials. The soils were friable and infiltration appeared to be very high. This is in sharp contrast to the materials prior to amendment when they were crusted, impermeable, and subject to severe erosion. The acid base account was 61 t/1000 t. This reservoir of neutralizing material in the soil after twelve growing seasons may be interpreted to mean that these soils will not reacidify in the future.
>
> The vegetation growing on this site was very robust (Fig. 10). Basin wildrye plants were commonly over 100 cm and some plants were over 125 cm tall. Grass cover was almost 60% and distributed very uniformly across the length of the treated landscape. Plant species changed from almost entirely Basin wildrye on the upland portion of the transect to almost entirely Baltic rush on the last frame measured near the Clark Fork River. Although present within the boundaries of the Demonstration, the seeded wheatgrasses were not found around our study transect. The two seeded wildryes (Basin and Russian), an invading Poa (probably secunda), and the very common Redtop were identified within the sampling frames. Three other grass or grass-like species were observed adjacent to the transect. These included Tufted hairgrass, Nebraska sedge, Smooth brome, and Baltic rush.

Figure 10. Dr. Frank Munshower evaluating perennial vegetation , dominated by Basin Wildrye, on the Clark Fork Demonstration Project in 2002.

> Total cover of desirable species exceeded 60%. Desirable forb cover was poor for a community in this environment. Undesirable forb species comprised another two percent cover, but by any criteria, forbs were poorly represented. Thick expanses of Willow (Salix exigua) and Western snowberry were scattered across this Demonstration, but the study transect was intentionally placed to avoid any of them. These clumps were expanding and this together with the vigorous grasses and a thick litter layer (>70%) contributed to the poor performance of the forbs. Standing plant biomass on this site was very large. It exceeded 2500 kg/ha and was composed almost entirely of forage grasses. This Demonstration needs livestock grazing to reduce the size of the plants, crumble the litter layer, and trample the litter into the ground. Grazing would also open the canopy to the establishment of perennial forb species."

A comparison of the site before treatment and after 14 growing seasons is shown in Fig. 11. In 1989, areas of bare tailings with white salts were evident in higher portions of the floodplain on the inside of meander bends. Little or no willow regeneration was occurring and dead willows abounded. In 2005, perennial grasses covered the tailings areas and were also encroaching into unseeded areas on point bar deposits. Juvenile willow stands were filling in many areas of the floodplain.

Perennial vegetation has been sustained on previously barren tailings deposits for 14 years in the Clark Fork Demonstration Project. Extensive monitoring of soil chemistry, runoff quantity and quality, and vegetation succession has amply demonstrated the success of the phytostabilization approach. This effective reclamation technique is also less costly than alternative approaches such as removal and is also less disruptive of existing land uses.

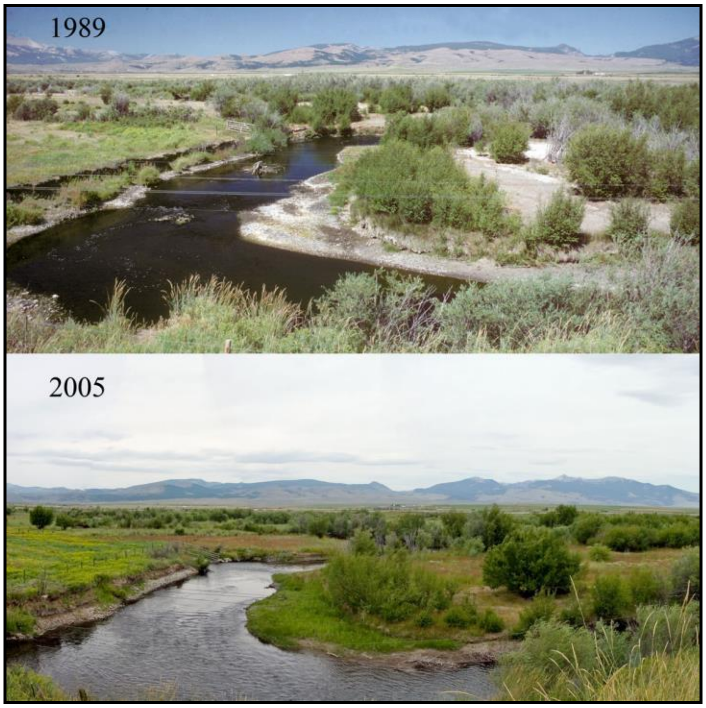


Figure 11. Comparison of a portion of the Clark Fork River floodplain before reclamation (above) and 14 years after reclamation (2005).

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