MODELING RECHARGE AND RUNOFF TO PREDICT COPPER AND ZINC TRANSPORT FROM LIME-AMENDED TAILINGS AT THE SILVER BOW CREEK CERLCA SITE[1]

William M. Schafer[2], John G. Goering[3], Tom R. Grady[2], Edward Spotts[2], and Dennis R. Neuman

Abstract: Remediation of mining waste deposited along the margins of Silver Bow Creek as a result of historic mining was evaluated in a multi-year research project funded cooperatively by the State of Montana, EPA, and ARCO Coal. The objective of the Streambank Tailings and Revegetation Study (STARS) was to evaluate the environmental performance of base addition, deep mixing techniques, and revegetation relative to the fate and transport of key metals of concern at the site. This paper summarizes the effect of lime amendments and revegetation on potential leaching of metals into groundwater, and runoff and erosion from streambank areas contaminated with tailings. Water flux in the unreclaimed and revegetated tailings was simulated using UNSAT2. Results of modeling water flux in the vadose zone indicated that 3 to 8 cm of groundwater recharge occurs in an average year in untreated tailings. Revegetation alters the site water balance so that groundwater recharge is unlikely. The amount of metals that migrate into surface water during high-intensity summer thunderstorms was predicted for existing conditions and for lime-treated and revegetated tailings. The US Department of Agriculture GLEAMS model was used to predict long-term runoff and erosion from the site. A three-year GLEAMS simulation indicated that STARS treatments would decrease runoff by 2 to 3-fold, and would change the timing of runoff. On the existing tailings, runoff was predicted intermittently from March through September. On reclaimed areas, runoff was predicted only in March and April when Silver Bow Creek provides more dilution. Substantial reductions in metal loading could be achieved due to reduction in runoff from mid-summer thunderstorms which are historically associated with fish kills.

Introduction

The Silver Bow Creek site located downstream from the Butte mining complex in Montana is one of the largest Superfund (Comprehensive Environmental Response, Liability and Compensation Act) mining waste sites in the United States. Large volumes of metallic sulfide tailings were fluvially transported by Silver Bow Creek and the upper Clark Fork River in the early 1900's. As a consequence, the floodplain system is widely contaminated with metal-enriched, low pH, acid-forming materials which have contributed to degradation of surface water quality.

Streambank tailings at the Silver Bow site may pose a significant environmental risk to both surface water and groundwater. Fish mortality has been a common occurrence in the Clark Fork River downstream of Silver Bow Creek during high-intensity convective thunderstorm events. Dissolution of metals in runoff from tailings areas probably causes short term increases in metal loads. Addition of alkaline amendments to increase soil pH and decrease metal solubility in conjunction with revegetation may reduce metal transport during runoff events.

Although widespread alluvial groundwater contamination is absent along Silver Bow Creek, recharge to groundwater by metal-enriched tailings pore water has the potential to degrade water quality. Tailings are generally located 30 to 100 cm above groundwater and overlie natural floodplain soils. Potential evaporation exceeds

---

[1]Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994.

[2]William M. Schafer, Principal, Tom Grady, Senior Project Manager, and Ed Spotts, Project Manager, Schafer and Associates, Bozeman, MT, USA.

[3]John G. Goering, Research Scientist, and Dennis R. Neuman, Research Scientist, Reclamation Research Unit, Montana State University, Bozeman, MT, USA.

Proceedings America Society of Mining and Reclamation, 1993 pp 40-49
DOI: 10.21000/JASMR94010040

https://doi.org/10.21000/JASMR94010040

precipitation in this semi-arid area. As a result, three conditions must exist for appreciable migration of metals to occur. The tailings pore water must contain elevated metal levels, downward flow of water must occur through the tailings, and metals must not be attenuated by underlying natural soils in the vadose zone. Direct sampling of tailings pore water using lysimeters indicated that elevated levels of iron, aluminum, manganese, copper, cadmium, zinc, and arsenic are common.

The STARS investigation was initiated to develop methods for remediating streambank tailings areas. A series of small plots was amended with lime and seeded with metal-tolerant plants in 1989. Various amendment incorporation methods were evaluated in the field investigation. Environmental performance monitoring of the STARS treatments was conducted from 1989 through mid-1992 (Schafer & Associates et al. 1993). The purpose of this investigation is to report on the effectiveness of selected STARS treatments in reducing the transport of metals into surface water and groundwater.

Methods

Field Site Description

Fluvially-deposited tailings and mine waste along 35 km of Silver Box Creek have generally denuded the floodplain in a 15 to 300 m wide corridor. The tailings have pore waters with pH from 3.0 to 4.5 and elevated concentrations of total or soluble copper, zinc, arsenic, cadmium, iron, aluminum, manganese, and lead. Two field study sites were selected on tailings with differing physical characteristics. The "Rocker" field site, which is typical of high-gradient stream reaches, consists of coarse sands and gravels with thin inter-stratified silt layers. Groundwater is located at a depth of 135 cm. The "Ramsay" field site is typical of low-gradient stream reaches. Tailings deposits are 30 to 60 cm thick and extend laterally 200 m from the channel. Mine waste and natural sediments at Ramsay are silt and clay-textured and groundwater was located at 190 cm.

Unsaturated Flow Modeling Using UNSAT2

A number of public domain models are available for simulating variably saturated flow in porous media. A saturated-unsaturated flow model, UNSAT2, was used to simulate differences in the rate and direction of convective water flux in untreated and revegetated tailings. UNSAT2 (Davis and Neuman 1983) has been widely applied to predict water flux in agricultural soils, in waste management facilities, and in earthen dams. UNSAT2, which was used as a 1-D model for this simulation, contains a number of options for simulating the capillary influence of groundwater, evaporation from bare soil surfaces, and withdrawal of water for transpiration by plants.

The numerical basis for unsaturated flow simulation in partially saturated soils is derived from the Buckingham-Darcy flux law [1], (Jury et al. 1991). The first hydraulic head term refers to the soil matric or suction potential. The second term in the hydraulic head expression is the unity downward gradient for vertical flow. In a soil at equilibrium with a shallow water table h is equal to -z so that the matric potential gradient is -1 and the total head (H) is zero, hence no flux occurs. By measuring the matric potential at a given distance above the water table, the direction of flow in unsaturated soil can be inferred. The soil matric potential always has a negative sign while the suction potential is equal in value to matric potential but is expressed as a positive number. The negative sign in [1] is used so that downward flux will be negative while upward flow is positive. When the matric potential gradient is less than -1 then upward flux occurs. Conversely, when the matric potential gradient is greater than -1, downward flux will occur.

$$J_w = -K_u\left(\frac{\partial h}{\partial z}+1\right)$$

where J_w is the rate of water flux (cm), [1]

K_u is the unsaturated hydraulic conductivity (cm/s),

and h and z are components of total head (cm) such that (h+z=H)

The Richards equation [2] which is the fundamental numerical expression governing transient water movement in unsaturated soil is derived by combining [1] with the continuity equation. UNSAT2 like other transient flow models was developed on the basis of the Richards equation with additional source and sink terms for plant water extraction.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K_u\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad [2]$$

UNSAT2 version 2.1, written in Fortran-77 is a two-dimensional finite element model. In addition to conventional fixed head, fixed flux, and impermeable boundary conditions, UNSAT2 also provides a number of special boundary conditions controlled by atmospheric variables. Examples include seepage faces, infiltration, and evaporation surfaces. The type of boundary as well as the value of the boundary data can be changed using a simulation restart feature. The relationship between hydraulic conductivity, suction, and water content can be described using the vanGenuchten equation [3] in version 2.1.

$$S_e = \frac{1}{[1+(\alpha h)^N]^{(1-\frac{1}{N})}}$$

$$\text{where } S_e = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)} \qquad [3]$$

θ = volumetric water content (cm^3/cm^3), θ_r = residual water content

θ_s = saturated water content, and N and α are vanGenuchten parameters

GLEAMS Model Theory and Structure

The USDA-ARS GLEAMS model (Knisel 1980) was used to simulate runoff and erosion from STARS treatments compared to untreated streambank tailings. The USDA GLEAMS model was used to evaluate qualitative changes in runoff from untreated and revegetated streambank tailings areas. Rainfall-runoff tests were also conducted to identify effects of treatment on metal concentration in runoff. The GLEAMS model consists of several component submodels for calculation of root zone hydrology, erosion, nutrient flux, and pesticide flux. Separate parameter input files are developed to run each component. Pass files are created by each component run for use in subsequent batch routines. Only the hydrology and erosion components of the GLEAMS model were used for this simulation.

The first component, hydrology, uses daily rainfall data, monthly temperature and solar radiation data, and various soil parameters for computation of the daily water balance. The amount and timing of runoff as well as other components of the water balance are computed, and pertinent information on storm size and runoff are passed to the erosion model component.

The technique used for estimation of runoff from daily rainfall data is the Soil Conservation Service (SCS) curve number approach which has been widely adopted throughout North America. The curve number approach

(Mockus 1985) relates the depth of runoff for a given depth of rainfall to the antecedent soil water content and to the "curve number" (CN). Curve numbers vary from 0 to 100, and are related to the infiltration capacity of the soil. Detailed guides have been developed for estimating curve numbers (Mockus, 1985). High curve numbers are typical of impermeable soils and disturbed areas while low curve numbers are found on well-vegetated permeable natural soils.

Rainfuall runoff is numerically related to runoff by the curve number. During a rainfall event, no runoff is presumed to occur until the rainfall depth exceeds 20% of the remaining soil water storage capacity. Soil storage is the difference between saturation and the antecedent moisture content (which is influenced by historical rainfall and evaporation). While the SCS curve number approach relies on a generalized assessment of the antecedent moisture condition, the GLEAMS model maintains a daily water balance so that s can be computed. In addition, the water balance module tracks cumulative runoff, evaporation, transpiration, percolation, and changes in soil water content.

The erosion component of the GLEAMS model utilizes the Yalin equation to compute the sediment transport capacity of runoff. Estimated soil loss can be either "detachment-limited" or "transport-limited". Detachment can occur due either to rain-drop splash or to the energy of overland flow. Overland flow from hillslopes can be routed in a number of ways. The simplest simulation is for overland flow to be routed directly to a channel at the edge of the domain. In addition, overland flow can be concentrated into a channel within the field boundary. Additionally, the hillslope profile can be segmented into various shapes (*eg.* uniform, convex, concave, or complex). Overland flow and sediment are routed through each segment. Deposition or flow-induced detachment can occur within any hillslope of channel element within the model domain. The hydrology and erosion components of the GLEAMS model have been validated at experimental research watersheds in Montana, Texas, Oklahoma, Ohio, Georgia, Nebraska, West Virginia, Mississippi, Iowa, Arizona, and New Mexico (Knisel 1980). In general, the long-term trend in runoff and erosion rates were accurately predicted by GLEAMS although model performance on individual storms was less reliable.

MODEL CALIBRATION

UNSAT2 Domain and Boundary Conditions

To simulate unsaturated flow at the STARS field sites, the hydraulic properties of typical samples were characterized using a variety of field and laboratory tests. Simulation was performed at the Rocker and Ramsay Flats sites in because these sites were most representative of the variety of streambank tailings conditions along Silver Bow Creek.

All soil samples characterized by desorption analysis (relationship between measured water content and suction) were grouped into 5 "type" textures (Fig. 1). The relationship between water content and water potential was fit to the soil hydraulic relationship developed by vanGenuchten [3]. Desorption and unsaturated hydraulic conductivity (K_u) curves for each "type" soil are presented in Figs. 1 and 2.

The domain modeled for each site was a 240 cm deep profile. Elements were thinner at the soil surface to avoid numerical instability associated with the steep water potential gradients that develop at the soil surface in response to evaporation. The type textures selected and the depth to the water table were based on field logs of lysimeter, piezometer, and neutron probe installations at each site.

The domain was initially modeled with a constant head boundary at the groundwater table to simulate the free water surface. The nodes at the soil surface were a special type called evaporation/infiltration (EI) nodes within UNSAT2. During simulation, a potential evaporation or infiltration flux can be set. In an EI node, the actual evaporation or infiltration can be equal or less than the potential rate depending on the ability of the soil system to transmit water to satisfy the potential flux at the surface.

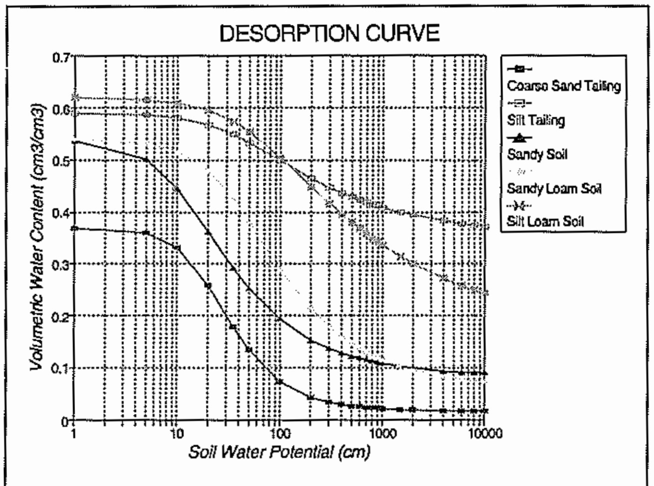

Figure 1. Desorption curves for type soils 1 through 5 for the STARS investigation.

In order to simulate the fully-drained soil profile (*eg.* field capacity), the domain was initialized as a nearly-saturated condition (a suction of -20 cm). A fixed head boundary of 0 cm of suction was set at the groundwater table at each site (Rocker at 135 cm, and Ramsay at 190 cm). The profiles were allowed to freely drain with no imposed surface flux for 90 days at Rocker and 180 days at the less permeable Ramsay site to reach fully-drained conditions.

For the simulation, the year was partitioned into three time periods beginning on June 1. The net water balance for each portion of the year was inferred from climatological observations (Fig. 3). The first 90 days was assumed to have a net water deficit (precipitation minus 70% of potential evaporation) of 25 cm which was applied equally throughout the 90 day "summer". The next 180 days consisted of a slow rate of surface infiltration amounting to 5 cm over the fall and winter. The final 90 days of the simulated year was the "spring" when precipitation greatly exceeded evaporation. A total of 10 cm of infiltration was assumed to occur over the 90 day period. These values for potential surface flux were imposed equally for each day of the 0 to 90, 91 to 270, and 271 to 360 day simulation period. The head conditions existing at the end of the initial draindown period were used as input representing day 0 conditions.

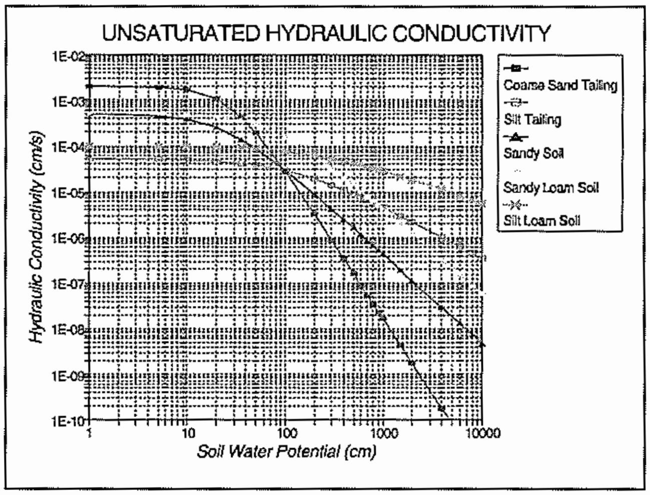

Figure 2. Unsaturated hydraulic conductivity curves for type soils 1 through 5 for the STARS investigation.

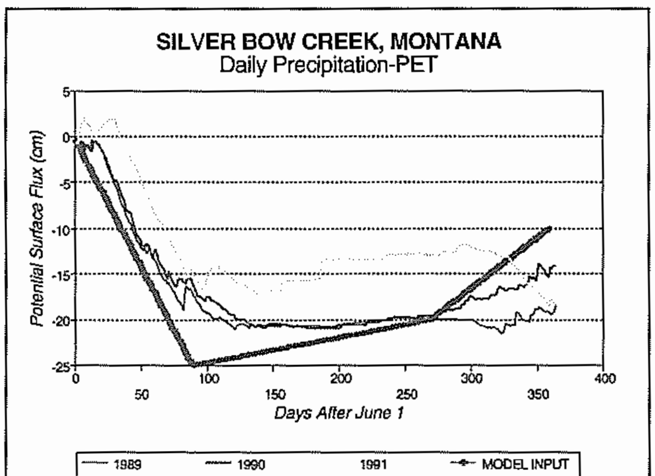

Figure 3. Cumulative evaporation deficit calculated by subtracting 70% of potential evaporation from precipitation is plotted for 1989 through 1991.

At each site, two individual soil surface conditions were simulated. A bare soil condition was used to simulate existing tailings. A vegetated plot representative of the deep plow plot was also simulated. The model domain was changed from a fixed head boundary below the water table to a zero flux boundary during the year simulated. This head change was necessary to construct a mass water balance of the water lost to evaporation. The climate modeled was conservative in that slightly wetter-than-average conditions were used. Hence these simulations would tend to slightly overestimate the tendency for streamside tailings to generate groundwater recharge in an average year.

GLEAMS Model Parameter Estimation. The GLEAMS model requires extensive parameter estimation and input before it can be used to simulate runoff and erosion from unknown areas. Due to the complexity of the GLEAMS model, only the control and the most successful amendment/revegetation treatment at each location were simulated using GLEAMS.

Precipitation input for GLEAMS runs was from the Anaconda, Montana National Oceanographic and Atmospheric Administration (NOAA) weather station (average precipitation 32.5 cm). A comparison of rain gauge measurements from each of the STARS field sites indicated that the Anaconda site correlated well with other stations in the basin and tended to have somewhat higher cumulative precipitation. Three full years of input data (1989 through 1991) were used in the GLEAMS simulations. Mean monthly average temperature and solar radiation values were calculated for a climate station located at Ramsay for the entire period of record. GLEAMS results are not highly sensitive to small variations in daily temperature and solar radiation, hence monthly inputs were used.

Input parameters for the hydrology and erosion simulation are listed in Table 1. The most sensitive parameter in the GLEAMS model is the runoff curve number (CN). Due to the sensitivity of this parameter, great care was taken in estimating CN values. Rainfall simulation test data were used to calculate CN values. The control plots at Ramsay had an unusually high curve number (95) presumably because of the rainfall-induced compaction on the exposed tailings. The coarse texture of tailings at Rocker resulted in a control curve number estimated to be 55. Due to the extremely high infiltration rate, no runoff occurred at Rocker during the rainfall simulation tests. The revegetated plots at Ramsay had much lower measured CN values than the control (59) due to the effects of tillage and revegetation. The curve numbers selected for the GLEAMS simulation (78 at Ramsay Flats) were conservatively set higher than the measured CN values due to potential bias in site selection for the rainfall simulation tests.

In general, a relatively thin root zone depth was input to simulate the control plots because observed changes in soil water content due to evaporation were confined to the upper 30 cm of soil. Values for hydraulic conductivity and soil water-holding capacity were based on measurements taken at each site.

The leaf area index (LAI) values and the crop type are important variables in simulating the on-site water balance. For the control plots, a LAI value of near zero was input so that GLEAMS would default to soil evaporation. For the vegetated plots, numerous preliminary GLEAMS runs were performed to try to simulate the observed changes in soil water content from the site. Very high values of LAI had to be input for simulated plant evapotranspiration to approach simulated soil evaporation in magnitude. Despite the fact that actual LAI values on the deep-till plots are near 1 or less, higher LAI values were input to improve model results. The beginning and end of the growing season and relative seasonal LAI values were input to simulate actual conditions.

Table 1. Input parameters used for the GLEAMS model - Silver Bow Creek, Montana.

GLEAMS MODEL DOMAIN	
HYDROLOGIC PARAMETERS	**EROSION PARAMETERS**
Area = 1,000 by 1,000 trapezoidal watershed Saturated Hydraulic Conductivity = measured at each site Soil Profile Percent Full = Initial water content 85% of field capacity Evaporation Coefficient = varies by site SCS Curve Number = varies by site, based on rainfall simulation Root Zone Depth = varies by site, generally 6 inches for control and 36 inches for vegetated Soil Characteristics = porosity, field capacity, wilting point, organic matter percent, clay, and silt content varies by site, based on observed soil morphology Monthly Mean Daily Maximum and Minimum Temperature = Based on Ramsay Flats climate station Monthly Mean Daily Solar Radiation = Based on Ramsay Flats climate station Vegetation Characteristics = varies by site, growing season duration and LAI based on calibration results	Slope = Overall 1.5 %, 1,440 feet at 1.5 % then steepening to 30% for last 30 feet Watershed shape = length to width ratio 2:1 Soil Erodibility K Factor = varies by site, based on USLE nomograph Cropping Practice P Factor = set to 1.0 for all simulations Cover Factor = varies by site, generally 1.0 for control and 0.2 for vegetated

Simulation Model Runs

Groundwater Recharge Estimation Using UNSAT2

Rocker. Changes in stored water under the bare soil and revegetated modeling scenarios are presented in Fig. 4. In the bare soil evaporation case, a measurable quantity of water was withdrawn from the coarse-textured tailings in the upper 60 cm of the soil profile (Fig. 4). The matric potential decreased to -15,000 cm (the imposed value for minimum permissible head at the surface node) at the soil surface in response to summer evaporation. This decline in matric potential created a very steep upward gradient causing water to move to the surface from a depth of about 30 to 60 cm in depth. The rate of water movement in the surface layer became so slow, however, that only 4.2 cm of actual evaporation occurred, a small fraction of the potential evaporation of 25 cm. Bare soil has been found to serve as an effective evaporation barrier by other investigators (Hillel 1980). During the subsequent fall and winter period, the imposed infiltration of 5 cm more than replenished the water withdrawn by evaporation so that water moved downward through the profile (Day 270). Additional percolation occurred during the rapid infiltration "spring" period (Day 360). Overall, the bare soil at Rocker had a net groundwater recharge of 8.4 cm or about 25 percent of the average annual precipitation.

Simulation of a revegetated plot at Rocker suggested that plant roots would remove water to a much greater depth than surface evaporation. A significant decrease in water content occurred throughout the domain, but the decline in matric potential was most pronounced within the root zone (upper 90 cm). The revegetated plot had 5.2 cm less water at the end of the year than at the beginning and therefore was not expected to generate recharge. Vegetation at the Rocker site was expected to be sub-irrigated as evidenced by the gradual decline in the water table during the summer. Overall, the bare streambank tailings areas would be expected to have 8.4 cm of percolation over the year while the revegetated plot was not expected to generate any percolation.

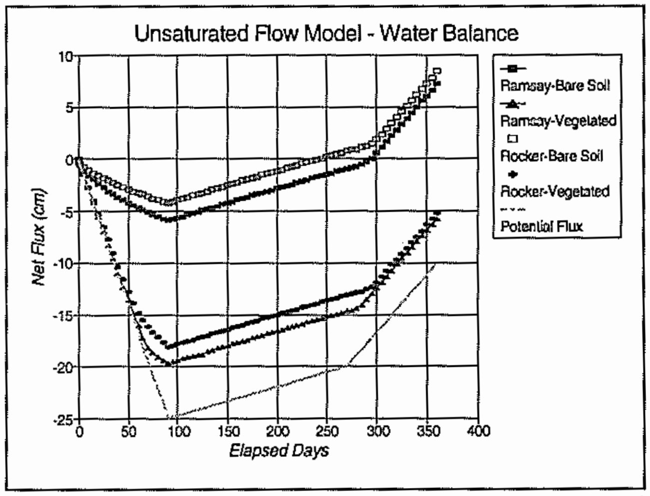

Figure 4. Cumulative water flux from bare soil and vegetated tailings at Rocker and Ramsay. A net annual increase in soil water indicates the potential for groundwater recharge.

Ramsay. Patterns of water use and changes in stored soil water simulated at the Ramsay Flats site were similar in many regards to Rocker despite significant differences between the sites. Ramsay soil had a slower hydraulic conductivity and greater depth to groundwater than at Rocker.

Despite the low permeability of the tailings at Ramsay, an appreciable amount of groundwater recharge is expected where bare tailings are exposed. In the bare soil case, a total of 6 cm was removed by evaporation during the summer period. As expected surface evaporation did not extract water content much below the top 30 cm of soil. Overall for the year the bare soil site gained 7.2 cm of water, only slightly less than at the coarser-textured Rocker site.

The simulation of the vegetated plot suggested that water would be removed by plants to 105 cm in depth. Plants withdrew 19.7 cm of water during the summer period. The matric potential of the vegetated Ramsay plot dropped to -15 bars at the soil surface and from -2 to -6 bars in the remainder of the root zone. Recharge the following winter created an obvious wetting front as water was replenished in the upper 45 cm of tailings. After the spring recharge period, the vegetated case at Ramsay was 5.8 cm drier than at the beginning of the year indicating that groundwater recharge is not likely to occur after vegetation becomes established.

Runoff and Erosion Modeling

Rocker. Simulation of the control and vegetated areas at Rocker were conducted using GLEAMS (Table 2). The soil material at Rocker was coarser in texture than at Ramsay Flats and so had a lower water-holding capacity, a much higher infiltration rate, and had less erosive soils than at Ramsay Flats. The water balance results for three years of simulated rainfall at Rocker indicated that 4.29 cm inches of percolation (*eg.* groundwater recharge) would occur on the control plot, while the higher evaporative use of water by established vegetation would prevent percolation. Runoff averaged 1.68 cm and 1.55 cm on the control and vegetated areas respectively. Predicted runoff was less at Rocker than at Ramsay due to the lower runoff curve number of both the control and vegetated treatments at Rocker. Runoff was only predicted in March and April, presumably in response to snowmelt events. Less difference in runoff was noted between the control and deep plow plots because reclamation had less overall effect on the curve number due to the already rapid infiltration on the control plot. Predicted soil loss at the Rocker site was 0.7 tons/acre for the control and 0.14 tons/acre for the deep plow plot. These low rates of soil loss were due to the coarse texture and rapid infiltration rates of soil at Rocker.

Ramsay. Runoff and erosion were simulated for the Ramsay control and vegetated treatments Ramsay using the calibrated GLEAMS model (Table 2). Significant differences in the amount of runoff and erosion were predicted between the control and deep plow treatments. For the 3-year simulation, 3.71 cm of runoff occurred from the control, while only 1.70 cm was predicted from the deep plow plot. No percolation below the root zone was predicted for either treatment, hence evaporation and transpiration accounted for the remaining average annual rainfall of 32.5 cm.

Table 2. Summary of water balance results and soil loss from the USDA CREAMS runoff model for the Rocker and Opportunity sites Flats (1989 to 1991).

WATER BALANCE TERM	RAMSAY CONTROL	RAMSAY DEEP PLOW	ROCKER CONTROL	ROCKER DEEP-TILL
WATER BALANCE SUMMARY				
Precipitation (cm/yr)	32.5	32.5	32.5	32.5
Runoff (cm/yr)	3.71	1.70	1.68	1.55
ET (cm/yr)	30.0	35.8	26.9	32.8
Percolation (cm/yr)	0.0	0.0	4.29	0.0
Soil Loss (t/acre/yr)	13.7	1.2	0.7	0.14

The timing of runoff also differed between the control and vegetated treatments. Peak monthly runoff for both treatments occurred in April or May, depending on the year. Measurable amounts of runoff occurred throughout the summer from the control plot, while no runoff occurred after the end of May from the vegetated plot. This difference in the timing of runoff is thought to be significant in that most fish kills on the Clark Fork have been observed in July and August after convective thunderstorms. Runoff during midsummer may contain higher concentrations of dissolved metals due to the formation of metal-enriched salt crusts in the soil surface during warm weather. In addition, the higher spring instream flow means that runoff from streambank areas is more diluted when it mixes with the channel in spring than in summer.

Significant differences in erosion rates were also noted between the control and deep-plow treatments. For the control site, an average annual soil loss of 13.7 tons/acre was predicted while only 1.2 tons/acre was predicted for the deep plow site. The ten-fold reduction in erosion was due to the reduction in runoff as well as the protection provided by the vegetative cover established on the deep plow plots.

Discussion

Flux of Metals to Groundwater

Transport of metals from streambank tailings to groundwater would require three distinct conditions including increased solubility of metals in tailings pore water, downward flow of water, and limited attenuation of metals in the underlying buried soil layers. While direct measurement indicates that tailings pore water has elevated concentrations of soluble metals, modeling indicates that a substantial quantity of downward convective flow occurs from untreated tailings. The lack of widespread groundwater contamination along Silver Bow Creek therefore indicates that natural soils serve as an effective geochemical barrier to metal transport. Revegetation will further reduce the risk of groundwater contamination by reducing the net groundwater recharge.

Assessment of Surface Water Impacts

Runoff rates predicted by the GLEAMS simulation were compared with US Geological Survey (USGS) streamflow records on lower Silver Bow Creek to determine the mass loading of runoff from streambank areas compared with instream flows. In addition, chemical characteristics of water collected during rainfall-runoff trials were used to calculate mass loading of metals into Silver Bow Creek during typical high-intensity thunderstorms. The purpose of this transport analysis was to;

- determine if modeling results identify surface runoff of metals as a critical transport mechanism;
- evaluate the effectiveness of STARS treatments as a means of reducing potential impacts to surface water;
- and to determine the relative importance of dissolved versus total metals delivered to Silver Bow Creek.

Hydrograph Mass Loading. To compute the mass loading of metals in surface runoff from streambank areas, it was first necessary to estimate the contribution of runoff water from streambank areas. For this analysis, the contributing area was assumed to be the lower 10 miles of the Silver Bow Creek floodplain. Only the lower portion of the floodplain was used because most convective storms are rather localized, and it was implausible to assume that the entire watershed would be affected by a convective storm cell. The streambank tailings contributing area was assumed to consist of a 100 foot wide corridor (120.8 acres) along Silver Bow Creek. Rainfall-runoff characteristics from the untreated tailings control plot were used to simulate the response of the streambank tailings area. Runoff from the streambank tailings area was assumed to have zero time of concentration due to its close proximity to the channel. Duration of each daily runoff event was assumed to be 6 hours.

Actual flows from the USGS gaging station (#1232600) near Opportunity, MT were used to determine the amount of dilution that would occur when streambank tailings runoff reached Silver Bow Creek. The entire 3-year period of record used in the GLEAMS simulation run was reviewed, and three time periods were selected representing the single largest runoff event from each year. In 1989 (Fig. 5), a 0.80 inch rainstorm on August 23 resulted in 0.11 inches of runoff. This event over a 6-hour duration resulted in 2.23 cfs of flow from the streambank area which would have made up 8.9% of the instream flow of 25 cfs reported for August 23. As expected, the tailings area runoff peak from the August 23 event occurred on the rising limb of the basin-wide hydrograph. This response would be expected due to the size of the Silver Bow Creek watershed at Opportunity (284 mi^2). Similar analysis of stream hydrograph records and computed runoff in May, 1991, and in September, 1991, resulted in streambank runoff computed to be 15.1 % and 9.2 % of baseflow.

Metal Mass Loads. Runoff from simulated rainfall tests from untreated and lime-amended plots at Opportunity were analyzed for a suite of dissolved and total metals. Table 3 lists the levels of dissolved and total copper and zinc in runoff samples representing the "first flush" of runoff (0.05 inch) as well as the long-term runoff. During an intense thunderstorm, the calculated concentration of total copper and zinc in Silver Bow Creek may range from 1.4 to 9.0 mg/l and 1.1 to 6.9 mg/l respectively. Dissolved copper and zinc may range from 0.4 to 4.5

CONSTITUENT	CONTROL PLOT		LIME-TREATED PLOT	
	INITIAL RUNOFF (mg/l)	LONG-TERM RUNOFF (mg/l)	INITIAL RUNOFF (mg/l)	LONG-TERM RUNOFF (mg/l)
Copper - Total	60	14.3	1.31	0.60
Copper - dissolved	30	4.0	0.45	0.093
Zinc - Total	46.2	11.4	1.66	0.41
Zinc - dissolved	35	9.3	0.55	0.033

Table 3. Total and dissolved Cu and Zn in simulated rainfall-induced runoff from control and lime-treated plots.

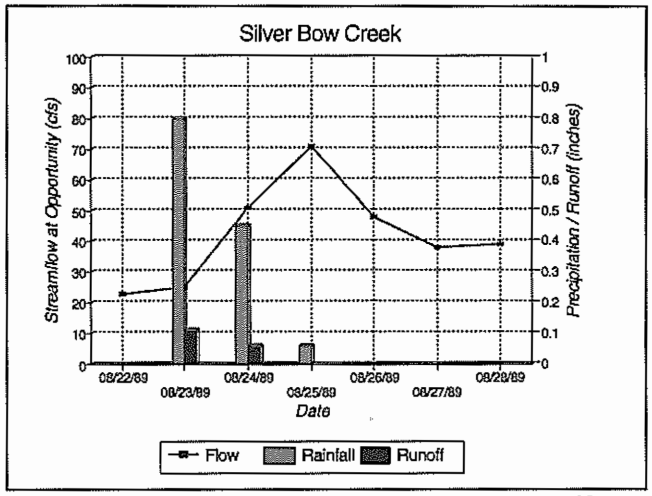

Figure 5. Comparison of rainfall, estimated runoff, and streamflow in August, 1989.

mg/l and 0.93 to 5.25 mg/l respectively. These levels of copper and zinc exceed the acute criteria for protection of freshwater life by several orders of magnitude. The hardness-corrected copper and zinc standards at a hardness of 100 mg/l are 0.018 and 0.117 mg/l.

The runoff contribution of metals to Silver Bow Creek from revegetated plots was also calculated. On each of the dates when runoff was simulated from bare tailings, no runoff was predicted from any of the lime-amended and vegetated plots. As a consequence, predicted metal loading was decreased to zero by the STARS treatments. It should be noted that while no runoff was predicted for convective thunderstorms during the summer months, runoff was expected to occur during snowmelt. The maximum contribution of streambank runoff to Silver Bow Creek for revegetated plots occurred in March or April of the year and was equal to less than 2 percent of the instream flow. Coupled with the 25-fold or greater reduction in total metal concentration in runoff from revegetated plots, the overall contribution to Silver Bow Creek from the streambank areas would be expected to decline by 100 to 200-fold due to basin-wide implementation of the STARS technology.

Literature Cited

Davis, L.A., and S.P. Neuman. 1983. Documentation and User's Guide; UNSAT2 - Variably Saturated Flow Model. Final Report for the U.S. Nuclear Regulatory Commission. NUREG/CR-3390.

Hillel, D. 1980. Applications of Soil Physics. Academic Press. New York. 385 pgs.

Jury, W.A., W.R. Gardner and W.H. Gardner. 1991. Soil Physics. John Wiley and Sons. New York. 328 pgs.

Knisel, W.G. (Editor) 1980. CREAMS: A field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. USDA Conservation Research Report 26.

Knisel, W.G., F.M. Davis, and R.A. Leonard. 1992. GLEAMS Version 2.0 User's Manual. USDA Southeast Watershed Research Laboratory. Tifton, GA.

Mockus, V. 1985 (Revision) National Engineering Handbook Section 4: Hydrology. USDA-SCS.

Schafer and Associates, and Reclamation Research Unit. 1993. Silver Bow Creek RI/FS. Streambank Tailings and Revegetation Studies. Phase III Final Report. Submitted to Montana Department of Health and Environmental Sciences.