Ref ID 88270

Planning, Rehabilitation and Treatment of Disturbed Lands
Billings Symposium 1993

MODELING THE FATE AND TRANSPORT OF METALS IN SURFACE WATER AT THE SILVER BOW CREEK CERLCA SITE

by:
William M. Schafer[1], J.G. Goering[1], T.R. Grady[1], E. Spotts[1], and D.R. Neuman[2]

Abstract

In-situ remediation of mining waste deposited along the margins of Silver Bow Creek 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 amendment addition, deep mixing techniques, and revegetation on the fate and transport of key metals of concern at the site.

This paper summarizes a portion of the STARS project relating to the effect of lime amendments and revegetation on runoff and erosion from streambank areas contaminated with tailings. In addition, the consequence of metals migration into surface water during high-intensity summer thunderstorms was evaluated for both the existing as well as treated tailings. The USDA-ARS 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, flows were only expected in March and April when Silver Bow Creek provides more dilution. Substantial reductions in metal loading due to runoff from mid-summer thunderstorms (historically associated with fish kills) were also predicted.

1 - Schafer and Associates, Bozeman, MT. 59715
2 - Reclamation Research Unit, Montana State University, Bozeman, MT 59717

INTRODUCTION

The Silver Bow Creek site located downstream from the Butte mining complex is the largest CERLCA mining waste site in the nation. Large volumes of sulfide tailings have been fluvially transported in Silver Bow Creek and the upper Clark Fork river. As a consequence, the floodplain system is widely contaminated with metal-enriched low pH materials which have contributed to degradation of surface water quality.

The STARS investigation was initiated to develop *in-situ* methods for remediating streambank tailings areas. A series of small plots were amended with lime and seeded with metal-tolerant species in 1989. Various amendment incorporation methods were evaluated in the field investigation. Environmental performance monititoring of the STARS treatments was conducted from 1989 through mid-1992 (Neuman et al. 1993 this publication, Schafer & Associates and Reclamation Research, 1989a and 1989b). The purpose of this investigation is to report on the effectivness of selected STARS treatments in reducing the transport of metals into Silver Bow Creek via surface runoff and erosion.

METHODS

GLEAMS Model Theory and Structure

The USDA-ARS GLEAMS model was used to simulate runoff and erosion from STARS treatments compared to untreated streambank tailings. 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 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". 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)

Runoff is numerically related to runoff by [1]. During a rainfall event, no runoff is presumed to occur until the rainfall depth exceeds 0.2 of the remaining soil water storage capacity. Soil storage [2] is related to the relative degree of soil saturation (which is influenced by historical rainfall and evaporation) and by the maximum storage [3] which is inversely proportional to the curve number for condition I. Condition I is the curve number for dry soil moisture conditions. While curve numbers for condition II (average soil moisture) are tabulated in USDA references, CN(I) values corresponding to CN(II) values can be calculated using [4].

$$Q = \left[\frac{(P-0.2s)^2}{(P+0.8s)}\right] \qquad [1]$$

where Q = *Runoff depth (inches)*
P = *Rainfall depth (inches)*
s = *soil storage coefficient (inches)*

$$s = s_{max}\left[\frac{(UL-SM)}{UL}\right] \qquad [2]$$

where s_{max} = *see equation* [3]
UL = *Upper limit of soil water storage (inches)*
SM = *Current stored soil moisture (inches)*

$$s_{max} = \left[\frac{1000}{CN(I)} - 10\right] \qquad [3]$$

$$CN(I) = -16.91 + 1.348[CN(II)] - 0.01379[CN(II)^2] + 0.0001177[CN(II)^3] \qquad [4]$$

Runoff volumes for increasing rainfall amounts are shown in Figure 1. High curve numbers are typical of impermeable soils and disturbed areas while low curve numbers are typical of well-vegetated permeable natural soils. Implicit in the SCS curve number method is that runoff initiation occurs after 0.2 times the storage. In many urban areas where pavement and bare soils are common, runoff occurs during much smaller rainfall events. In addition, infiltration is assumed to decrease to zero after a rainfall depth equivalent to s has occurred. This assumption too may be erroneous especially for permeable soils.

Nonetheless, the SCS curve number method has been widely validated using research watersheds from throughout the U.S.

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 can keep track of cumulative runoff, evaporation, transpiration, percolation, and changes in soil water content [5].

Daily evaporation is the sum of soil and plant evaporation. The maximum daily potential evaporation (PET) [6] is based on the mean daily temperature and solar radiation, each of which are input as mean monthly values in the GLEAMS model. The PET

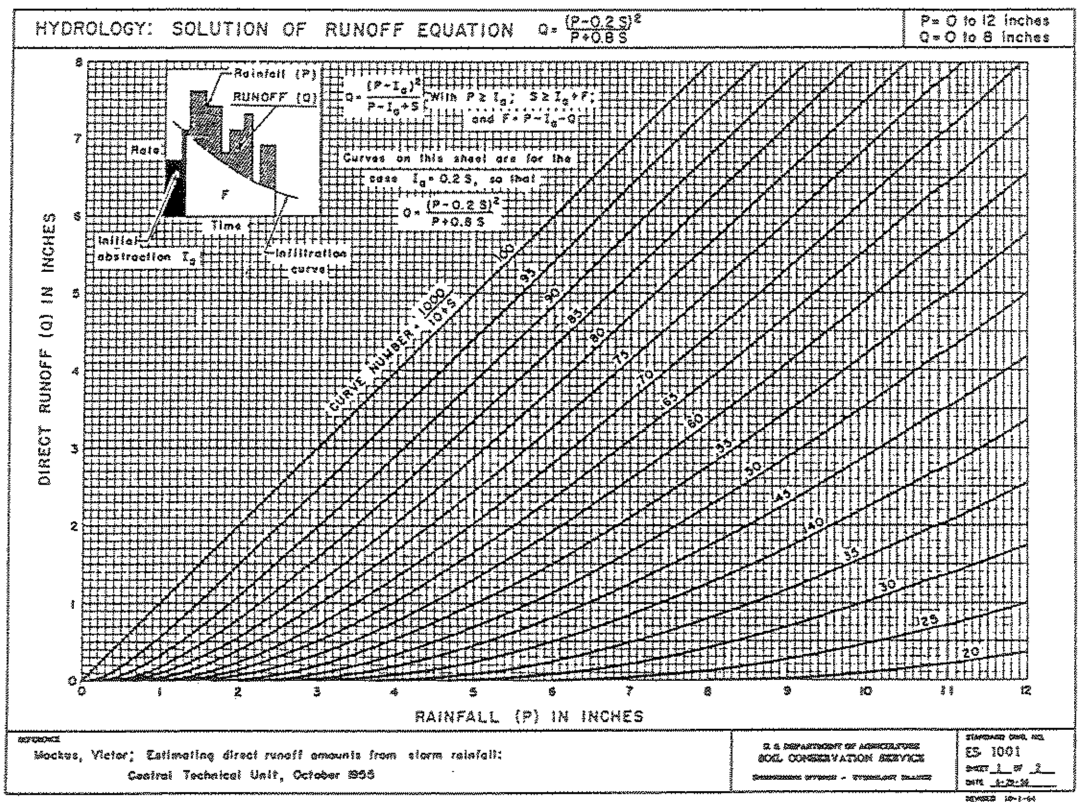

Figure 1. **Rainfall-runoff relationships for soils with varying curve numbers (from SCS National Engineering Handbook, Section 4).**

calculated by the Ritchie equation is generally higher than that calculated by the solar thermal unit equation selected for PET calculation in the STARS work plan (Schafer and Associates and MSU, 1990).

Soil evaporation [7] is calculated as a negative exponential function of the leaf area index (LAI). Hence, as the plant canopy coverage increases, soil evaporation decreases in importance. Prior research on soil evaporation from bare soil surfaces (Hillel, 1980) has shown that it occurs as a two-stage process. When the soil surface has a high water content, soil evaporation continues at a rate limited by the potential evaporation (E_o). When the upper few millimeters of the soil surface dries, however, the soil evaporation rate decreases due to the slow rate of vapor phase transmission of water. The two-stage soil evaporation process utilized by the GLEAMS model is given in [8]. Values for α_s for different soil textures are given in the GLEAMS manual. When the calculated soil evaporation exceeds ϵ_s, the slower stage of soil evaporation is triggered.

$$P = RO - ET - PERC \pm SOIL\ WATER \qquad [5]$$

$$E_o = \left[\frac{1.28\ \delta\ \eta_o}{\delta\ \gamma}\right]$$
$$E_o = potential\ daily\ evaporation\ (inches)$$
$$\delta = \left[\frac{5304}{T^2}\right] e^{21.255 - \frac{5340}{T}}, T\ in\ degrees\ Kelvin \qquad [6]$$
$$\eta_o = \frac{(1-\lambda)(R)}{58.3}$$
$$\lambda = albedo$$
$$R = solar\ radiation\ (langleys/day)$$
$$\gamma = psychrometric\ constant$$

$$E_s = E_o\ e^{-0.4\ LAI} \qquad [7]$$

Plant evapotranspiration is assumed to be a linear-weighted fraction of the PET for LAI values up to 3.0. When soil water is limited (less than 25 percent of available water), the plant evaporation decreases linearly until the soil is dry. Values of LAI can either be provided by the GLEAMS pre-processor for over 75 agronomic crop and forage species or can be input as a function of growing season length and julian date. LAI values of zero default to simple bare soil evaporation. Soil water utilized by plants is extracted preferentially from upper soil layers. As the growing season progresses, water extraction can occur at progressively greater depth. This algorithm simulates root extension of annual crops and root activity of perennial crops.

The erosion component of the GLEAMS model utilizes the Yalin equation to compute the sediment transport capacity of runoff. Estimated soil loss can either be "detachment-limited" or "transport-limited". Detachment can occur either due to rain-drop splash or due to the energy of overland flow.

$$
\begin{gathered}
E_s = E_o e^{-0.4LAI} \ where \ \epsilon_s < E_o \\
E_s = \alpha_s\left[t^{0.5} - (t - \frac{1}{2})^{0.5}\right] \ where \ \epsilon_s > E_o \\
\epsilon_s = 9(\alpha_s - 3)^{0.42} \\
\epsilon_s = maximum \ daily \ soil \ evaporation \\
\alpha_s = evaporation \ coefficient
\end{gathered} \qquad [8]
$$

$$
\begin{gathered}
E_p = \left[\frac{(E_o \ LAI)}{3}\right] \ for \ LAI<3 \\
E_p = E_o - E_s \ for \ LAI>3
\end{gathered} \qquad [9]
$$

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 being modeled. In addition, overland flow can be concentrated into a channel within the field boundary. Finally, the hillslope profile can be segmented into various shapes (*eg.* uniform, convex, concave, or complex). Overland flow and sediment is routed through each segment. Deposition or flow-induced detachment can occur within any hillslope of channel element within the model domain.

The GLEAMS model also predicts the particle size distribution of eroded sediment. When deposition occurs within the field area or channel or when transport capacity is exceeded the transported sediment may consist on average of finer particles than the average grain size in surface soils.

GLEAMS Model Validation

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. 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

Parameter Estimation: The GLEAMS model requires calibration 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, MT NOAA weather station (average precipitation 12.8 inches). 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 the Ramsay Flats climate station 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. 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 Flats and Opportunity had unusually high curve numbers presumably because of the rainfall-induced compaction on the exposed tailings. A curve number of 95 was used for the control plots at each site. The coarse texture of tailings at Rocker resulted in a control curve number estimated to be 55. Measured curve numbers for Ramsay Flats and Opportunity were 94 and 93 while the Rocker site had a CN of less than 50. Due to the extremely high infiltration rate, no runoff occurred at Rocker during the rainfall simulation tests. The deep-till/revegetated plots at Ramsay Flats and Opportunity had much lower measured CN values than the control (59 and less than 50) due to the effects of tillage and revegetation. The curve numbers selected for the GLEAMS simulation (78 at Ramsay Flats and 65 at Opportunity) 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 12 inches 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 in order for plant evapotranspiration to approach 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

Ramsay Flats: Runoff and erosion was simulated for the control and deep plow plots at Ramsay Flats 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 three year simulation, 1.46 inches of runoff occurred from the control while only 0.67 inches 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 12.8 inches.

The timing of runoff also differed between the control and deep plow 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 deep plow 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.

Rocker: Similar simulations of the control and deep plow plots at Rocker were also conducted (Table 5.2). The soil material at Rocker was coarser in texture than at Ramsay Flats, hence 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 1.69 inches of percolation (*eg.* groundwater recharge) would occur on the control plot, while the higher evaporative use of water by established vegetation in the deep plow plot would prevent percolation. Runoff averaged 0.66 inches and 0.61 inches on the control and deep plow plots respectively. Predicted runoff was less at Rocker than at Ramsay Flats due to the lower runoff curve number of both the control and deep-plow plots 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 (CN = 40 for both cases) 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.

Opportunity: GLEAMS simulation of the Opportunity control site (Table 5.2) yielded an estimated annual 1.69 inches of runoff and 0.42 inches of percolation for 12.8 inches of precipitation. Runoff occurred intermittently from March through September with peak contribution in April. Percolation occurred from April through June when the soil profile was at its annual maximum.

The deep plow plot at Opportunity had substantially less predicted runoff (0.66 inches/year) than the control plot and no percolation. Runoff occurred only during snowmelt in March and April, periods of the year when runoff would be expected to have less impact on fisheries and macroinvertebrates due to the higher in-stream flows. The decrease in runoff was due to the reduction in the curve number observed between bare tailings (curve number = 94) and the deep-plowed and vegetated condition (curve number = 65).

Predicted annual soil loss for the control plot and deep plow treatment was 9.2 and 0.67 tons/acre respectively.

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	OPPOR-TUNITY CONTROL	OPPOR-TUNITY DEEP-TILL
WATER BALANCE SUMMARY						
Precipitation (in/yr)	12.8	12.8	12.8	12.8	12.8	12.8
Runoff (in/yr)	1.46	0.67	0.66	0.61	1.69	0.32
ET (in/yr)	11.8	14.1	10.6	12.9	10.9	12.3
Percolation (in/yr)	0.0	0.0	1.69	0.0	0.42	0.0
SOIL LOSS SUMMARY						
Soil Loss (t/acre/yr)	13.7	1.2	0.7	0.14	9.2	0.67

FATE AND TRANSPORT ASSESSMENT

Hydrograph Mass Loading: Runoff rates predicted by the GLEAMS simulation were compared with USGS streamflow records at Opportunity 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 fate and 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.

In order 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 Opportunity 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 gauging station (#1232600) at Opportunity were used to determine the amount of dilution which would occur when streambank tailings runoff reached Silver Bow Creek. The entire three 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 (Figure 2), a 0.80 inch rainstorm on 8/23 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 8/23. As expected, the tailings area runoff peak from the 8/23 event occurred on the rising limb of the basin-wide hydrograph. This response would be expected due to size of the Silver Bow Creek watershed at Opportunity (284 mi^2).

Similar analysis of stream hydrograph records and computed runoff in May, 1991 (Figure 3) and in September, 1991 (Figure 4) resulted in streambank runoff computed to be 15.1 % and 9.2 % of baseflow.

Metal Mass Loading: 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. Assuming that runoff from streambank tailings can comprise from 10 to 15 % of the total flow in Silver Bow Creek during an intense thunderstorm, the calculated level of total copper and zinc 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 mg/l and 0.93 to 5.25 mg/l respectively. In addition, the predicted tailings erosion

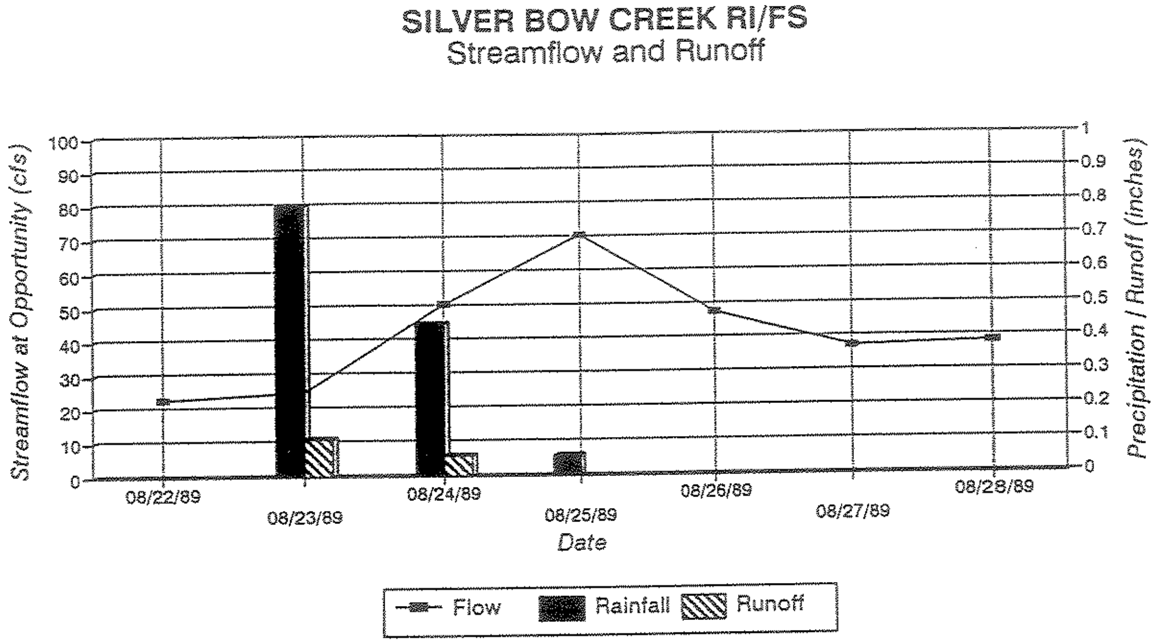

Figure 2. Comparison of daily rainfall and estimated streambank tailings runoff with Silver Bow Creek flow in August, 1989.

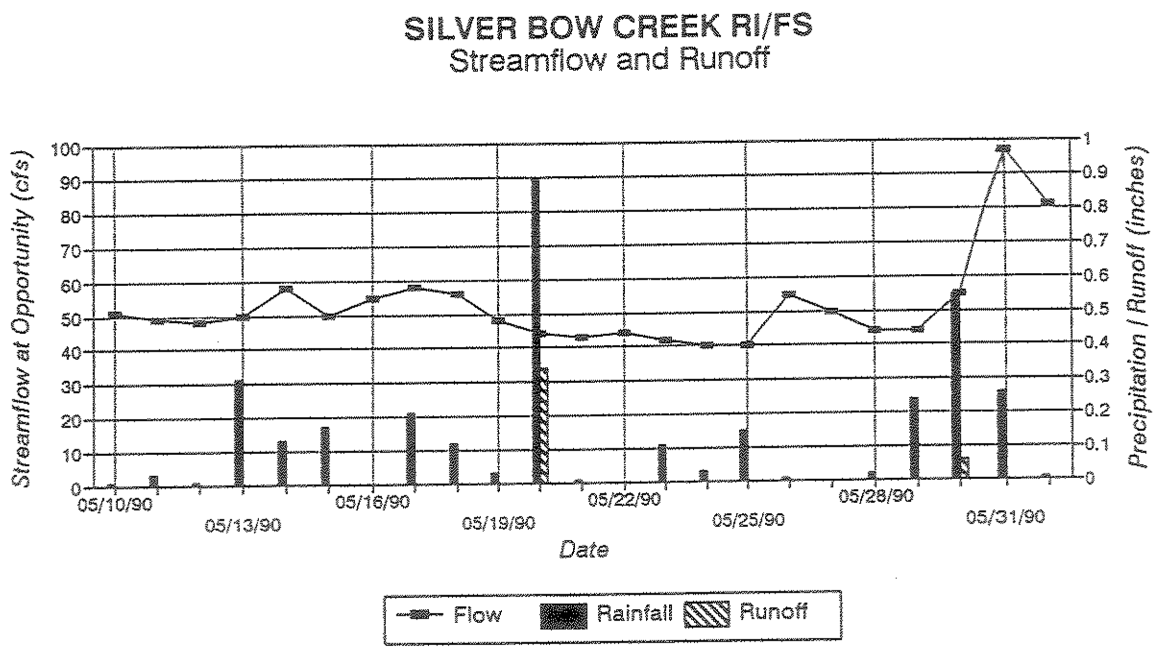

Figure 3. Comparison of daily rainfall and estimated streambank tailings runoff with Silver Bow Creek flow in May, 1990.

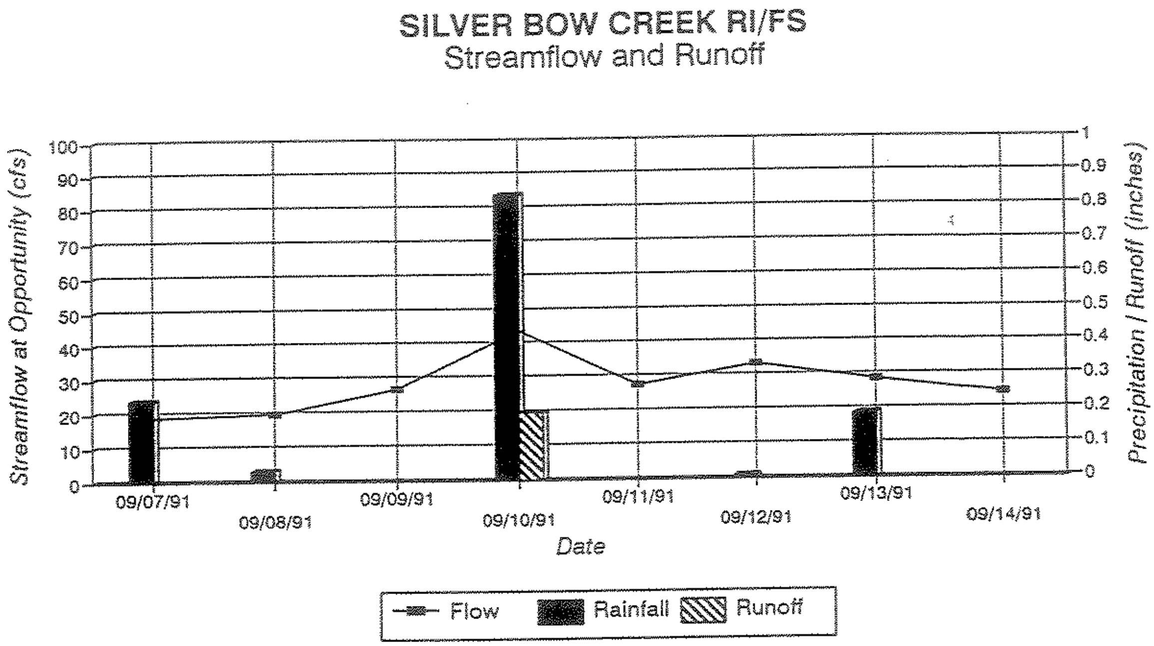

Figure 4. Comparison of daily rainfall and estimated streambank tailings runoff with Silver Bow Creek flow in September, 1991.

rate for these runoff events would be expected to deliver an equal amount of metals to Silver Bow Creek to those predicted on the basis of runoff test results. Hence, total metal loads could be twice the concentrations stated. These levels of copper and zinc exceed the acute criteria for protection of freshwater life by many 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. Clearly, runoff from streambank tailings areas is a critical metal migration route in the existing Silver Bow Creek system.

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.

The chemical speciation of metals in surface runoff (Table 4) show many interesting differences between the control and lime-amended plots. Runoff from the control plots consist of three chemical fractions: dissolved ions, relatively inert ions associated with the solid fraction (TSS fraction); and other ionic forms dominated by metal hydroxide precipitates and adsorbed phases. The biological "availability" is expected to differ between the three phases with dissolved being the most readily available and the TSS fraction being mostly unavailable.

Only 20 percent of the copper and zinc in runoff from the control plots was associated with the TSS fraction, with all of the remaining zinc in a dissolved form. The remaining copper consisted of nearly equal fractions of dissolved and precipitated forms. This difference in partitioning between copper and zinc would be expected due to the tendency for copper to precipitate from solution at lower equilibrium pH than zinc.

In runoff from the lime-amended treatments, 30 to 60 percent of the total metal load was in the TSS fraction. The remaining metals were equally divided between the dissolved and precipitated fraction. This change in metal partitioning from relatively available forms in runoff from control plots to more unavailable forms on treated plots further magnifies the 20 to 30-fold reduction in total metal levels in runoff from limed plots.

Table 3. Total and dissolved copper and zinc in simulated rainfall-induced surface from control and lime-treated plots at Opportunity. "Initial runoff" represents the first 0.05 inches of runoff while "long-term runoff" represents an average of the next 0.5 to 1.0 inch of runoff.

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 4. Speciation of metals in surface runoff from streambank tailings areas at Opportunity.

CONSTITUENT	CONTROL PLOT		LIME-TREATED PLOT	
	INITIAL RUNOFF (% of Total)	LONG-TERM RUNOFF (% of Total)	INITIAL RUNOFF (% of Total)	LONG-TERM RUNOFF (% of Total)
Copper - Dissolved	50	30	35	15
Copper - TSS Fraction	20	20	40	30
Copper - Other	30	50	25	55
Zinc - Dissolved	75	80	35	10
Zinc - TSS Fraction	25	20	45	65
Zinc - Other	0	0	20	25

REFERENCES

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

Reclamation Research Unit, Schafer and Associates, and CH2M Hill. 1989. Silver Bow Creek RI/FS. Streambank Tailings and Revegetation Studies. Phase I Final Summary Report. Volumes I-III. Submitted to Montana Department of Health and Environmental Sciences.

Schafer and Associates, Reclamation Research Unit and CH2M Hill. 1989. Silver Bow Creek RI/FS. Streambank Tailings and Revegetation Studies. Phase II Final Report. Submitted to Montana Department of Health and Environmental Sciences.

Schafer and Associates, Reclamation Research Unit, and CH2M Hill. 1990. Silver Bow Creek RI/FS. Streambank Tailings and Revegetation Studies. Phase III Work Plan. Submitted to Montana Department of Health and Environmental Sciences.