THE IMPACT OF SEDIMENT CONTROL MEASURES ON EPHEMERAL SEMIARID STREAM WATER QUALITY, BRIDGER COAL COMPANY, SOUTHWESTERN WYOMING[1]

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Abstract. Comparisons of sediment rating curves between paired watersheds by dummy regression show areas treated by alternate sediment control techniques (ASCT) to sedimentation ponds did not contribute additional sediment to stream flow. At a minimum, one year's streamflow data are required for this analysis of semiarid ephemeral streams. Storm sediment yield and storm water yield show a strong relationship which documents the in-phase geomorphic nature of the studied watersheds, and it provides a graphical measure of the similarity in delivered sediment from basins with and without areas treated by ASCT. ASCT can be considered "best technology currently available" for the study site.

INTRODUCTION

In the coal mining industry, erosion and sediment control practices other than sedimentation ponds have been referred to as alternate sediment control techniques (ASCT). The Office of Surface Mining, Reclamation, and Enforcement (OSMRE) refers to these techniques under the general classification of sediment control measures, as described in OSM CFR 816.45. ASCT has been employed by Bridger Coal Company in southwest Wyoming since September 1983. Bridger Coal Company was granted an experimental practice permit revision as a variance from OSM 30 CFR 816.46(b)2 and 817.46(b)2, wherein operators are required to route storm runoff through a sedimentation pond before it leaves the permit area. This report summarizes the results obtained from that experimental practice, and it demonstrates ASCT to be the "best technology currently available" (BTCA) as described in 515(b)(10)(B)) and 516 (b)(9)(B) of PL 95-87. BTCA is demonstrated by an analysis which documents the effectiveness of ASCT in protecting the water quality of local ephemeral streams.

The reasoning behind use of technologies other than sedimentation ponds is that, as stated in sections 515(b)(10)(B) and 516(b)(9)(B) of PL 95-87, the law requires operators to use the "best technology currently available" (BTCA) to prevent additional contributions of suspended solids to streamflow or runoff outside the permit area. Bridger Coal Company contested sedimentation ponds as the sole BTCA for the western U.S. In a recent court ruling, Judge Flannery of the U.S. District Court for the District of Columbia, issued a decision that OSMRE had failed to adequately explain its rationale for the adoption of 816.46(b)2 and 817.46(b)2 (Flannery, 1985). These regulations were remanded by the court, and they will no longer be enforced by OSMRE (Workman, ND). That is, both federal and Wyoming state regulations no longer require the use of sedimentation ponds. Rather, they require BTCA to prevent additional contributions of suspended solids to streamflow, as determined on a case by case basis.

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Well researched summaries of available alternate sediment control techniques are presented by Simons, et. al. (1983) and the Mining and Reclamation Council of America (1985). Field examples include both the present study at Bridger Coal Company and the McKinley Mine in western New Mexico (Hinton, et. al. 1985).

At Bridger Coal Company, the sediment control techniques employed are those commonly used in construction and agriculture: deep ripping of subsoil on the contour, topsoil replacement on the contour, topsoil application directly from stripping operations, contour furrowing and other mechanical manipulation on the contour, crimped dead mulch, and emplacement of rock check dams. Upon visual inspection, these techniques appear to reduce erosion from reclaimed surfaces over areas which are not similarly treated. In order to verify this observation, this study was undertaken to quantitatively document the effects runoff from mined and reclaimed areas, treated by these sediment control techniques, has on suspended sediment concentrations in the local ephemeral streams.

The Office of Technology and Assessment (OTA, 1986) discusses the continuing lack of water quality data from surface mined lands, and it presents a consensus on how water quality data from western streams should be gathered in order to provide useful information about the impacts of surface coal mining on hydrologic systems. The OTA (1986) makes special mention of the inherent variability in hydrologic and sedimentologic data. Provided in this report is a discussion of that variability and how it affects an assessment of ephemeral stream water quality.

This report demonstrates ASCT to be BCTA at Bridger Coal Company. The results conclusively show that no additional contributions of sediment above background levels have occurred in Deadman Wash during the period of record. From these results, it is apparent that background sediment yield is the appropriate parameter against which to measure for additional contributions of sediment.

DESCRIPTION OF STUDY AREA

The Jim Bridger Mine is located 35 miles northeast of Rock Springs, Wyoming in the Rocky Mountain Wyoming Basin physiographic province (Figure 1). The climate is arid to semiarid at an elevation of 6800 to 7200 feet mean sea level. Temperatures are cool with summer highs in the 80's F (29° C) and lows in the 40's F (7° C), while winter highs are from 10° to 30° F (2° C) and lows are 0° to 15° F (-14° C). The area is underlain by fluvial interbedded sands, silts, and clays of the tertiary Fort Union Formation which forms the eastern flank of an anticline known as the Rock Springs uplift. Extensive fluvial erosion has created a high drainage density. Numerous bluffs and hog backs are breached by streams draining from the Continental Divide. Shallow residual soils are complemented by pockets of very fine eolian sandy soils. The desert vegetation consists of grasses and shrubs which, in an even proportion with rock, provide an average of 32 percent ground cover.

All streams in the study area are ephemeral, and they carry a mixed load of suspended and bed materials (Schumm, 1977). Channels are either continuously or discontinuously incised into fine grained quaternary alluvium. Both incised and unincised reaches meander, and their banks approach the vertical as a result of the cohesive silty alluvium which supports a relatively lush growth of greasewood (Sarcobatus vermiculatus) and big sagebrush (Artemisia tridentata). These steep banks are undercut during flow events, and they contribute large quantities of sediment to the channel bed by block caving immediately following stream flow recession. Excluding these cut banks, incised channels are becoming narrowed by lateral bank accretion and rye grass (Elymus cinereus) colonization.

Mean annual precipitation is eight inches per year (20 cm/yr), 70 to 80 percent of which falls as rain from thunderstorms between April and September, and the remainder of which falls as snow during the winter months. During the summers of 1984, 1985, and 1986, an average of 3.30, 3.53, and 4.48 inches of rain were recorded between April 1 and September 30, respectively. The majority of snowfall is lost to sublimation and wind.

DATA COLLECTION

A monitoring network consisting of seven stream gauges, three recording rain gauges, and seven storage rain gauges was installed in August 1983. Bubbler gauges were used for water level sensing due to problems with stilling well siltation in the sandy washes of the study site. Earlier experience with stilling wells proved that sediment sumps were filled and intake pipes were clogged during a single runoff event, resulting in loss of recession limb data.

Minnesota Fabricators automatic US PS-69 pump water samplers were employed to remotely collect suspended sediment samples through floating intakes. The sampler and floating intake are connected via buried piping in order to avoid damage by floating debris. The single intake is constructed of redwood in the shape of a ships hull, and it is tethered by a wire rope reinforced suction hose to a point 3 feet (1 meter) above the channel bed on a steel post driven 5 feet (1.6 meter) into the bed. This allows the intake to remain at a fixed depth of 0.3 feet (0.1 meter) below the water surface for all flow depths up to the elevation of the tether. By so doing, only suspended sediment is sampled. To prevent sediment from accumulating in the intake orifice during dry periods, the float is held upright on the channel bed by two metal legs.

Open channel control is employed in all cases except SWPS-3 (Figure 1), where a sheet pile control wall was constructed to stabilize the section which lies immediately below an expanding headcut. Due to the sand bed channels and open channel control, stage/discharge ratings are constantly shifted using discharge measurements. No other controls were employed due to high rates of bed sediment transport which quickly bury protruding structures and erosive bank materials which are undermined by turbulence around control walls and weirs.

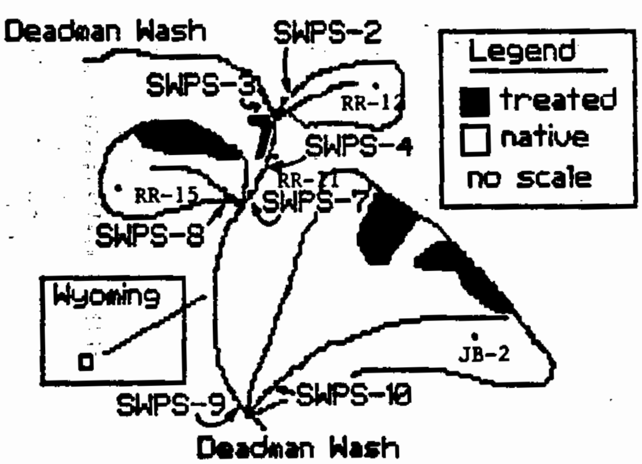

Figure 1. Location map of the seven stream gauging stations. Deadman Wash flows towards bottom of figure. Weighing bucket rain gauges are denoted RR while the tipping bucket gauge is denoted as JB-2.

Precipitation was monitored by two Belfort Model 5-780 weighing bucket rain gauges and one Meteorology Research, Inc. Model 302 tipping bucket rain gauge, all protected by windscreens. These were supplemented by storage rain gauges, without windscreens, located at each stream gauging site. The Model 302 rain gauge recorded every minute, while the Model 5-780 rain gauges used eight day charts with half hour resolution. These rain gauges were situated along the long axis of the mine normal to the prevailing drainage direction (Figure 1).

PRECIPITATION

A line diagram of frequency for daily rainfall depth between April 1 and September 30 shows that for the three years of record (1984 through 1986), there was a similar frequency of events which were less than the 2 year/1 hour precipitation (NOAA, 1973) totaling .1 to .3 inches (.25 to .75 cm) per day (Figure 2). Both 1984 and 1985 show a greater occurrence of days with precipitation events lying between the 2 year/1 hour and 2 year/24 hour precipitation depth (NOAA, 1973).

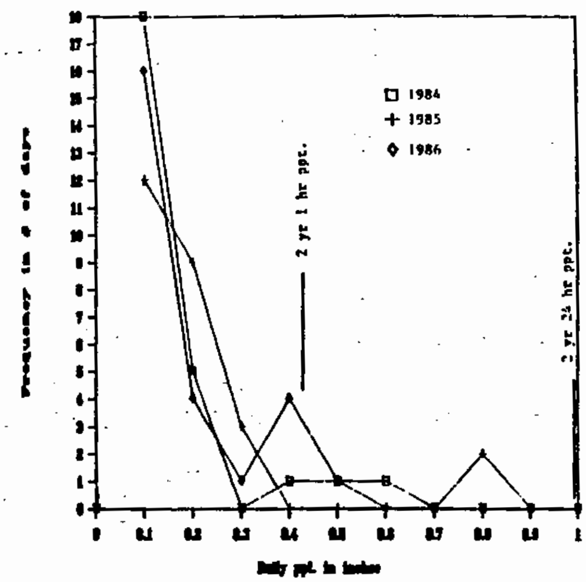

Figure 2. Frequency of daily precipitation depth for the years 1984 through 1986, as recorded at weighing bucket rain gauge RR-11.

Four of these stations lie on a reach of Deadman Wash, the ephemeral stream draining the entire mined area, with 30.9 square miles of drainage area at the downstream permit boundary; and two lie on tributary watersheds (Figure 1). A seventh gauging site on an undisturbed control watershed has collected no data since its construction in April 1985 (Figure 1).

Of the five events larger than the 2 year/1 hour precipitation, the smallest was recorded in 1986, two were measured in 1984, and two were observed in 1985. Figure 2 indicates there is heterogeneity of rainfall for 1984 through 1986; and, in particular, 1986 is deficient in the larger storms.

Rainfall events generally last less than 1.5 hours with high intensity precipitation (.25 to 1.00 in/hr) occurring for less than .5 hours (Figure 3). Field observations indicate high rainfall rates may actually occur as a series of bursts, lasting only minutes each.

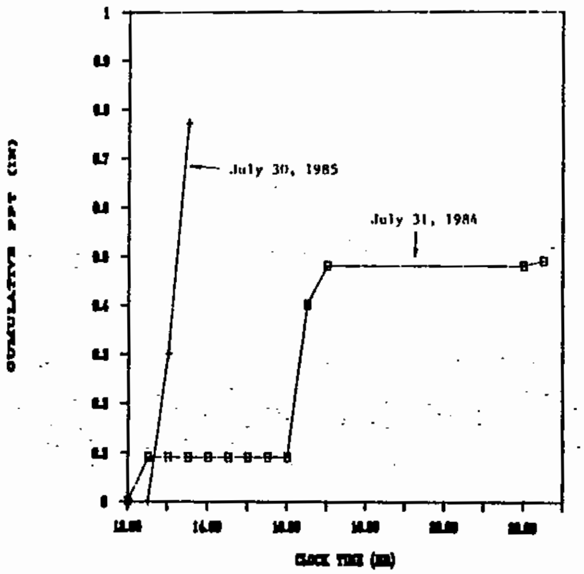

Figure 3. Hyetographs of runoff producing thunderstorms measured at weighing bucket rain gauge RR-11.

DISCUSSION AND ANALYSIS

Methodology

A series of paired watershed studies were simultaneously undertaken at three inflow points to Deadman Wash in order to measure potential differences in water quality between two types of watersheds. One watershed type includes areas treated by sediment control techniques other than sediment ponds, and the other contains only undisturbed areas. The paired watershed approach is discussed by Ponce (1982).

Two methods of pairing watersheds were employed. In the first, upstream and downstream stations were placed on Deadman Wash with the treatment area between. In the second, runoff from separate watersheds, one containing treatments and the other not, were compared. These paired watersheds are presented in Table 1, and they can be located on Figure 1.

Upstream or undisturbed watersheds SWPS-7 and SWPS-9 contain treated areas in their watersheds. This is an undesirable situation for upstream gauging sites in a paired watershed experiment. However, the total upstream watershed area was very large relative to the treatment area. In addition, tests were conducted to compare the records of the SWPS-3 watershed, which contains no treatment area, with SWPS-7 and 9.

Table 1
Paired Watersheds

Watershed Pair	Status	Drainage Area (Square Miles)	Area Treated By ASCT (Acres)
SWPS-3	upstream	16.5	0
SWPS-4	downstream	19.0	41
SWPS-7	upstream	19.8	41
SWPS-8	downstream	.9	149
SWPS-9	upstream	27.8	190
SWPS-10	downstream	3.1	263

Sediment Rating Curves

Suspended sediment concentration relates logically to soil erosion, and it is the water quality parameter of interest in this study. If good sediment rating curves are found to exist at gauging sites, then a statistical comparison of the linear model of instantaneous discharge (Q) on total suspended sediment concentration (C) would give a sound measure of potential differences in water quality. In this way, water quality before and after the addition of waters from disturbed mining areas which has been treated by sediment control measures could be quantitatively compared. First, the appropriate period of record for construction of the sediment rating curve was investigated, and second, the appropriate statistical tool was implemented.

Between September 1983 and October 1986, a considerable volume of instantaneous suspended sediment concentration data has been gathered at the six paired stream gauging stations (Table 1). Only during storm events exceeding the 2 year/1 hour precipitation was measurable stream flow recorded at all monitoring sites simultaneously. Smaller thunderstorms produced runoff over very limited areas and commonly only one or two gauging stations have recorded flow. However, given time, many flow events have been measured at the six gauging sites.

Some descriptive statistics summarize the C record (Table 2).

Table 2
C Descriptive Statistics

Station	No. of Samples	No. of Storms	$\bar{X}$ Log C	Antilog	SD Log C	CV
SWPS-3	246	12	3.73	5383	.6075	.16
SWPS-4	75	5	4.18	15116	.5890	.14
SWPS-7	146	9	4.19	15442	.4477	.11
SWPS-8	65	6	4.31	20393	.5249	.12
SWPS-9	111	7	4.26	18221	.4197	.10
SWPS-10	382	19	3.94	8660	.4264	.11

Mean C values are influenced by the varied magnitude of flows which have been recorded at each site. A better measure of the central tendency of suspended solids concentration relative to its variability is the coefficient of variation (CV), which shows consistent values for all stations. The similarity in the CV suggests the water quality among gauging sites may be quite close (Table 2).

In order to determine the appropriate period of record which would yield a sediment rating curve adequate for statistical purposes, the sources of variation of C with Q were considered. If sediment concentration is related only to the available energy to transport sediment, then a good relationship should exist between Q, and C such as:

$$C = a\,Q^{b} \qquad (1)$$

where a and b are determined by linear regression of log C and log Q.

Data collected at SWPS-10, a three square mile drainage containing both reclaimed and undisturbed area (Figure 1), does not show a strong relationship between Q and C (Figure 4). VanSickle and Beschta (1983) explain similar scatter by proposing a sediment storage term which is added to (1). By accounting for changing sediment supply during a series of four storms in a coast range watershed, they enhanced the predictive power of (1). The considerable scatter of Figure 4 implies a supply limited situation, perhaps with thresholds, may exist in Deadman Wash as well. VanSickle and Beschta (1983) note that sediment supply effects the annual sediment budget as well as causing hysteresis in storm event time series plots of Q and C. Hysteresis loops, such as those observed on Deadman Wash (Figure 5) are also discussed by Harvey (1980) and Walling and Teed (1971).

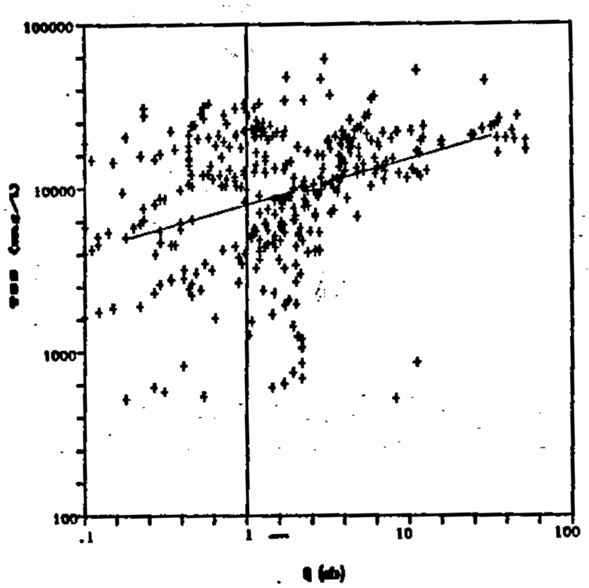

Figure 4. Scatter diagram of C and Q. Data collected between September 1983 and October 1986.

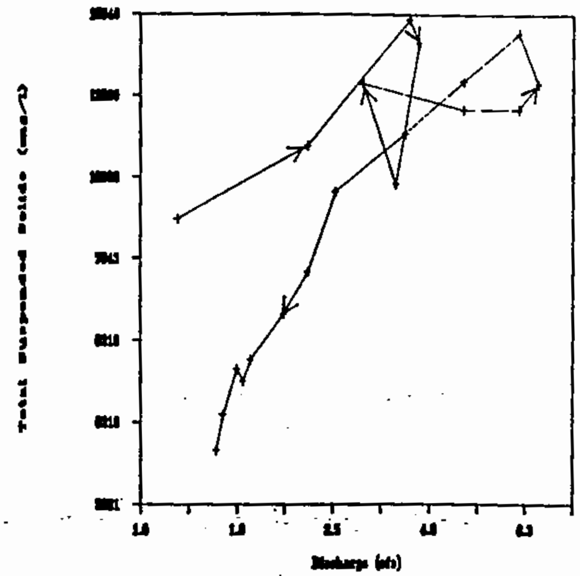

Figure 5. Hysteresis loop of C and Q time series for the September 6, 1984, thunderstorm event at SWPS-10.

The VanSickle and Beschta (1983) model was successful for a coastal, forested, perennial stream. A more simplified attempt was made here to account for the inner storm hysteresis observed in the Q vs C time series (Figure 5).

A dimensionless relative time parameter,

$$t_r = ((t_i - t_{in})/t_b)(t_b/(t_p - T_{in})), \qquad (2)$$

was calculated for each sample collected during a hydrograph where:

t_i = Time of ith sample in clock time
t_{in} = Initial time of rise of hydrograph in clock time
t_b = Time base of hydrograph in hours
t_p = Time of hydrograph peak discharge in clock time

Equation (1) becomes:

$$C = a\,Q^{b}\,10^{ct_r} \qquad (3)$$

The R^2 improvement by the inclusion of t_r was small (Table 3). t_r could not be obtained for many low flow samples used in model (1). These include grab, depth integrated, and single stage sediment samples collected when water level mechanisms were decommissioned during spring and fall, or when water levels were below the fixed elevations of the manometer orifices. Without these low flow data, b took different values between (1) and (3); and, in the case of SWPS-4, changed from positive to negative. Intuitively this is not reasonable, and (3) was discarded in favor of (1). Inclusion of the t_r variable requires additional low flow data. For all of the following analyses, model (1) was utilized.

Table 3
R^2 Improvement By Inclusion of t_r

Station	R^2 $C = aQ^b$	R^2 $C = aQ^b 10^{ct_r}$	R^2 Improvement
SWPS-3	.25	.35	.10
SWPS-4	.18	.13	-.05
SWPS-7	.36	.31	-.05
SWPS-8	.44	.45	.01
SWPS-9	.17	.22	.05
SWPS-10	.18	.22	.04

The dependence of C on Q is not great. SWPS-10 (Nine Mile Wash) (Figure 4) shows a sediment rating curve of:

$$C = 7944\ Q^{.28}$$

The sediment rating curve for Flynn Creek in the Oregon Coast Range (VanSickle and Beschta, 1983) shows a much larger exponent, b, and the coefficient, a, is considerably less. That is, for very low flows, Flynn Creek transports very low sediment concentrations. By comparison, Nine Mile Wash transports many thousands of milligrams per liter suspended solids at less than 0.1 cubic feet per second (cfs). The contrasting C levels are related to the differences in ground cover and availability of fine sediment during small runoff events in the semiarid environment as compared to the humid environment (Langbein and Schumm, 1958).

Despite our problems quantifying a sediment storage term in a multivariate sediment rating curve, sediment storage, and hence availability, contribute to the scatter in Figure 4. The problems associated with defining sediment storage and transport processes in time and space have been discussed by Walling (1983). The continuing need for better understanding of erosion and deposition processes of cohesive sediments is outlined by Wagner and Kuan (1983). They reiterate the complexity of sediment erosion and deposition mechanisms and the incomplete level of our understanding of them. Our efforts with the t_r variable show that considerably more work is required to quantify the effects of changing sediment supply from semiarid basin sediment storages.

A lumped parameter used to quantify the net effects of sediment storage is the sediment delivery ratio (SDR). Several factors have been shown to affect the SDR of a watershed. Annual seasons influence the SDR for agricultural lands (Sheridan, 1982); the sediment delivery ratio has been related to relief ratio and drainage area (Maner, 1958: Roehl, 1962: Williams and Berndt, 1972); and Clarkin (1986) shows that the sediment delivery ratio is a function of the percent of the basin area which is composed of depositional sites, expressed as a percent depositional area. Clarkin notes that long term sediment delivery ratios are nearly constant until gully networks become continuous and depositional area or sites are lost to gully surface area. At that time, sediment delivery ratios for a given basin increase.

Stored sediments within the Deadman Wash basin are produced from alluvial storage into the incised channel network by caving of bank blocks following recession of stream flow. This process is discreet in time, and so the material stored in the stream channel is depleted and replenished between storms.

Sediment storage quantities in the channels and on the surface of a watershed will be nearly constant during a single flow event. Between flow events, sediment storages can vary by processes such as bank caving and soil drying and crumbling. The resulting variation in sediment storage, and hence the availability of sediment for transport, is expressed graphically as scatter in Figure 4.

Table 4 presents a one way analysis of variance table comparing mean C values from five storm data sets from SWPS-10 (Figure 6). These flow events at the SWPS-10 stream gauge have significantly different mean C values. This is in part due to differences in discharge, but Figure 6 shows vertical displacement of individual storm trends at any given discharge. No man induced changes were conducted in the SWPS-10 watershed during the period of record; and the differences can be attributed to the changing availability of sediment for transport.

TABLE 4
ANOVA Table Comparing Mean C Concentrations for July 20, 23, 30, 1985, September 2, 1985, and July 31, 1984 Flow Events at SWPS-10

Source	df	SS	MS	F
Between	4	2.56×10^9	6.40×10^8	8.97*
Within	65	4.64×10^9	7.14×10^7	
Total	69	7.20×10^9		

*Significant at the 99.9 percent confidence level.

By use of a longer period of record than the individual storm, the effects of varied sediment supply can be averaged out, providing sediment ratings which can better be compared between sites. More consistent ratings can be reproduced using an annual record. No attempt has been made to annualize the data. That is, individual year data sets are biased according to the character of precipitation events which occurred. As previously discussed, 1984 and 1985 experienced similar precipitation records, while 1986 had fewer events exceeding the 2 year/1 hour precipitation.

Trend lines fit to the individual 1984 through 1986 data sets for SWPS-10 in Figure 7 show ratings for 1984 and 1985 are very similar, while the 1986 trend shows a comparatively higher level. This plot

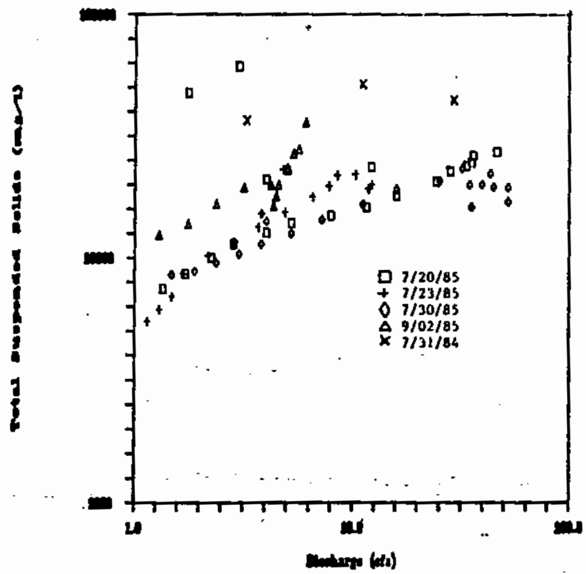

Figure 6. Suspended sediment rating data for five thunderstorm events at SWPS-10.

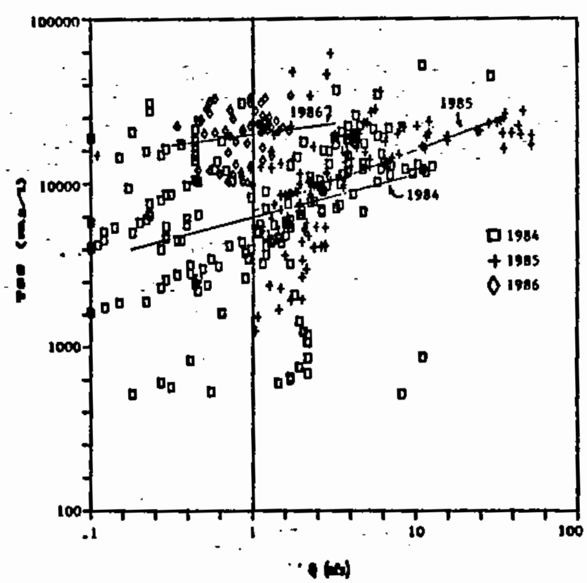

Figure 7. Sediment rating curves developed from annual data sets at SWPS-10.

indicates that an annual record of C and Q can be expected to produce a consistent rating only if precipitation does not vary greatly.

Sediment storage depletion and resupply must therefore occur at up to one year time intervals. This expectation presumes steady state time, as described by Schumm (1980). As the effect of longer periods of time is considered, additional variables, such as climate and vegetation, can vary; and the basin hydrology, which is dependent on them, can be expected to change. However, for short periods, such as a few years, hydrology can be assumed to be an independent variable and climate and vegetation constants.

The 1986 sediment rating (Figure 7) demonstrates that not in every year will all the factors of sediment supply and transport produce the same results because of both the variability in precipitation and dissimilarities in the state of sediment storages. As such, it would be inappropriate to expect consistent sediment ratings to exist over time periods less than one year or beyond several years.

Since the intent of this study is to identify potential impacts of ASCT on instream water quality, the following statistical comparison, which is designed to identify a significant difference in water qualities, should utilize a period of record long enough to average out the effect of sediment storage on model (1). Based on the past three year record, one year of record is a minimum.

Statistical Tool

The appropriate statistical tool to compare linear regressions (sediment rating curves) is the covariance analysis (Ponce, 1980). Covariance requires the sediment rating curves to be parallel, and the linear model should be appropriate. Over the 1984 through 1986 period, covariance was attempted on single event C data sets for regulatory purposes. No two sites in this study, during any single event, proved to have both significant simple linear regression models at the 95 percent confidence level, and parallel sediment rating curves, thus precluding the use of covariance for individual event comparisons.

In order to look for variations in C concentrations on a storm by storm basis, an alternative analysis was conducted for compliance purposes using the Student's t test for comparison of means from two populations when the population variance is unknown and the data are unpaired (Ponce, 1980; Snedecor, 1980). Underlying assumptions for the Student's t test are: (1) the samples are normally distributed, (2) the samples have the same variance, and (3) the samples are randomly collected (Kleinbaum and Kuper, 1978). The first requirement is difficult to test with small sample size. The second assumption is commonly violated by the measured data, but this problem is easily accounted for with the Cochran's or Welch's approximation to the Behrens-Fisher problem, which accounts for unequal sample variances (Snedecor, 1980). Assumption three is commonly violated by hydrologic data, which tends to be serially correlated; and tests for first order serial correlation are significant at or above the 95 percent level for all storm data sets collected in this study (Dawdy, 1964). This decreases the sample variance, as compared to a random sample, which can result in the improper rejection of the null hypothesis of, say, equal sample means.

Single storm suspended sediment time series show considerable irregularity, and it was thought that at some order, k, serial correlation of individual storm suspended sediment data, would no longer be significant. Only those storms with greater than ten samples were utilized; Dawdy (1964) notes that the parametric test for significant serial correlation in a time series requires that k/n, where n is sample size, be less than 0.1. The correlogram for the June 25, 1985, event at SWPS-3 (n=31) shows that at the 99 percent level, serial correlation is no longer significant when k=19 (Figure 8). Clearly the k/n criteria is violated, however, for the purpose of illustration k=1 through 22 are used here.

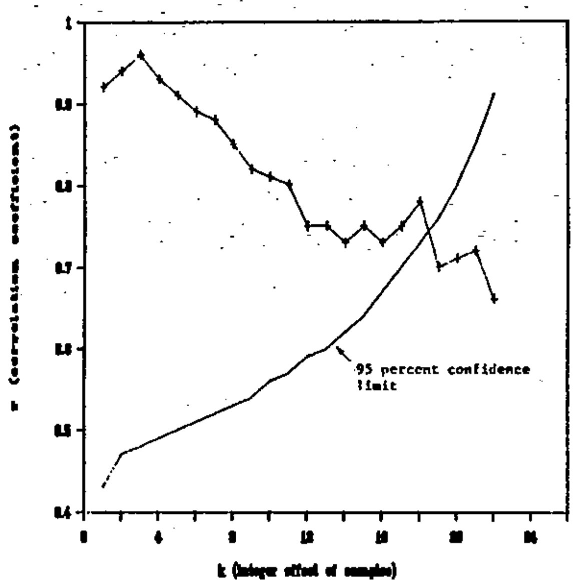

Figure 8. Correlogram of C time series for June 25, 1985, event at SWPS-3.

With a sampling interval of 11.25 minutes, k=19 converts to a minimum sampling period of 3.6 hours in order to avoid serial correlation within storm data sets. Few storms have been recorded where gauge height exceeded the critical minimum depth for pump sampling for a period of three hours or greater. Therefore, in order to avoid highly significant serial correlation within individual storm data sets, only one sample per storm can be used for comparisons of suspended sediment concentrations. Any conclusions drawn from the t test where significant serial correlation exists may be seriously flawed; and significant serial correlation will exist when samples are collected at intervals which are short enough to allow collection of 10 or more samples per event (6 to 12 minutes).

The simple test also fails to account for the covariance of C with site and Q. A simple comparison of C storm means does not distinguish between variation of C associated with Q or other independent variables. For this reason and because the assumptions of the t test itself are seriously violated by single event data, results of the t test conducted on single event data should be carefully interpreted.

In order to make better statistical inferences about C concentrations among the gauging sites, the longest possible period of record is desirable. Annual data sets should be considered a minimum record for water quality comparisons between sites. The entire three year record available for the sites in this study is used in the following statistical analyses so that the effects of variable sediment supply and discharge can be included.

R^2 values are generally low for individual site sediment ratings derived with (1), but an overall F test shows the sediment ratings from the three years of record are significant at the 95 percent level (Table 5). The equations in Table 5 are in units of milligram per liter (mg/l) and cfs.

Table 5
Gauging Station Ratings

Station SWPS-3 $C = 7084\ Q^{.29}$	$R^2 = .35$ n = 246 F = 57.5
Station SWPS-4 $C = 8734\ Q^{.28}$	$R2 = .18$ n = 75 F = 4.4
Station SWPS-7 $C = 10155\ Q^{.34}$	$R^2 = .36$ n = 146 F = 30.8
Station SWPS-8 $C = 6968\ Q^{.58}$	$R^2 = .44$ n = 65 F = 20.3
Station SWPS-9 $C = 8258\ Q^{.27}$	$R2 = .17$ n = 111 F = 14.0
Station SWPS-10 $C = 7945\ Q^{.28}$	$R^2 = .18$ n = 382 F = 54.2

With this result and by observation of scatter diagrams, such as Figure 4, the linear model is appropriate.

Given the significant regressions, covariance analysis can be initiated. First, a test is conducted for parallelism and then a separate test is conducted for a common intercept. Two tests are required, each of which is conducted at a preset level of significance. However, the net result of two consecutive tests at one alpha level is a larger overall probability of rejecting a true null hypothesis. To maintain a known probability of a type I error, a single test is required. Dummy regression can be used to simultaneously test for coincidence of two models. A dummy or index variable, z, is used to denote upstream (z = 1) or downstream (z = 0) data used in a multiple regression analysis (Kleinbaum, 1978). The overall model is:

$$\text{Log } C = B_0 + B_1 \text{Log } Q + B_2 z + B_3 \text{ Log } Q\ z \qquad (4)$$

where the B values are regression coefficients. Evaluating (4) for the upstream station yields:

$$\text{Log } C = (B_0 + B_2) + (B_1 + B_3) \text{ Log } Q \qquad (5)$$

and for the downstream station:

$$\text{Log } C = B_0 + B_1 \text{ Log } Q \qquad (6)$$

Before the test for coincidence was undertaken, the dummy regression was also used to separately test for parallelism. In this way, the requirement for parallelism and a test for coincidence could be conducted at a known alpha. The null hypothesis for parallelism alone becomes H_0: $B_3 = 0$; and for the test of coincidence, it becomes H_0: $B_2 = B_3 = 0$.

Using dummy regression, paired watersheds were compared, in addition to a check of the SWPS-7 and SWPS-9 upstream stations relative to the overall SWPS-3 upstream control (Table 6). The null hypothesis, as expressed above, is significant at the 95 percent level unless otherwise noted.

Table 6
Results of Dummy Regression Between Watershed Pairs

Watershed Pair	Parallelism Result	Coincidence Result
SWPS-3, 4	accept H_0	accept H_0
SWPS-7, 8	reject H_0	$.025 < \alpha < .001$
SWPS-3, 7	accept H_0	reject H_0
SWPS-3, 9	accept H_0	accept H_0
SWPS-9, 10	accept H_0	accept H_0

The regression lines of SWPS-7 and SWPS-8 are not parallel at the 95 percent level, and the positive result under the coincidence test must be discarded. Figure 9 graphically shows the difference in slope between the two sediment ratings. Since statistical comparison of the sediment ratings between these two sites is inappropriate, a t test was conducted to compare the means of the three year records at SWPS-7 and 8. SWPS-7 Data for discharges less than the low flow cut off at SWPS-8 were excluded. Despite the drawbacks of the t test for comparing C data, a t test using a null hypothesis of equal means, results in acceptance of the null hypothesis at the 95 percent level (Table 7), that is, the mean C values are equal.

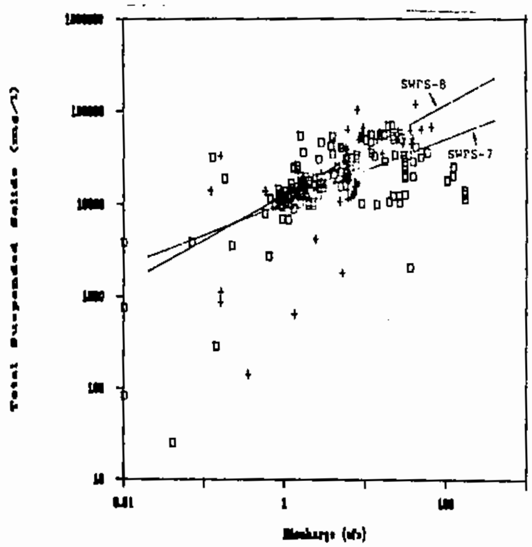

Figure 9. Superimposed sediment rating curves for SWPS-7 and SWPS-8 with data of September 1983 to October 1986.

Table 7. t test of SWPS-7 and SWPS-8 mean C concentrations. All data for discharges greater than .12 cfs collected between September 1983 and October 1996 included.

HYPOTHESES : Ho: Recieving Tss >= Disturbed Tss
Ha: Recieving Tss < Disturbed Tss
Alpha = 0.05
df for F test: numerator and denominator = n-1
F ratio is of larger s^2 over smaller s^2

Station	Log Mean Tss	Log St.Dev.	n	Station	Log Mean Tss	Log St.Dev.	n
SWPS-7	4.2425	0.3074	141	SWPS-8	4.3095	0.5249	65

F	Critical F value	t	Standard t test: Critical t value	Welch's solution Behrens-Fisher: Critical t value
2.915717	1.42	-1.14896	NA	-1.67

Results:

F test	t test
unequal variance	Accept Ho

All other tests of parallelism resulted in acceptance of the null hypothesis, and the coincidence tests resulted in rejection only between SWPS-3 and SWPS-7. The intervening drainage area between SWPS-3 and 7 consists of disturbed treated areas between SWPS-3 and 4, native badland areas, and untreated runoff from haulroad embankments 500 feet upstream of SWPS-7. Natural variation in C, in possible conjunction with haulroad runoff, result in an elevated sediment rating curve at SWPS-7, as compared to SWPS-3. Haulroads are exempt from sediment control, and the SWPS-3 with SWPS-4 coincidence test shows that the treated disturbed area between SWPS-3 and SWPS-7 is not at fault. Therefore, it is appropriate to use SWPS-7 as the upstream undisturbed watershed station for comparison to SWPS-8.

A check of SWPS-3 against SWPS-9 (Table 6) shows that the two sediment ratings are coincident. Any extra sediment load at SWPS-7 has been buffered by the intervening channel and lateral inflows.

Dummy regression analyses between SWPS-3 and 4 and SWPS-9 and 10 show that the other two treated vs. control paired watersheds have coincident sediment ratings; no differences in water quality are detectable (Figure 10, Table 6). Given the proportionately small treated area within any of the study watersheds, no quantitative measure of the efficiency of ASCT can be made. However, the net effect of ASCT on mine disturbed areas and the budget of sediment storages within the watersheds has been to produce one consistent sediment rating among watershed pairs.

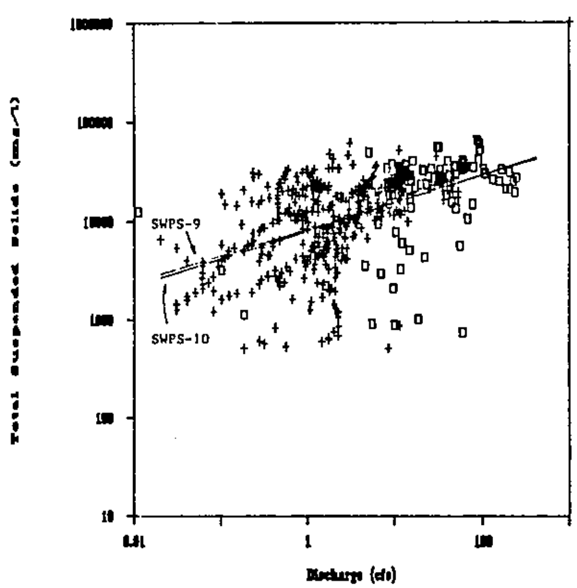

Figure 10. Superimposed sediment rating curves for SWPS-9 and SWPS-10 with data of September 1983 to October 1986.

This result is interesting in view of other research results. The sediment budget of similar watersheds has been shown to naturally vary in space and time (Bergstrom and Schumm, 1981; Harvey, 1980). Various researchers have shown how geomorphic or hydrologic thresholds, when exceeded, cause sediment storage elements within a watershed to release sediment, which is recorded at the basin outlet as increased sediment yield (Bergstrom and Schumm, 1981; Harvey, 1980; Schumm and Hadley, 1957; Schumm and Parker, 1973). Watersheds adjacent to the one producing heightened sediment concentrations may be out of phase; that is they may be accumulating sediment in depleted storages at the same time as adjacent watersheds are releasing sediment from storage. The fact that the basins in this study show a unified sediment rating implies that all are, at least temporarily, in phase; and the net impact of mining and sediment control treatments has not upset this state.

SEDIMENT YIELD

Sediment yield is the integration of sediment load overtime, which is, in turn, the product of sediment concentration and discharge. By considering sediment yield rather than instantaneous sediment concentration, the observed variation of interstorm concentration can be averaged and a general measure of overall storm suspended sediment concentration can be more clearly seen. In addition, a considerable volume of data currently exists on sediment yield from semiarid basins in the western United States (Hadley and Schumm, 1961; King and Mace, 1953; Schumm, 1969; Soil Conservation Service, 1975).

A plot of individual storm sediment yield with individual storm water yield per unit area, for all storm events monitored during the three year period of record, shows a strong relationship (Figure 11). The equation of the best fit line in Figure 11 is:

$$Y = .04\, X^{1.18} \qquad (7)$$

where Y is sediment yield in tons per acre, and X is water yield in acre-feet per square mile. With an exponent greater than 1.0, this relationship shows that sediment yield increases more rapidly than water yield. That is, the average C (sediment yield/water yield) increases with increasing water yield. It also suggests that for higher discharges where a considerable length of channel flows, sediment concentration increases downstream due to water losses in the ephemeral channels. Hadley and Schumm (1961) observed this behavior in the Cheyenne River basin.

Using Figure 11, a simple method for assessing differences in C between paired watersheds can be devised. First, instantaneous C and Q must be collected at an adequate time spacing to accurately calculate storm sediment and water yield. Second, the point can be plotted on Figure 11. If the point falls within the predictive interval of Figure 11, then no significant variation from background sediment yield will have occurred at the chosen level of α.

Figure 11 can be considered a sediment rating curve for all gauging stations with the scatter removed by the use of an averaging

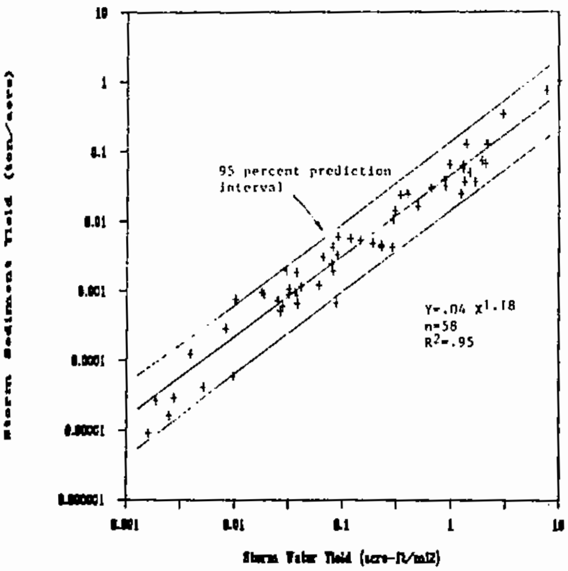

Figure 11. Storm event sediment and water yield per unit area for all storms and sites monitored between September 1983 and October 1986. The 95 percent prediction interval brackets the data.

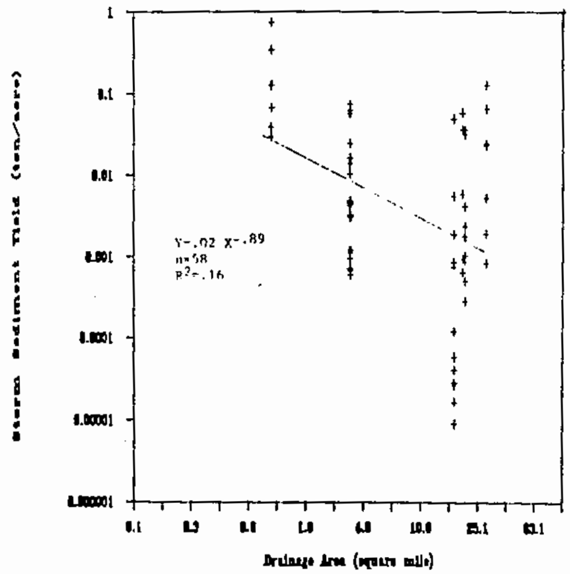

Figure 12. Storm event sediment yield per unit area relative to drainage area. Considerable variability can be seen for each site.

technique. By removing the effect of watershed area, Figure 11 shows that all six gauging sites exhibit one general rating curve, despite differences in drainage area.

Drainage area has been shown to influence long term annual sediment yield per unit area (Hadley and Schumm, 1961). They show a decrease in sediment yield per unit area with increasing drainage area in eastern Wyoming. Hadley and Schumm (1961) used reservoir surveys to obtain a long term estimate of annual sediment yield. The Deadman Wash gauging data are limited in time and cannot be used for calculation of a similar long term estimate; however, individual storm sediment yield can be related to drainage area (Figure 12). Drainage area of the gauged sites varies from 0.5 to 27.8 square miles. A general trend for storm sediment yield to decrease with increased drainage area is evident (Figure 12).

Sediment yield for larger semiarid basins decreases for several reasons. The increased number of sediment storage elements in larger basins provides more opportunity for deposition; storms of given areal coverage will impact a smaller percentage of large basins; and flow durations are short, further promoting temporary sediment deposition and storage in larger basins. The process of temporary sediment storage was observed experimentally by Harvey (1980). He saw local channel aggradation followed by movement downstream to a new temporary storage site. Similar observations were made by Bergstrom and Schumm (1981) in a Wyoming badlands area.

A large range exists for each gauging site in Figure 12. The trend line suggests what might be expected from a storm between the 2 year/1 hour and 2 year/24 hour storm for the general area, but considerable error could result from its use in predicting sediment yield for an individual storm.

Individual storm sediment yield varies as a function of storm magnitude. Storm magnitude consists of many factors, including rainfall depth, intensity, and duration, as well as the speed and direction of the storm track relative to the basin, and the basin area covered. Yu (1985) notes that the storm hyetograph and storm track are extremely important in predicting runoff produced by small, frequent storms. Runoff modeling studies incorporate many of these rainfall variables (Nicks, 1982). Antecedent soil moisture is also important in runoff production. Artificial rainfall, which was applied to study plots at a reclaimed coal mine, showed that erosion is highly dependent upon antecedent soil moisture and the time rainfall distribution (Hartley, 1984).

By including measured meteorology into a multiple regression analysis, the average sediment concentration can be more accurately predicted. In this analysis, an equation of the general form:

$$C = a\ Q^{b}\ RT^{c}\ ANT^{d}\ RI^{e}\ D^{f} \qquad (8)$$

where:

C = average storm C in milligrams per liter

Q_p = peak rate of runoff in cfs

RT = rate of rise of hydrograph in feet per minute

ANT = antecedent precipitation over 48 hours preceding storm in inches

RI = peak 30 minute rainfall intensity in inches per hour

D = storm rainfall depth in inches

was calculated. A similar analysis was undertaken by Walling and Teed (1971) for a small catchment in England. The mean sediment concentration is obtained by dividing storm sediment yield by storm water yield, and it is an indication of overall storm water quality.

Regression analysis was undertaken using those gauging stations where a sufficient number of storms had been recorded to afford adequate degrees of freedom. With five independent variables, at least six degrees of freedom are required; more are highly desirable. For this reason, only stations SWPS-3, 7, and 10 could be included (Table 2).

Not all of the independent variables are direct measures of the parameter of interest. Antecedent soil moisture is represented by ANT, the 30 minute interval of RI exceeds the interval of peak intensities indicated by field observations, and RT is a rough measure of the location of the storm within the basin. Some interdependence may be present between RT and RI. However, these variables serve to indicate potential relationships in the manner inherent in lumped parameter black box modeling.

The maximum R^2 improvement multiple regression method was employed which resulted in models significant at or greater than the 95 percent level (Table 8).

Table 8
Average Storm C Models

Station SWPS-3	
$\bar{C} = 2459\, Q_p^{.27}\, RT^{-.10}\, ANT^{-.21}\, RI^{.08}\, D^{-.30}$	$R^2 = .79$ $n = 12$ $F = 5.33$
Station SWPS-7	
$\bar{C} = 27918 + 68\, Q_p - 3280\, RT - 9965\, ANT - 11381\, D$	$R^2 = .86$ $n = 8$ $F = 5.94$
Station SWPS-10	
$\bar{C} = 7873\, Q_p^{.15} RT^{.23} ANT^{-.11} RI^{-.07} D^{.37}$	$R^2 = .57$ $n = 18$ $F = 3.45$

Logarithmic transforms provided the highest R^2 values at stations SWPS-3, and 10 while arithmetic data only provided a significant regression at SWPS-7. The sample size at SWPS-7 is small and additional data should be sought before conclusions are drawn. The improved R^2 values of the average C models (Table 8) over sediment rating curves of instantaneous C (Table 5) was suggested by the close fit of the data to the regression line in Figure 11.

CONCLUSION

Utilizing at lease one year's flow record, sediment rating curves can be successfully constructed for Deadman Wash and its tributaries. Individual storms sediment ratings are not consistent or significant. At a minimum, one year's record should be utilized in constructing a sediment rating for streams like Deadman Wash; and several years of data are highly desirable.

Dummy regression analysis is an appropriate technique for comparing these sediment rating curves between gauging stations in paired watershed studies of water quality. Using this technique, it was possible to show the sediment ratings between upstream and downstream watershed pairs, established to document the water quality impacts of mining areas treated by alternate sediment control techniques, are the same. That is, no difference in water quality was evident between any pairs.

Sediment rating curves based on three years of data are significantly represented by a linear model, but the data scatter over many orders of magnitude shows the power of the relationship is not great. Additional parameters such as t_r may provide some improvement in the predictive power of sediment ratings for Deadman Wash and streams like it. However, the results presented in this study were insignificant.

Conversely, all storms at all stations show a consistent relationship between water yield and sediment yield per unit area. Therefore, and as can be accurately predicted by rainstorm parameters, the average C values fit a model with narrow confidence bands. This indicates the watersheds monitored are in phase geomorphically, and alternate sediment control techniques have adequately controlled erosion off mined areas and prevented additional contribution of suspended solids to Deadman Wash.

By including storm dynamics into the analysis of average storm values of C, the relationship in Figure 11 was explained. Less predictive power exists in instantaneous C models. The scale at which meteorologic data collection would be required in order to expand the univariate instantaneous C models (sediment rating curves) to include instantaneous rainfall and storm track variables and hopefully increase the predictive power of the model would be prohibitive. Even if the data could be gathered, the effect of episodic erosion would continue to produce variate sediment transport in space and time, independent of hydrologic inputs. By the results presented in Figures 11 and 12 and Table 8, it is apparent that storm sediment yield and average storm C can be expected to provide fairly simple relationships wherein a large proportion of the variation can be explained.

The considerable scatter of sediment

rating data in the Deadman Wash watershed renders statistical comparisons of instantaneous suspended sediment rating curves fairly insensitive to water quality differences. Though the dummy regression analyses in this study showed no changes in sediment rating between upstream and downstream watersheds, the large magnitude of scatter about the trend lines and resulting large sum of squares error makes it difficult to reject the null hypothesis.

Based on the results of this study, a simple method for assessing differences in C between paired watersheds can be devised. First, instantaneous C and Q must be collected at adequate spacing to accurately calculate storm sediment yield. Second, several years of these data can be plotted as in Figure 11, confidence limits can then be constructed, and a simple graphical comparison made of individual storm sediment yield relative to the general trend. Should any point plot within the predictive interval of Figure 11, then no significant variation from background sediment yield will have occurred at the chosen level of α.

By this analysis and by a comparison of sediment rating curves, no additional contributions of sediment to stream flow has occurred over the period of the Bridger Coal Company experimental practice variance. In light of this result, ASCT can be considered BTCA at Bridger Coal Company.

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