APPLICATION OF A WATERSHED COMPUTER MODEL TO ASSESS RECLAIMED LANDFORM STABILITY IN SUPPORT OF RECLAMATION LIABILITY RELEASE[1]

Mark R. Peterson, Lyle W. Zevenbergen and John Cochran[2]

Abstract: The Surface Mining Control and Reclamation Act of 1977 (SMCRA) instituted specific requirements for surface coal mine reclamation that included reclamation bonding and tied release of liability to achieving acceptable reclamation standards. Generally, such reclamation standards include successfully revegetating the site, achieving the approved postmine land use and minimizing disturbances to the prevailing hydrologic balance. For western surface coal mines the period of liability continues for a minimum of 10 years commencing with the last year of augmented seeding, fertilizing, irrigation or other work. This paper describes the methods and procedures conducted to evaluate the runoff and sediment yield response from approximately 2,700 acres of reclaimed lands at Peabody Western Coal Company's (PWCC) Black Mesa Mine located near Kayenta, Arizona. These analyses were conducted in support of an application for liability release submitted to the Office of Surface Mining (OSM) for reclaimed interim land parcels within the 2,700 acres evaluated.

Additional Key Words: Hydrology, sediment yield, watershed modeling, liability release

Introduction & Purpose

Peabody Western Coal Company (PWCC) operates the Black Mesa and Kayenta surface coal mines, located approximately 25 miles southwest of Kayenta, Arizona. The mines are located on portions of the Hopi and Navajo Indian Tribal Lands. Mining operations occur on a physiographic feature known as the Black Mesa, which rises significantly higher in elevation than the surrounding areas. The mesa ranges in elevation from 6,000 to 8,000 feet while the surrounding areas range from 5,000 to 5,500 feet. The area is drained to the southwest via Moenkopi and Dinnebito washes to the Little Colorado River. The areas of present and future mining activity are located in the northeastern portion of the mesa at an elevation of 6,200 to 7,300 feet.

The purpose of this project was to evaluate the hydrologic and sediment yield response of certain reclaimed parcels encompassing approximately 2,700 acres at the Black Mesa Mine in support of an application for liability release submitted to the Office of Surface Mining (OSM). This study was conducted using a physical process–based watershed runoff and sediment yield model applicable to the conditions encountered at the mine site. Calibration and validation of the model were performed using site–specific data collected by Peabody Western Coal Company as part of a surface water monitoring program. The response of the reclaimed parcels was evaluated relative to undisturbed (premine) conditions in the corresponding undisturbed watersheds. The model serves as a tool for assessing the success of reclamation efforts in minimizing impacts to the "prevailing hydrologic balance" (25 CFR 816.108).

The model selected for this project was EASI (Zevenbergen et al., 1990). This model is an enhanced version of the MULTSED model (Simons et al., 1978; Fullerton, 1983), which has been demonstrated to be applicable for characterization of the effects of land disturbance and reclamation activities conducted at surface coal mine sites (WET, 1990).

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[1]Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5–8, 1995.

[2]Manager, Hydraulic Engineering, and Senior Hydraulic Engineer, RCE/Ayres Associates, Fort Collins, CO; Senior Hydrologist, Peabody Western Coal Company, Flagstaff, AZ

Proceedings America Society of Mining and Reclamation, 1995 pp 605-616

DOI: 10.21000/JASMR95010605

https://doi.org/10.21000/JASMR95010605

Database

As part of a supplemental hydrologic data collection program initiated on Black Mesa in 1985, PWCC has collected precipitation, runoff, and sediment yield data from a monitoring network consisting of 24 runoff plots, 7 small instrumented watersheds, and 6 recording rain gages. The surface water monitoring program, also referred to as Small Watershed Studies (SWS), involves sampling in 3 reclaimed coal resource areas along with comparable monitoring in an undisturbed watershed. In addition to hydrologic data, information has been collected describing vegetation cover densities, soil textural composition, and watershed topography.

The reclaimed coal resource areas in which monitoring was conducted resulted from sequential mining-related activities that began with vegetation removal and salvage of native topsoil. Following the removal of overburden and subsequent coal extraction, the spoiled overburden materials were regraded to form stable postmining topography. The regraded spoil was then covered with salvaged topsoil, disced, and revegetated with seed mixes selected to enhance the proposed postmining land uses of livestock grazing and wildlife habitat.

Rainfall

Rain recording gages were installed at the Black Mesa Mining Complex by PWCC personnel in May and July 1985. These gages were located in relatively close proximity to the test plots. Rain gages recording to a digital paper tape were used through 1989. These gages were limited in that they only logged data to the nearest 5-minute interval corresponding to each 0.1 inch of rainfall during the storm event. These gages were subsequently replaced between May and August 1989 with tipping bucket gages that logged data for 0.005625-inch increments of rainfall at time increments of as little as 1 minute. During July 1990, the tipping bucket gages were modified to log data at 0.01-inch increments of rainfall. Consequently, the rain gage data after 1989 tend to much more accurately describe the temporal variability and occurrence of short-duration, high-intensity components of storm events at the mine site.

Soils

Soils data describing the standard textural composition (clay, silt, and sand) of the plots were provided by PWCC. Generally, the reclaimed soils can be classified as sandy loams to clay loams. The dominant textural class for the reclaimed materials, based on the collected samples, is sandy loam. The undisturbed soils tend to contain slightly greater percentages of silt and are generally classified as loams.

Vegetation

Under premine conditions, vegetation includes piñon and juniper forests with little or no understory and shrubs and grasses of varying density. Lower elevations are vegetated primarily with sagebrush and small amounts of grasses. As elevation increases, sagebrush is replaced by greater numbers of piñon and juniper trees. Premine cover conditions were classified as either piñon juniper or sagebrush complexes.

Vegetation cover density data for reclaimed lands used in the subsequent physical-process modeling were obtained by PWCC vegetation specialists from survey of the test plots during the period from 1985 through 1992. Additionally, detailed transect surveys were conducted during April and October 1992. Estimates of areal and basal vegetative cover densities, as well as rock and litter were provided by PWCC personnel.

Topography

Basin delineation and other physical characteristics of both the premine and reclaimed watersheds were defined using AutoCAD topographic files. Computation of areas, overland flow distances, and channel lengths were computed within AutoCAD. Channel widths input to the EASI model were based on consideration of the topographic mapping and limited field observations.

Runoff and Sediment Yield

Runoff and sediment yield data were collected from a total of 24 test plots under natural rainfall conditions at the Black Mesa Mining Complex during the period from 1985 through 1991. Six test plots 10 feet wide and having a slope length of 35 feet were installed in each of three Coal Resource Areas (CRAs) denoted as N1/N2, N6, and J27. Plot locations were selected to typify the range of slopes encountered in the reclaimed watersheds. An additional six plots were installed in the undisturbed J3 watershed for a range of vegetative cover conditions. Data collection procedures consisted of measurement of the total runoff volume and sediment yield after each storm event.

Data were also collected from small instrumented watersheds at the Black Mesa Mine. The monitoring systems consisted of Santa Rita supercritical flumes instrumented with stage recorders and automated peristaltic–pump sediment samplers. Flumes were located near the plot sites in each of the four study areas with flumes in each of CRA areas N1/N2, N6, and J3 and one flume in CRA area J27. Data collected at the flume sites consisted of continuous discharge hydrographs and corresponding suspended sediment concentrations. Total runoff volume for each event was computed by integrating the area under the runoff hydrograph. Total sediment yield for each event was computed as the cumulative product of instantaneous measured sediment concentration data and corresponding discharge rates.

Methodology

Model Calibration and Validation

The purpose of the calibration/validation process was to develop a physical–process model that could be used to evaluate water and sediment runoff for a range of conditions that could not be directly evaluated under field conditions. Computer modeling of hydrologic processes is a commonly used method to evaluate watershed response and assess impacts of land–use change. When calibrated, the watershed model provides a means to make relative comparisons of response under undisturbed (premine) and reclaimed conditions.

The model calibration was conducted using data obtained from instrumented watersheds and small hillslope plots collected under natural rainfall conditions. Data collection under such conditions has the advantage of accurately representing the natural phenomenon that initiate and produce runoff and sediment yield. A disadvantage to use of remotely operated data monitoring systems is the reduction in control over the data collection process. Factors influencing the quality and quantity of data must often be inferred based on experience gained over a period of time and/or from close examination of the data to identify limitations in the experimental process or equipment. In spite of these limitations, unattended data collection activities are the only viable means for collection of data under natural rainfall conditions at the Black Mesa Complex due to (1) the high temporal and spatial variability in rainfall response, (2) the relatively short duration nature of thunderstorm events, (3) the large number of monitoring sites, and (4) the remote nature of the monitoring site locations.

Initially, calibration of the EASI model was conducted by grouping the undisturbed and reclaimed test plots according to soil textural classification. Approximately one–third of the data for each textural classification were withheld for validation of the model. In 3 instances where there were less than 7 to 8 data sets (rainfall, runoff and sediment yield) for a given soil type, all of the data were used for calibration. Parameters that affect the amount of runoff generated by the model were calculated from observed data or estimated through model testing. Values for ground cover, canopy cover and plot slope were determined from the observed plot data. Rainfall interception potential, depression storage, and Manning's n were estimated based on previous experience in the application of EASI at surface mine sites in the semiarid southwestern United States (Water Engineering & Technology, 1990). Initial soil saturation was estimated based on consideration of antecedent rainfall amounts. Values for soil porosity and final soil saturation were based on data describing hydrologic classification of soils (Brakenseik and Rawls, 1985; Simons, Li & Associates, 1983).

To compare the observed and model–estimated values of the hydraulic conductivity, suction head, and erosion detachment coefficients for a soil, the sum of the squared differences (SS) between the observed and model estimated values was calculated using the following equation:

$$SS = \sum_{i=1}^{n} (O_i - P_i)^2 \tag{1}$$

where O is the observed value, P is the model result, and N is the number of data points. The calibration parameters were then varied to minimize the value for SS.

Figures 1 and 2 compare the overall test plot calibration and validation results to the observed values of runoff and sediment yield, respectively. From this figure, the model appears to have responded equally for both the calibration and validation data sets. Both sets of data plot in similar ranges with similar amounts of scatter about the line of perfect agreement.

Results from the calibration/validation process using the hillslope plots were utilized to evaluate the models ability to predict response from a combination of hillslopes and channels. Additional refinements to the calibration parameters were made to improve the model's ability to replicate the observed runoff and sediment yield response from the small instrumented watersheds. Generally, these refinements involved adjustments to the infiltration rates and/or sediment detachment coefficients. It should be noted that the rainfall data are a crucial element for modeling observed runoff and sediment yield response from small watersheds. Therefore, flume data were used only when corresponding incremental rainfall data were available. **Figures 3 and 4** compare the model predicted runoff and sediment yield to the small watershed flume observations. **Figure 5** compares observed and predicted hydrographs for one of the events. Overall, the model approximated the shape of many of hydrographs reasonably well.

Watershed Processes

Runoff and sediment yield in the semiarid western United States is largely governed by the occurrence of high–intensity, short–duration rainstorms of limited areal extent (Renard and Simonton, 1975). Research has indicated that relatively few events may produce the greatest erosion. Hjelmfelt et al. (1986) reported that only 3 to 4 percent of rainfall events accounted for 50 percent of long–term sediment yields. Although there is perhaps a relatively limited physical basis for definition of an "average annual" runoff or sediment yield in a semiarid environment due to the extreme variability in response and importance of single infrequent events, such a term does provide a useful basis for long–term comparison between reclaimed and undisturbed conditions.

Comparisons between runoff and sediment yield from undisturbed and reclaimed areas in the N1/N2 and J27 watersheds were developed for specific modeling endpoints. Mining and reclamation activities did not exactly replicate the topography, drainage network, or drainage areas that existed prior to mining. Consequently, direct comparisons of total runoff and sediment yield cannot be made between undisturbed and reclaimed response at a given point in a watershed. Comparisons were made on the basis of unit rates of runoff (inches) and sediment yield (tons/acre) at the various modeling computation endpoints.

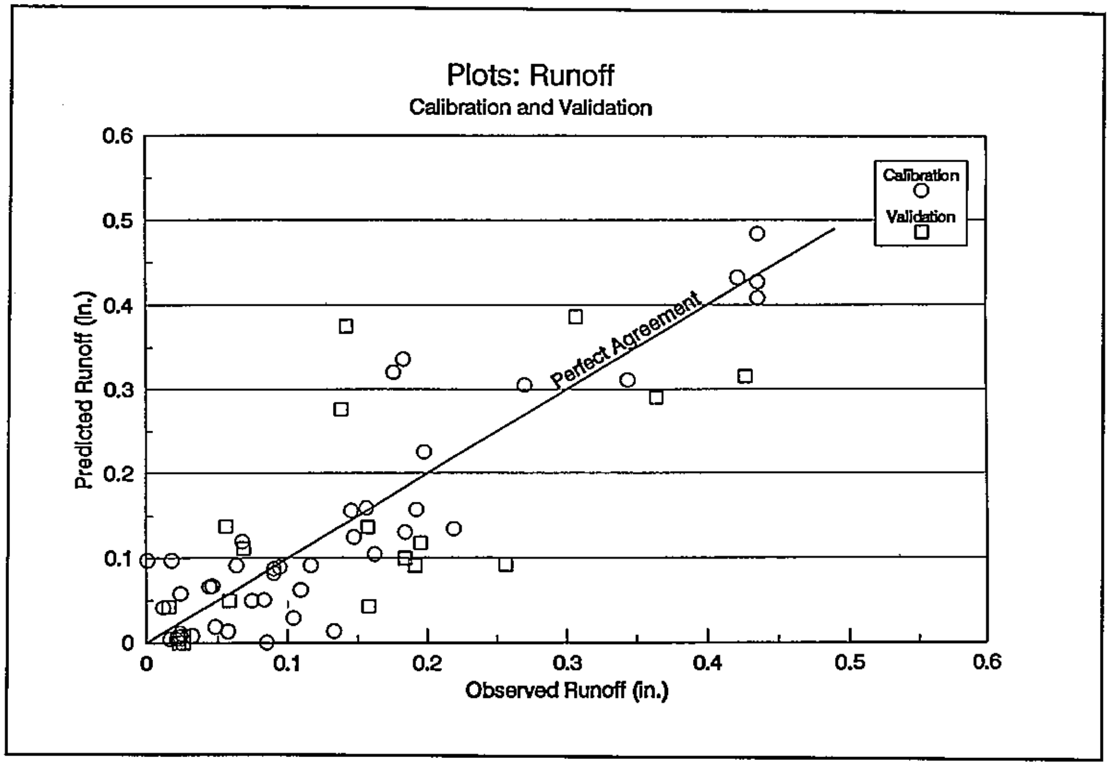

Figure 1. Observed versus predicted runoff from plots for both calibration and validation data.

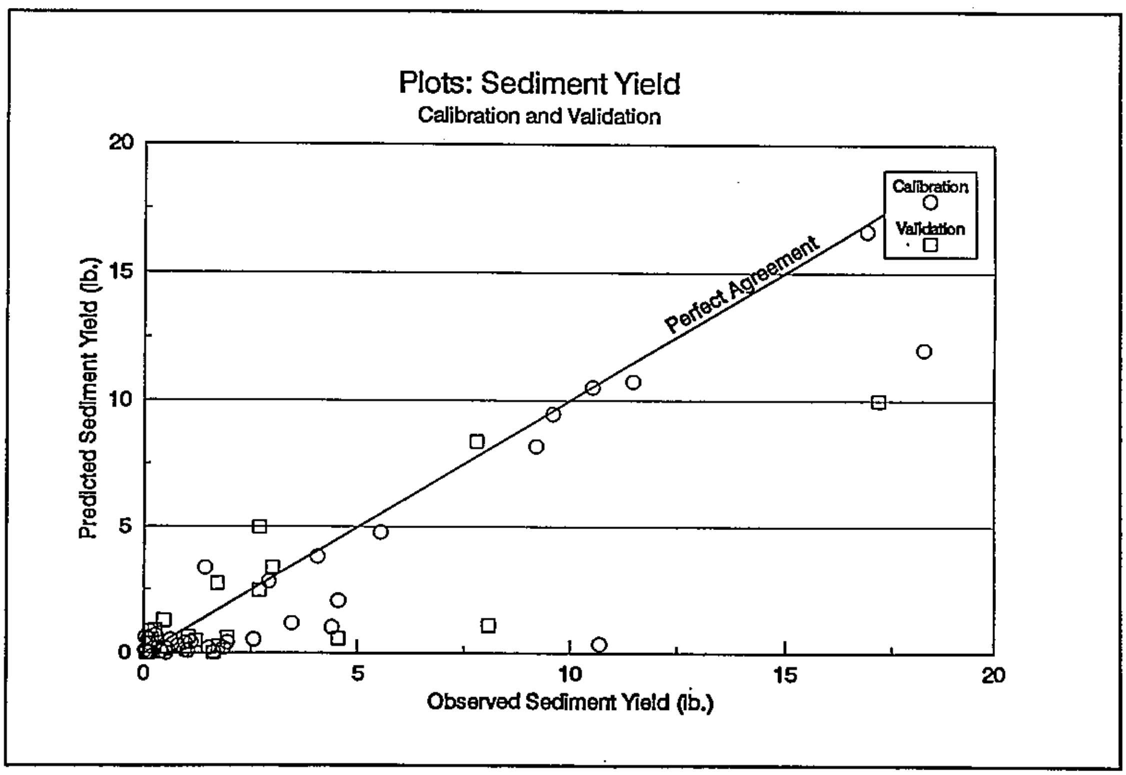

Figure 2. Observed versus predicted sediment yield from plots for both calibration and validation data.

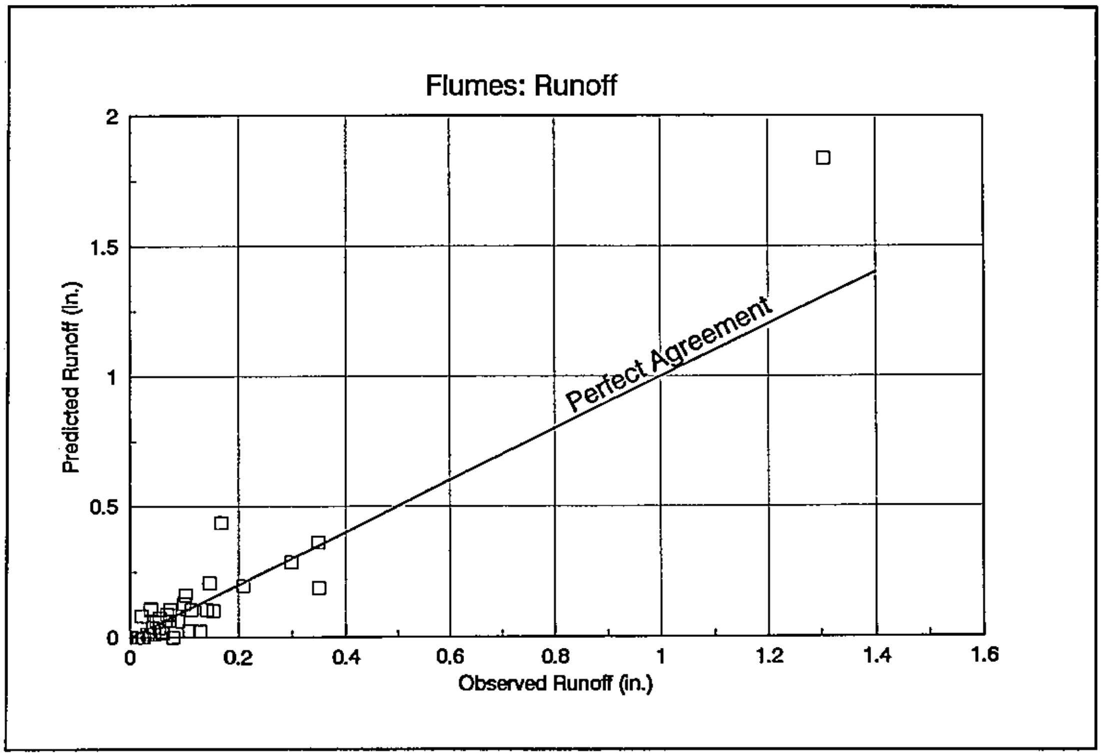

Figure 3. Observed versus predicted runoff from flumes using mean infiltration parameters.

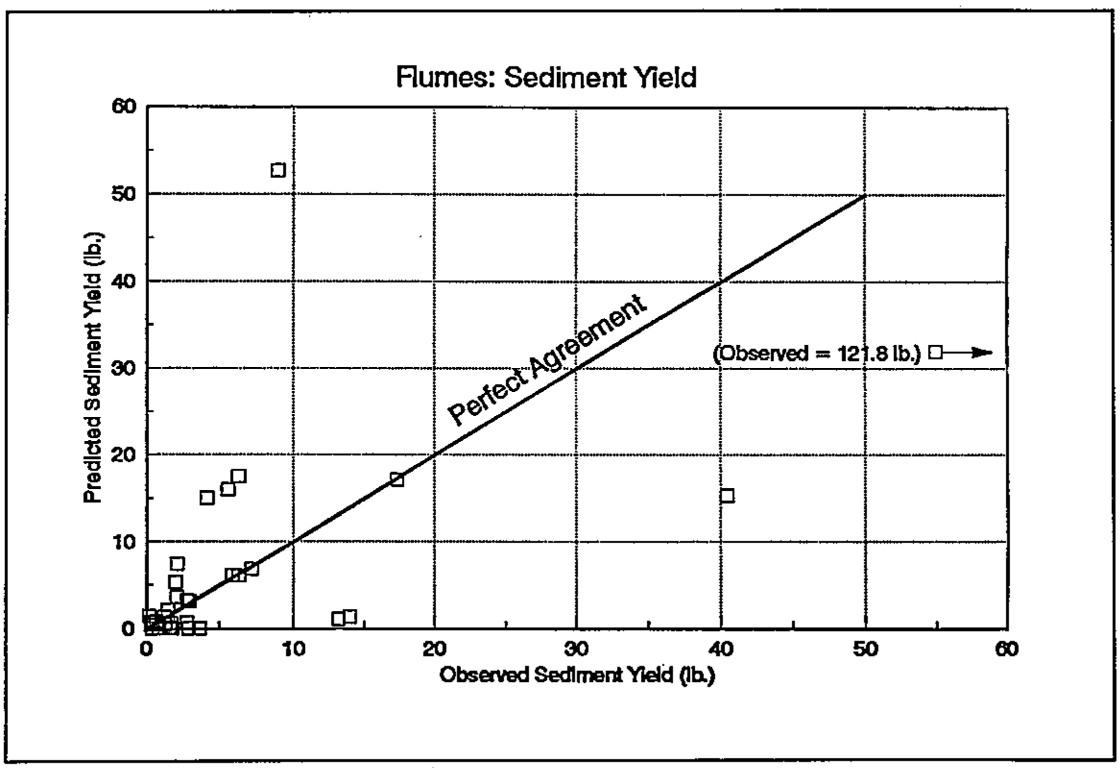

Figure 4. Observed versus predicted sediment yield from flumes using mean infiltration parameters.

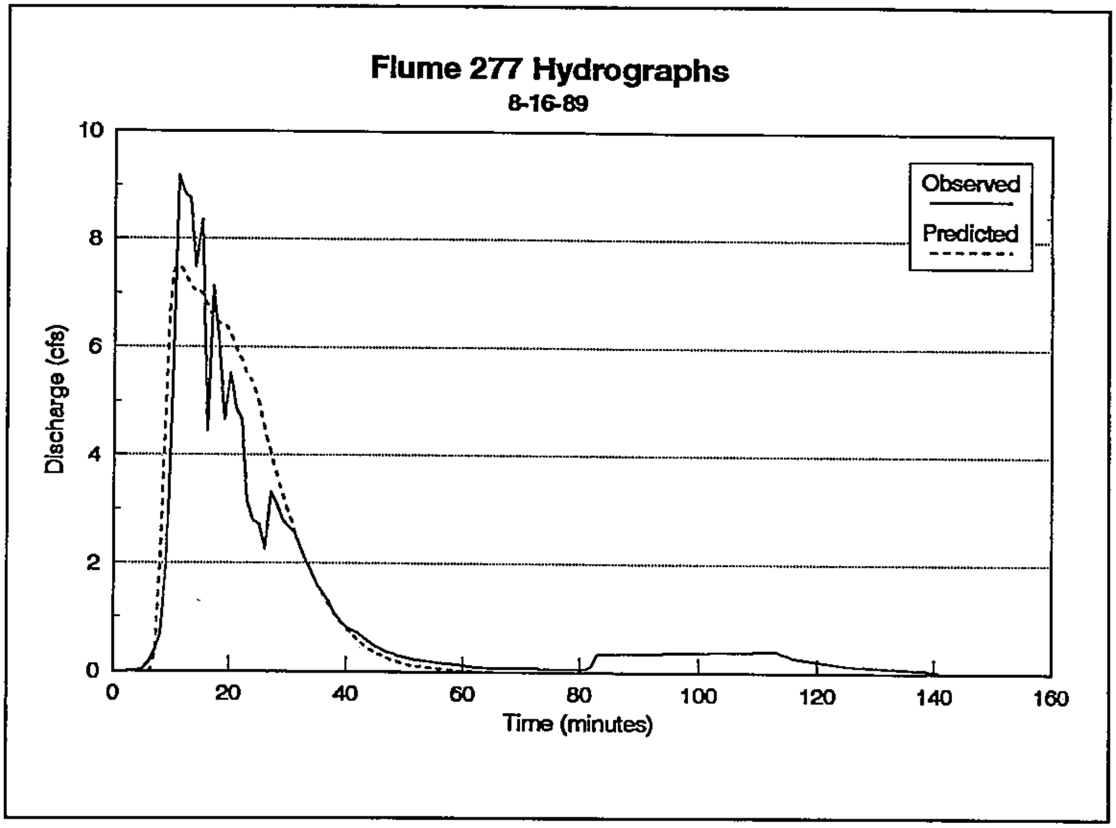

Figure 5. **Observed versus model predicted hydrographs at a small watershed flume site.**

Very detailed models of the reclaimed watersheds in the N1/N2 and J27 CRAs were developed using EASI. Separate models were developed for reclaimed conditions and the corresponding conditions that existed prior to mining. Comprehensive watershed models consisting of a series of interconnected hillslopes, subwatersheds (zero and 1st order subbasins), channels and ponds were developed to represent both pre– and postmine N1/N2 and J27 watershed conditions. The premine watershed models ranged in size from 12 to 834 acres. Altogether, these watershed models were developed using 587 hillslopes, 374 subwatersheds, 284 channels and 1 pond. The corresponding postmine watershed models were developed using 513 hillslopes, 87 subwatersheds, 214 channels and 37 ponds. Reclaimed watershed representations within the model ranged in size from 5 acres to 654 acres.

Table 1 shows the mean geometric properties of the undisturbed and reclaimed watersheds that were calculated using AutoCAD topographic mapping files and represented in the EASI model as hillslope, subwatershed, and channel elements. The calculated properties are channel slope, hillslope length, hillslope gradient, and drainage density and include hillslope portions of subwatersheds in the hillslope statistics and include channel portions of subwatersheds in the channel statistics. On average, reclaimed hillslopes are approximately twice as long as undisturbed hillslopes, although the average gradient is slightly reduced. The reclaimed channels also tend to be flatter and the reclaimed drainage densities are half the undisturbed drainage densities.

Rainfall Input

The site–specific rainfall data available for the Black Mesa Mining Complex were used to evaluate the frequency and magnitude of the measured events relative to existing predictions for rainfall depth–duration (Miller et al., 1973).

Table 1. Total and Mean Watershed Physical Properties as Represented in the EASI model.						
Watershed	Total Area (ac)	Total Channel Length (ft)	Mean Channel Slope	Model Drainage Density (mi/mi^2)	Mean Hillslope Length (ft)	Mean Hillslope Gradient
N1/N2 Premine	2693.4	308685	0.068	13.9	291	0.134
N1/N2 Postmine	2732.5	166095	0.049	7.4	565	0.123
J27 Premine	145.8	14190	0.074	11.8	316	0.136
J27 Postmine	178.9	9840	0.061	6.7	944	0.087

Data collected at the PWCC rain gages were used to develop synthetic rainfall hyetographs for use in the long–term runoff and sediment yield analysis. A modified depth–duration curve was developed for events which were measured using recording gages. Rather than plotting rainfall depth versus time as measured by the gage, the data for each event were sorted by intensity prior to calculating the cumulative depth–duration value. Depth–duration (actually relative depth–relative duration) was determined for storm events having nominal durations of 30–minutes and 1–, 2–, and 3–hours. The NOAA Atlas was used to develop similar curves for the same durations. **Figure 6** shows the NOAA Atlas results and the average curves for the various durations developed from data collected at the mine site. For a duration of 3 hours, this analysis matches closely with the NOAA Atlas results. For shorter durations, however, the differences become quite significant. The NOAA Atlas indicates that for a 1–hour event, approximately 45 percent of the rain falls in a 10–minute period. From the average curve developed from the rain gage data, approximately 64 percent of the rainfall occurs in a 10–minute period. For a 1–hour event, the NOAA Atlas indicates that 29 percent of the total rainfall would occur in a 5–minute period. Evaluation of site–specific rainfall data indicates that approximately 43 percent of the total rainfall would be expected in a 5 minute period. These results indicate that peak rainfall intensities at the Black Mesa Mine can be 40 to 50 percent greater than comparable predictions obtained from the NOAA Atlas.

The 30–minute and 1–hour depth–duration average curves were used to develop synthetic hyetographs for use in the long–term runoff and sediment yield analysis. The rain gage data include recorded intensities of 6 inches per hour. This analysis indicates that intensities of 5.4 inches per hour can be expected for a 5–year return period. In a 100–year event, a peak intensity of nearly 10 inches per hour is possible. In order to replicate the properties of an intense thunderstorm, the synthetic hyetographs were developed by locating the peak intensities in the first hour of the event and alternating incrementally lower intensities before and after the peak. The lowest intensities were located after the first hour in order of decreasing intensity.

Computation of Average Runoff and Sediment Yield

Runoff and sediment yield for the reclaimed watersheds and the corresponding premine equivalent basins was computed for a series of storm events having recurrence intervals of 2–, 5–, 10–, 25–, 50– and 100–years. To define average annual conditions, the average annual sediment yield generated from these storm events was computed using a probability weighting procedure that considers the incremental probability of occurrence of relatively large events during any given year (Lagasse et al., 1985). This procedure provided a consistent basis for comparison of sediment yield on a unit basis from undisturbed and reclaimed mined–land conditions.

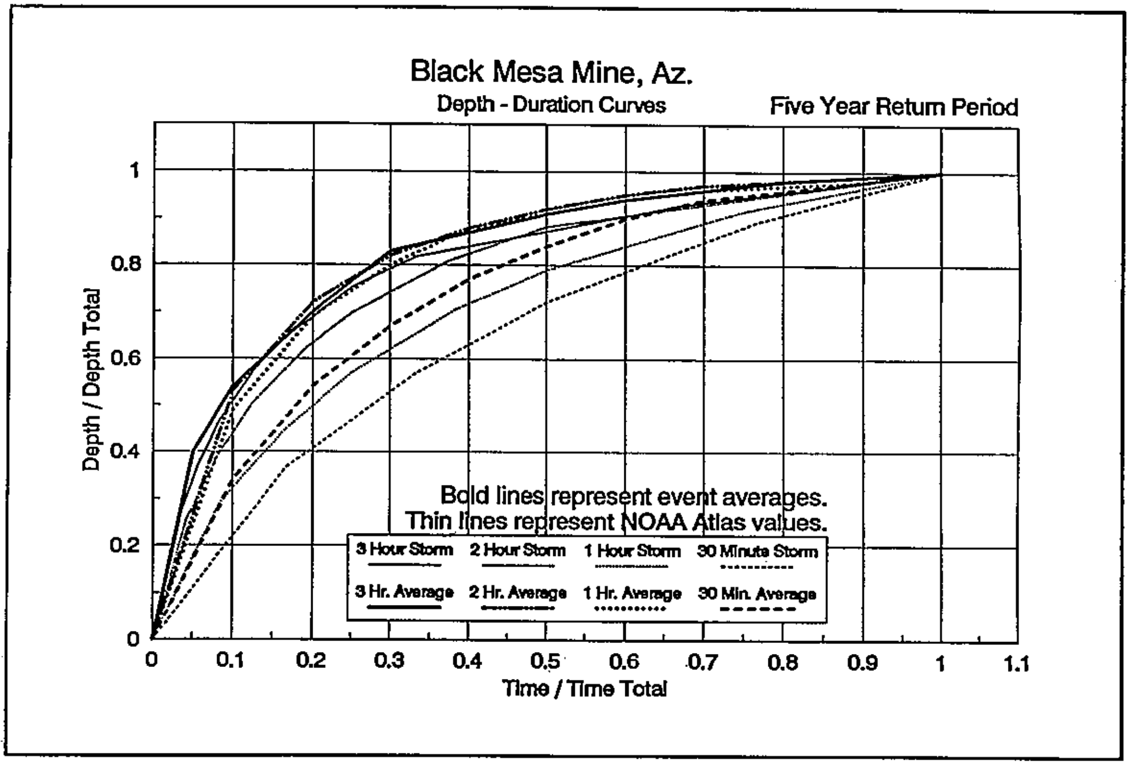

Figure 6. **Comparison of average depth-duration curves derived from PWCC raingage data versus NOAA Atlas.**

Results

Premine Watershed Response

Average runoff from CRA's under premining conditions was computed to equal 0.41 inch with average annual sediment yields varying from 3.4 to 7.0 tons per acre. The area–weighted average annual sediment yield in the N1/N2 Coal Resource Area equalled 5.4 tons per acre. The average area–weighted annual sediment yield from the J27 area equaled 5.8 tons per acre.

Hillslope response was evaluated by categorizing the premine hillslope units represented in the EASI model according to slope gradient. Six slope categories were used: less than 9 percent, 9 to 13 percent, 13 to 18 percent, 18 to 25 percent, 25 to 33 percent, and greater than 33 percent. For each of these slope classes, the average weighted hillslope sediment yield was plotted against slope length. Regression analysis was used to fit a power function of the following form to the data:

$$SY = aL^{b} \qquad (2)$$

where, SY equals mean annual sediment yield in tons per acre, L is hillslope length in feet, and a and b are coefficients. **Figure 7** illustrates the results of this analysis for a slope class of 18 to 25 percent. It should be noted that only a single regression was fit to the premine data for each slope class. These figures clearly show the differences in premine hillslope response corresponding to the sagebrush and piñon/juniper vegetation. The sagebrush covered hillslopes produce higher sediment yields than the piñon/juniper covered hillslopes. Data were not available to make this differentiation for all slope classes and the purpose of this analysis was to make generalized comparisons between pre– and postmine hillslope response. Hillslope sediment yields vary with slope length and gradient, but generally range from 0.1 to 0.6 tons per acre. The mean values for hillslope gradient, hillslope length, and sediment yield for the conditions modeled equalled 0.15, 310 feet and 0.33 tons per acre, respectively.

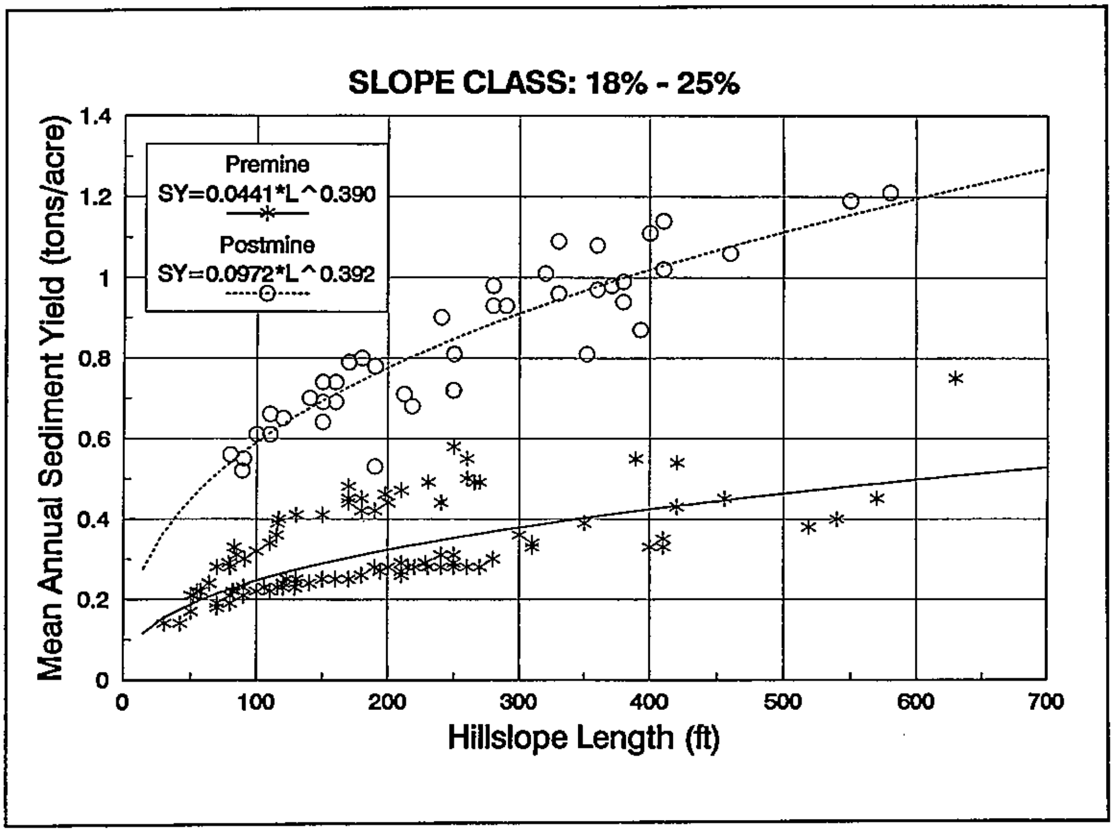

Figure 7. **Mean annual sediment yield versus hillslope length under premine and reclaimed conditions for slope gradients between 18 and 25 percent.**

Reclaimed Watershed Response

From the reclaimed basins, runoff was computed to equal about 0.42 inches and sediment yields ranged from 1.2 to 7.5 tons per acre per year. The area weighted sediment yield is 3.2 tons per acre in the N1/N2 CRA and 5.2 tons per acre for the J27 CRA.

Average reclaimed hillslope sediment yields corresponding to slope lengths and gradients for a slope class of 18 to 25 percent are also shown in Figure 6. For comparable slope lengths and gradients, the sediment yield response from the reclaimed hillslopes is approximately double that from undisturbed hillslopes. Overall, annual sediment yields from reclaimed hillslopes, for all six of the slope classes, range from about 0.2 to somewhat in excess of 1.5 tons per acre. The highest yields are associated with the long reclaimed slope lengths. Average slope gradient, length and sediment yield characteristics of the reclaimed hillslope units were 0.12, 650 feet and 0.94 tons per acre, respectively.

Discussion and Conclusions

In determining overall model calibration coefficients, the results from the plot and flume calibrations were weighted relative to the number of observations from each type of monitoring effort. Thus, more emphasis was given to the plot data. This is reasonable because there are fewer potential sources of error for these data than for the flume data due to the fact that all of the runoff and sediment were collected and measured directly.

The calibration values of the infiltration and erosion parameters worked best for the most extreme events (largest) in the data set. These events are least likely to be affected by antecedent soil moisture and the natural spatial variability of soil properties. At the plot and small watershed scale, observed and predicted runoff compared well, especially for the larger events. Therefore, it is concluded that the most significant processes governing runoff and sediment yield are accounted for in the EASI model.

Overall, the EASI model demonstrated the ability to adequately represent hydrologic and sediment yield response from both hillslopes and small watersheds reconstructed in the semi–arid Black Mesa region for a range of rainfall events exhibiting high variability in temporal distribution.

The calibrated model provided a working tool to evaluate long–term average annual response from the reclaimed watersheds. Comparisons between reclaimed conditions and undisturbed conditions were made at the basin outlets (modeling endpoints) using the representative premine data for the soils, cover, and drainage basin configurations that existed prior to mining. Since basins have been significantly altered, comparisons were made on a unit runoff and sediment yield basis.

Sediment yield from reclaimed hillslopes is generally 1.5 to 2 times higher than from premine hillslopes having comparable hillslope length and gradient. Based on consideration of all the pre– and postmine hillslope units represented in the EASI modeling of the N1/N2 and J27 areas, average sediment yield from the premine hillslopes equals 0.33 tons per acre versus 0.94 tons per acre from the reclaimed hillslopes. This is largely a reflection of (1) the longer reclaimed slope lengths and (2) the different vegetation types and associated higher cover densities on the premine lands.

Weighted runoff for postmine conditions (0.42 inch/year) is for all practical purposes, identical to the average runoff from premine watersheds (0.41 inch/year). Unit sediment yield rates from the reclaimed watersheds ranged from 1.3 to 7.4 tons/acre/year with an average area–weighted value equal to 3.5 tons/acre/year from the N1/N2 CRA and 5.2 tons/acre/year from the J27 CRA. Average premine watershed sediment yields in both the N1/N2 and J27 CRAs are higher than the reclaimed yields, equalling 5.4 and 5.8 tons/acre/year, respectively.

Consideration of the mean geometric properties of the watersheds indicate that reclaimed hillslopes are approximately twice as long as premine hillslopes, although the average reclaimed hillslope gradient is slightly reduced. Reclaimed channels tend to be flatter than premine channels. Drainage densities for reclaimed conditions are about one–half of the premine drainage densities. From the calculated statistics shown in Table 1, one would expect that the reclaimed hillslope would produce more sediment than the premine hillslopes, but that the reclaimed watersheds would have lower sediment yields, since sediment yield is highly correlated with drainage density. The watershed models support this conclusion. The modeling indicates that channels are the primary sources of sediment for both premine and reclaimed watershed conditions.

Acknowledgement

This work was conducted by RCE/Ayres Associates under contract to Peabody Western Coal Company. The views expressed are those of the authors and do not necessarily reflect the views of Peabody Western Coal Company.

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