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SHORT COMMUNICATION

WITHIN-STORM VARIATIONS IN RUNOFF AND SEDIMENT EXPORT FROM A RAPIDLY ERODING COAL-REFUSE DEPOSIT

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ABSTRACT

Measurements of rainfall, runoff and sediment export from a barren deposit of coal mine refuse in south-western Indiana were collected during three storms in the summer and autumn of 1990. Interfluve sheetwash, sediment mass flux, sediment concentration and, to a lesser extent, trunk gully discharge all responded quickly to changes in rainfall intensity. Grain-size distributions varied considerably during storms, containing exclusively fine-grained sediment at low sediment discharges but very large quantities of coarse (> 2 mm) sediment at peak sediment discharges. Although data from a fairly long, multipulsed storm indicate that sediment production is limited by supply, the imbricated layer of flat chips that exists at the surface of the deposit is apparently mobilized during most high-intensity pulses of rainfall, thereby producing large volumes of coarse sediment during summer thunderstorms.

KEY WORDS Sediment yield Gully erosion Coal-mine refuse

INTRODUCTION

Studies of sediment yields from surface-mine spoils have often focused on determining annual rates or total quantities of erosion (e.g. Gilley *et al.*, 1977; Mandel *et al.*, 1982; Haigh and Wallace, 1982; Esling and Drake, 1988). Less attention has been given to the erosive effects of individual storms. Olyphant *et al.* (1991) reported that more than 50 per cent of the annual sediment yield from a barren surface-mined coal refuse deposit in the mid-western U.S.A. was produced by only 15 per cent of the annual storms. Time-dependent characteristics of each storm event, however, were not addressed.

Experiments using simulated rainfall on rehabilitated mine spoil have shown that the sediment concentration in runoff tends to increase faster than the water discharge during the early part of an event, especially when antecedent soil conditions are dry (Lusby and Toy, 1976). Collier (1964) monitored suspended sediment (at stream-gauging stations downstream of surface-mined areas) during storms, and his data also indicate that sediment export peaked before water discharge. However, the time-dependent nature of sediment export at the source catchment itself is not well understood. This study presents sedimentologic and hydrologic data collected from an ephemeral gully on a rapidly eroding coal-refuse deposit during three storms, and provides evidence that production of coarse sediment increases non-linearly with total sediment export during periods of high-intensity rainfall.

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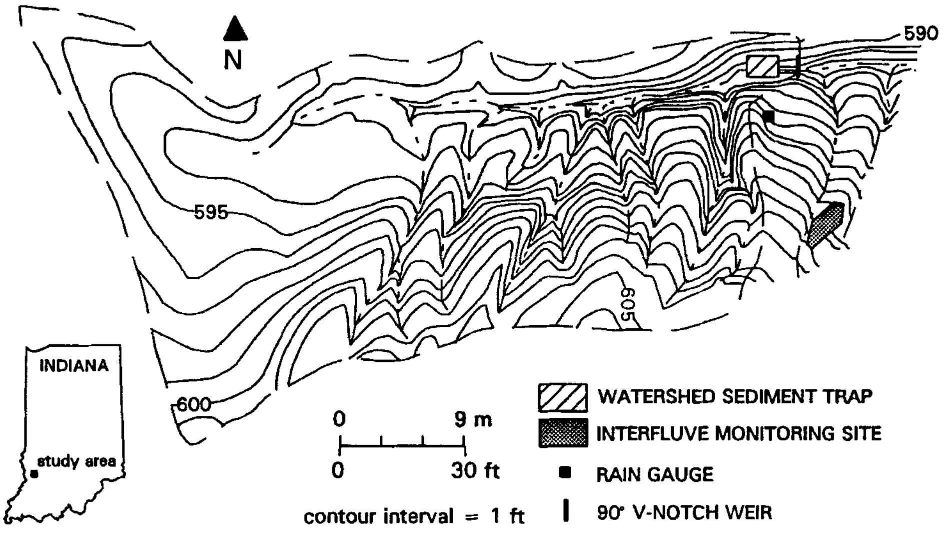

Figure 1. Topography of instrumented watershed and locations of the weir, sheetwash collector, rain gauge and rectangular sediment pond. Samples of sediment mass flux and concentration were collected at the upstream edge of the sediment pond during three storms in the late summer and autumn of 1990. The entire deposit was barren of vegetation when the measurements were made

STUDY SITE

A small gullied watershed that drains part of a coal-refuse deposit at the abandoned Friar Tuck mining complex (section 36, T. 8 N., R. 8 W) in Sullivan County, Indiana, was instrumented for detailed studies of runoff and sediment yield (Figure 1). Due to a low soil pH (< 3) that has resulted from pyrite oxidation, the deposit has been almost totally barren since its creation in the 1950s.

The composition of the deposit is predominantly black shale with little to no quartz sand/gravel present. The interfluve surfaces are covered by a thin (2–3 mm) veneer of flat shale chips with long axes of about 0·2–4 cm. These chips form an imbricated, armouring layer that decreases the soil infiltration capacity and enhances surface runoff. Averaged grain-size analyses of 20 surface and subsurface samples indicate that nearly 80 per cent of the sediment at the interfluve surface is composed of fragments greater than 2 mm (Smith, 1991). Figure 2 depicts this surface layer, part of which was easily brushed away to reveal a firmly packed subsurface with a much higher proportion of fine sediment, containing only 35 per cent material greater than 2 mm. The gully floors do not contain an imbricated surface layer, but 50–60 per cent of the sediment in the upper 8 cm of the channel bottoms is larger than 2 mm (Smith, 1991).

The study watershed is oriented west-to-east and is drained by a 53 m long trunk gully that receives runoff from eight steeply sloping (14°) tributaries. The total watershed area above the weir is 1024 m^2 and its drainage density is 0·25 m^{-1}.

DATA COLLECTION

Hydrologic data presented in this report were obtained from a sharp-crested V-notch weir equipped with a float-type stage recorder, a tipping-bucket rain gauge, and a trap that collected surface runoff and sediment from a 4·65 m^2 area of interfluve surface (interfluve monitoring site, Figure 1). The sides and lower end of the sheetwash trap were fitted with a gutter system that retained transported sediment but allowed runoff to drain into a collection barrel equipped with a second float-type stage recorder. A Campbell 21X data logger was programmed to monitor all instruments every 10 s and store total and average values at 2 min intervals during storms.

A rectangular concrete sediment trap (capacity 3·22 m^3) was constructed in the trunk gully immediately upstream of the weir pool (Figure 1). Flow from the gully was allowed to pour over a non-contracting

Figure 2. Close-up view of interfluve showing surface layer of coarse chips. Part has been brushed away to show contrast with subsurface

spillway into the sediment pond. Samples of sediment concentration and sediment mass flux were collected manually at this spillway every 1–2 min during two short (< 40 min) storms on 29 August 1990, and a larger (80 min) storm on 3 October 1990. Sediment mass flux was sampled by intercepting the flow jet (as it poured from the spillway) with specially fabricated nets made of nylon mesh sewn into frames of polyvinyl chloride tubing. The nets were large enough to contain the entire jet and removed all material larger than 0·125 mm from the flow. Each net was held in the jet for 5–30 s, then sealed in a numbered plastic bag. Sediment concentration was sampled with 250 ml wide-mouthed bottles that were held briefly in the jet. Time-dependent grain-size distributions were extracted from these bottled samples by wet-sieving at full-phi intervals. The finest fraction (< 125 μm) was further separated using 24 μm filter paper. Because the flow was highly turbulent and shallow (< 7 cm) as it passed over the spillway, depth-integration of samples was not deemed necessary.

RESULTS

Rainfall, runoff, sediment mass flux and total sediment concentration for the three study storms are plotted versus time in Figure 3. Peaks in the rainfall hyetograph (storm pulses) are marked in the figure. The hydrologic response to intense rainfall was extremely rapid, with interfluve runoff responding more quickly than channel flow. Flow in the trunk gully was initially detected at the weir 2–4 min after the sheetwash collector began recording flow. This lag was partially an artifact of the weir pool geometry, which requires a short time interval to fill (cf. Smith, 1976). The sheetwash collection barrel, which was located 9 m downslope of the interfluve monitoring surface, also required about 1 min to begin registering runoff. Thus, the first sediment samples for each storm event were collected at the spillway without corresponding runoff measurements. These effects were initial, and did not recur after the first positive reading for each stage recorder.

Interfluve and gully runoff both responded to brief intervals of high-intensity rainfall. Interfluve response was charactereized by sharp peaks and drops, while the flow in the gully was more subdued. The temporal response of the gully appeared to lag slightly behind that of the interfluve even after the initial pulses, when instrument lag was a problem.

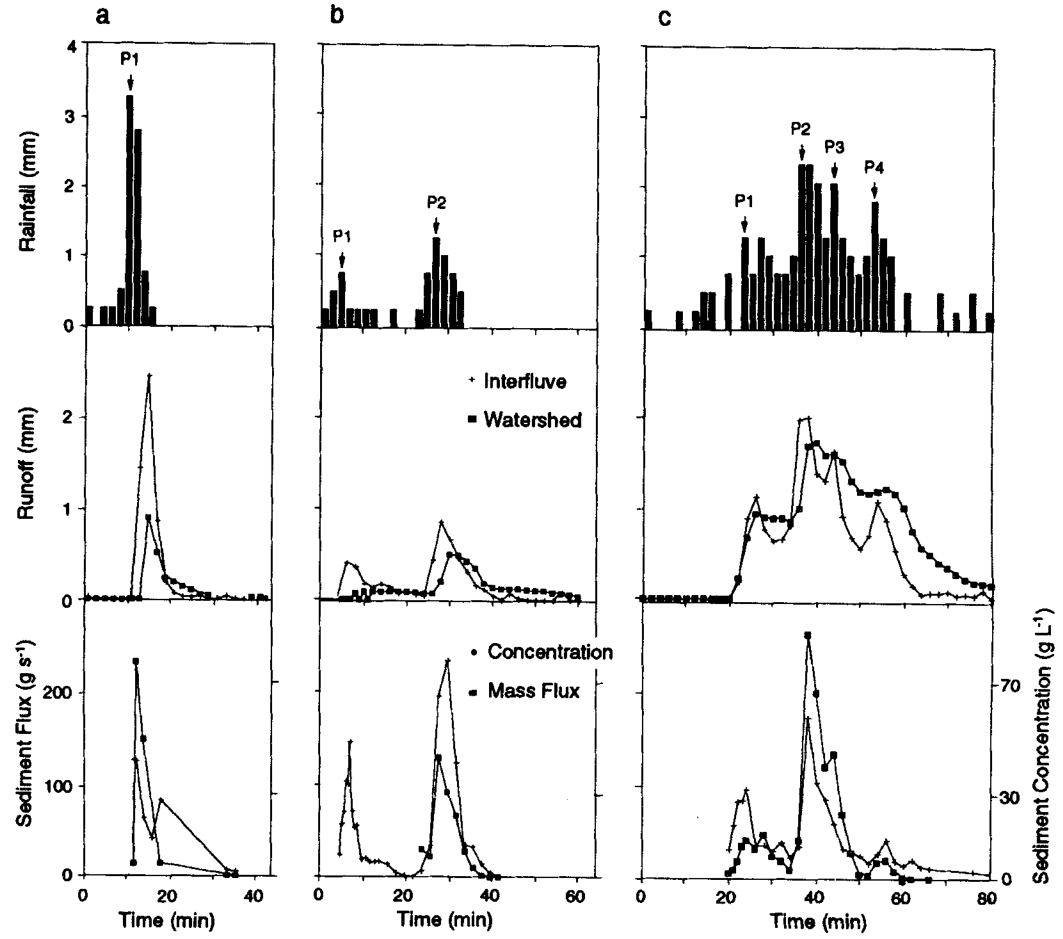

Figure 3. Temporal trends of rainfall (upper row), runoff (centre row), and sediment load (lower row) during storms that occurred on 29 August (a and b) and 3 October (c) 1990. Rainfall and runoff values are 2-min totals. Labelled arrows indicate pulses of high-intensity rainfall. See Figure 1 for locations of measurement sites: rainfall is from tipping-bucket rain gauge; watershed runoff is from V-notch weir; interfluve runoff is from interfluve monitoring site. Data on sediment concentration and mass flux were collected at the inflow to the watershed sediment trap

Sediment mass flux and concentration responded almost immediately to intense rainfall, tending to precede peaks in gully runoff. A comparison between measured mass flux captured by the nets and derived totals calculated from the product of sediment concentration and discharge indicated that the netted flux averaged about 75 per cent of calculated flux owing to loss of the fine fraction. The two methods produced total sediment flux values that were strongly correlated through time ($r = 0{\cdot}91$).

Grain-size analyses of the bottled sediment-concentration samples indicated that production of the larger fractions increased with total sediment concentration. Figure 4 illustrates a typical example of the temporal changes in grain-size distribution that occurred during the studied storm-runoff events. Note that the samples were composed of dominantly fine-grained material when the total concentrations (and mass fluxes) were low. However, as sediment export peaked in response to intense rainfall, the proportions of larger fractions increased.

In the manner of Mandel *et al.* (1982), grain-size data were divided into two categories (< 2 mm and > 2 mm). Plotting coarse versus fine grain-size concentrations for all three storms reveals a more general relationship than can be shown by plotting individual distributions. A single convex-upward curve emerges with a best-fit power-function exponent value of 0·47 (Figure 5). The exponent value of less than unity indicates that the contribution of small (< 2 mm) sediment sizes becomes proportionately less, relative to

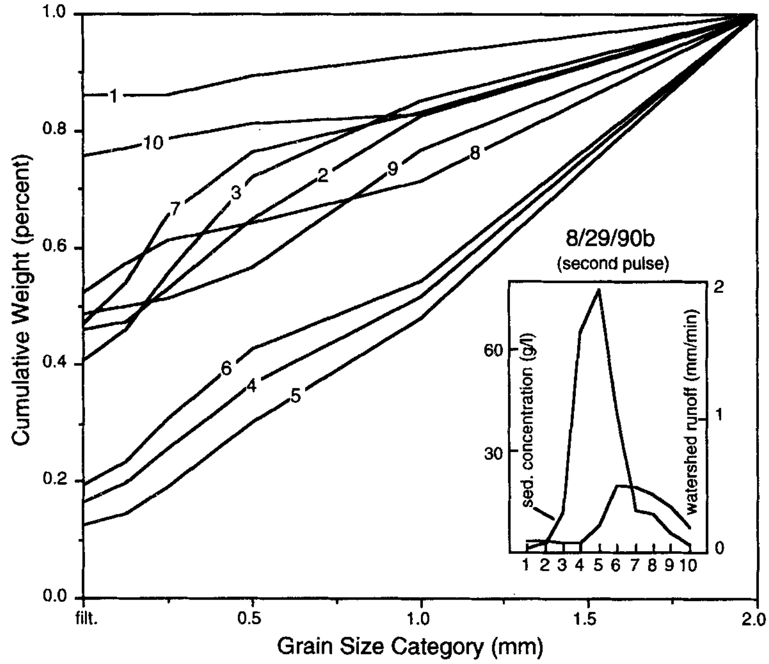

Figure 4. Cumulative grain-size distributions determined for samples of gully discharge collected during second storm pulse in Figure 3b. Inset permits temporal placement of each labelled distribution curve in the hydrographs of watershed runoff and sediment concentration (sampling interval is 2 min)

larger (> 2 mm) sizes, as total sediment concentration (and storm intensity) increases. At the highest total-sediment concentrations, the concentration of coarser grains constitutes a majority of the sediment load. The crossover point appears to occur when rainstorms are sufficiently intense to generate a total sediment concentration of 70 g l^{-1}.

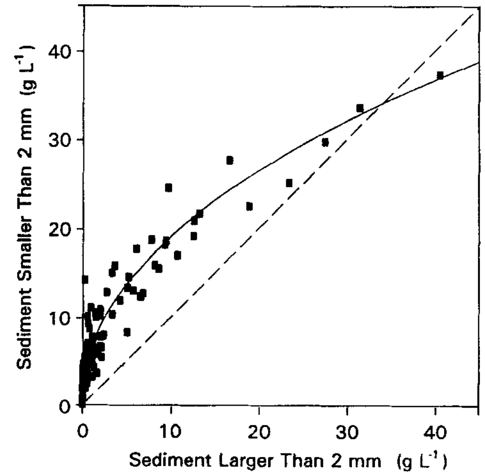

Figure 5. Plot of coarse (> 2 mm) versus fine (< 2 mm) sediment concentrations from grab samples of storm runoff. Dashed line shows 1 : 1 correspondence; solid line is best-fit power function given by: $y = 6{\cdot}49\,x^{0{\cdot}47}$. The equation parameters were estimated using the reduced major axis procedure described in Till (1973); correlation coefficient (r) is 0·89; the standard deviation of the exponent (log–log regression slope) is 0·02; standard deviation of the coefficient (log–log regression intercept) is 0·04

DISCUSSION

The presence of an imbricated surface layer (Figure 2) apparently enhances Hortonian overland flow at the study site. Baseflow is not possible, as the water table is 6 m below the gully floor, and the contribution of interflow is negligible as evidenced by the relatively rapid response of gully discharge to variations in rainfall. Runoff occurs almost immediately when the rainfall rate exceeds about 0·3 mm min^{-1}, and ceases soon after precipitation stops.

Runoff from the interfluves responds most sharply to rainfall, and ends before gully discharge. The watershed response is more subdued; even in the small study catchment the smoothing effect of differential source areas on the hydrograph can be observed. It is likely that the broad, gently sloping upland portion of the watershed continues to contribute runoff after flow from the steeper, more proximal tributary gullies has declined.

Peaks in sediment concentration and mass flux appear to precede watershed runoff, as also observed by Collier (1964) and Lusby and Toy (1976). One interpretation of the out-of-phase relationship between sediment concentration and runoff is that the supply of easily-transported sediment, which is initially high, gets depleted as storm runoff progresses (cf. Wood, 1977). The fourth pulse of high-intensity rainfall (P4, Figure 3) during the more lengthy event of 3 October generated little sediment despite high rates of runoff, also suggesting depletion. It has been shown that gullies at the field sites are effective conduits for the removal of available colluvium (Olyphant *et al.*, 1991), which was at its annual minimum (late summer and early autumn) when the present data were collected. If sediment export from eroding refuse deposits is limited by supply, a sequence of storms separated by periods of drying and colluvial build-up in the gullies may cause more erosion than a single large storm with equivalent total volumetric outflow.

However, the results of this study also indicate that coarse-grained material quickly dominates the sediment load at high rainfall intensities ($>$ 2 mm min^{-1}). The imbricated surface layer, which normally serves only to enhance runoff from the interfluves, may be mobilized by the intense downpours that accompany summer thunderstorms. Kinetic energy from rainsplash contributes by loosening and dislodging the chips, while increased flow depth over the interfluves permits entrainment and transport into nearby gullies. Figures 3 and 4 demonstrate that coarse-sediment production at the study site is more closely correlated with bursts of intense rainfall and sheetwash than with channel flow. The 'armouring' layer at the surface of the deposit is not analogous to a protective pavement. With sufficient rainfall intensity it becomes an additional sediment source, and for this reason may neither thicken with time nor prevent denudation of the deposit, which has been continuously eroding since its creation. It is still possible, given very intense rainfall, to produce large voumes of coarse sediment from barren refuse deposits of this type even during late summer, when sediment supply from the channel is greatly reduced.

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REFERENCES

Collier, C. R. 1964. 'Influences of strip-mining on the hydrologic environment of parts of Beaver Creek basin, Kentucky, 1955–59', *U.S. Geological Survey Professional Paper*, **427-B**, C31–C46, B48–B66.

Esling, S. P. and Drake, L. 1988. 'Erosion of strip-mine spoil in Iowa and its implications for erosion models', *Geomorphology*, **1**, 279–296.

Gilley, J. E., Gee, G. W., Bauer, A., Willis, W. O. and Young, R. A. 1977. 'Runoff and erosion characteristics of surface-mined sites in western North Dakota', *Transactions of American Society of Agricultural Engineers*, **20**, 697–700, 704.

Haigh, M. J. and Wallace, W. L. 1982. 'Erosion of strip-mine dumps in LaSalle County, Illinois: Preliminary results', *Earth Surface Processes and Landforms*, **7**, 79–84.

Lusby, G. C. and Toy, T. J. 'An evaluation of surface-mine spoils area restoration in Wyoming using rainfall simulation', *Earth Surface Processes and Landforms*, **1**, 375–386.

Mandel, R. D., Sorenson, C. J. and Jackson, D. 1982. 'A study of erosion–sedimentation processes on abandoned coal refuse piles in southeastern Kansas', in Graves, D. H. (Ed.), *Proceedings of 1982 Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation*, Lexington, Kentucky, Office of Engineering Services, University of Kentucky, 663–669.

Olyphant, G. A., Carlson, C. P. and Harper, D. 1991. 'Seasonal and storm-related aspects of sediment yield from a rapidly eroding coal refuse deposit in southwestern Indiana', *Water Resources Research*, **27**, 2825–2833.

Smith, L. C. 1991. *Time-trends of sediment yield during storms: Friar Tuck site, southwestern Indiana*, M.S. Thesis, Indiana University, Bloomington, 77 pp.

Smith, R. E. 1976. 'Field test of a distributed watershed erosion/sedimentation model', in *Soil Erosion, Prediction and Control*, Proceedings of a National Conference on Soil Erosion, 24–26 May, Purdue University, West Lafayette, Indiana, Soil Conservation Society of America, Ankeny, Iowa.

Till, R. 1973. 'The use of linear regression in geomorphology', *Area*, **5**, 303–308.

Wood, P. A. 1977. 'Controls of variation in suspended sediment concentration in the River Rother, West Susseex, England', *Sedimentology*, **24**, 437–445.