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Hillslope characteristics and particle size composition of surficial armoring on a semiarid watershed in the southwestern United States

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Abstract

Distributed process-based hydrologic models have been used to describe and predict the movement of sediment on small watersheds. However, to parameterize these models requires an understanding of the spatial variability of erosion processes and the particle sizes of the sediment being moved. In this study, a high resolution digital elevation model (DEM) and detailed sediment particle sampling allowed a comparison of hillslope characteristics and particle sizes of surficial armoring in a semiarid watershed. Individual particle size classes on hillslopes are correlated with the underlying sediment type, local slope, aspect, and area draining through a grid element. The strongest correlations are between the underlying sediment and overlying sediment. However, the distribution of the particle size classes is consistent with a hydrodynamic explanation for sorting. In particular, increased area draining through a grid node and increased slope are correlated with higher concentrations of the 16–64-mm particle size class. Both the coarsest and finest particle size classes are significantly correlated with the aspect of flow from a grid cell, with increased coarse particles and decreased fines on east-facing slopes. These spatial differences with aspect are attributed to dry season prevailing winds. These observations about process and spatial distribution are useful in predicting the spatial distribution of particles on the watershed for applications such as distributed hydrologic models. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Armoring; Hillslope erosion; Slope aspect; Semiarid; Spatial variability; Digital elevation model (DEM)

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1. Introduction

Distributed process-based hydrologic models have been used to describe and predict the movement of sediment on small watersheds. However, to parameterize these models requires an understanding of the spatial variability of erosion processes and the particle sizes of the sediment being moved. The distribution of particles on the surface of a watershed is a reflection of the geomorphic process acting on the watershed. Therefore, the distribution of sediment on the watershed may contain information about particle movement. A coarse surface armoring is often noted in arid and semiarid environments. Therefore, hillslope materials in many desert environments are essentially two layers, a thin coarse surface layer that constitutes the surface armoring, and the underlying uneroded sediment.

The genesis of surface armoring in desert environments has been ascribed to various processes. A review of these processes can be found elsewhere (Cooke et al., 1993). Among the more widely ascribed processes attributing to the formation of this surface armoring are:

- deflation (i.e. removal of fines by wind; Symmons and Hemming, 1968)
- water sorting and removal of fines by hydrodynamic mechanisms (Sharon, 1962; Parsons et al., 1992; van Wesemael et al., 1996; Wainwright et al., 1999)
- upward migration of particles due to frost or salt heave (Jessup, 1960)
- lifting of clasts during deposition of aeolian fines (McFadden et al., 1987)
- biological agitation (Haff and Werner, 1996).

In degraded rangeland watersheds near Tombstone Arizona, a convincing argument has been made that rainsplash, coupled with removal of fines by flowing water, could result in the formation of surface armoring and mounding beneath shrubs (Parsons et al., 1992). However, this study did not characterize particle size characteristics of the surface armoring in the context of three dimensions. Landscape characteristics and sediment transport mechanisms can have a significant directional component, which may affect surface armoring characteristics. Differences in surface armoring and erosion have been noted with slope position (e.g. Abrahams and Parsons, 1991; Abrahams et al., 1984, 1988; Kirkby and Kirkby, 1974; Osterkamp and Toy, 1994; Simaton and Toy, 1994; Simaton et al., 1994).

Differences have also been noted with hillslope orientation. Surface armoring on hillslopes in Spain has been found to be greater on southern exposures, which have the greatest period of sunlight during the day (Poesen et al., 1998). Furthermore, higher sediment yield rates and higher dissolved solids have been found on south-facing slopes in semiarid Spain (Cerda, 1998). This difference has been attributed to decreased vegetation and initial soil moisture which tends to be lower on south-facing slopes (Cerda, 1998; Poesen et al., 1999).

In this study, sediment was sampled on hillslopes throughout a small watershed so particle size distributions could be predicted to describe spatial differences and understand spatial processes in a process-based erosion model (Canfield, 1998). This necessitated observing relationships between particle size, landscape position and hillslope orientation. Furthermore, because composition of surface armoring has also been found to be related to the composition of underlying sediment (Canfield et al., 1984; Poesen et al., 1998), relationships between particle sizes of the surface armoring and the underlying sediment were also examined. Despite the importance of studies that document the multiple mechanisms which can produce observed surface armoring characteristics; for applications such as incorporating spatial variability into a process-based erosion model, it is necessary to understand the magnitude of the multiple processes.

1.1. Study location

This study examines the surficial armoring in the context of hillslope position, and as such, takes a larger scale view of hillslope morphology in the same area studied near Tombstone by Parsons et al. (1992). The study area is located on the Lucky Hills 104 watershed [LH104 (4.4 ha)] at the Walnut Gulch Experimental Watershed near Tombstone, AZ, operated by the USDA-ARS in Tucson. Rangelands in this area were degraded to raise cattle early in the century (Graf, 1983), and have not recovered since. Vegetation on the watershed is creosote bush and acacia, which are typical invasive species for degraded rangeland in the southwestern United States.

2. Objective

The objective of this study is to improve understanding of the mechanisms responsible for the spatial distribution of sediment particle sizes in surface armoring based on the relationship between sediment and hillslope characteristics. In particular, it is to better understand the effect of hillslope position on particle size distributions in the surface armoring.

3. Methods

Hillslope form is characterized using a field-derived 5 × 5 m DEM. Essentially, the attributes of a 5 × 5-m-grid element are used as a proxy for hillslope characteristics. In fact, these elements characterize macro-variability of the topography and cannot account for variability caused by features smaller than the grid size, such as rills and micro-topographic variability observed in the swales between shrubs by Parsons et al. (1992).

3.1. DEM analysis of Hillslopes

A high-resolution DEM of the Lucky Hills 104 watershed was prepared based on field sampling. Elevation data were collected on a 5 × 5-m grid throughout the watershed using a total station. These grid elevation data were then supplemented with spot elevation data collected in channels (Fig. 1). From this field data, both 5 × 5-m and 2.5 × 2.5-m DEMs were derived. Numerous topographic relationships were calculated

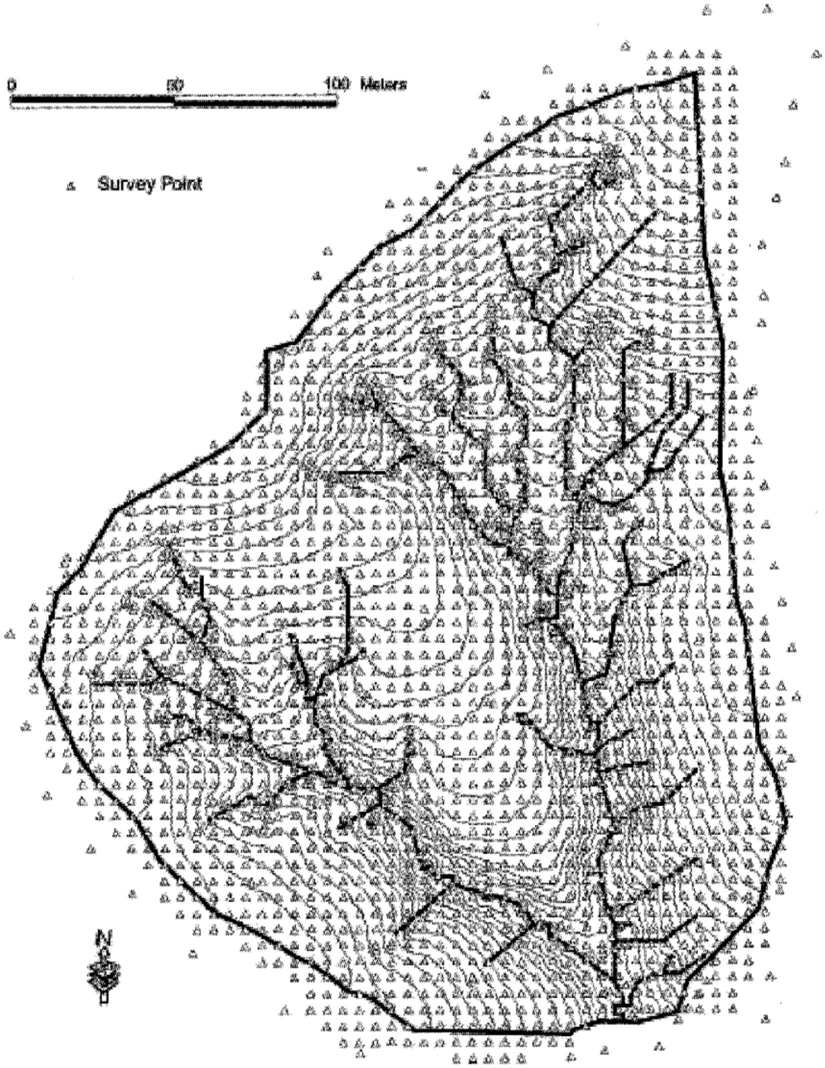

Fig. 1. Location of survey points collected on the Lucky Hills 104 Watershed. Survey points were collected using a total station. In total, 2993 survey points were collected (1988 on grid nodes and the remainder in channels).

from the DEM, but only three were chosen as representative; upland hillslope area contributing to a grid node, local slope steepness, and aspect of the flow vector.

3.2. Sediment sampling

The surface armoring was sampled in 50 locations on the watershed and the underlying uneroded sediment was sampled at 48 of those locations (Fig. 2). The surface

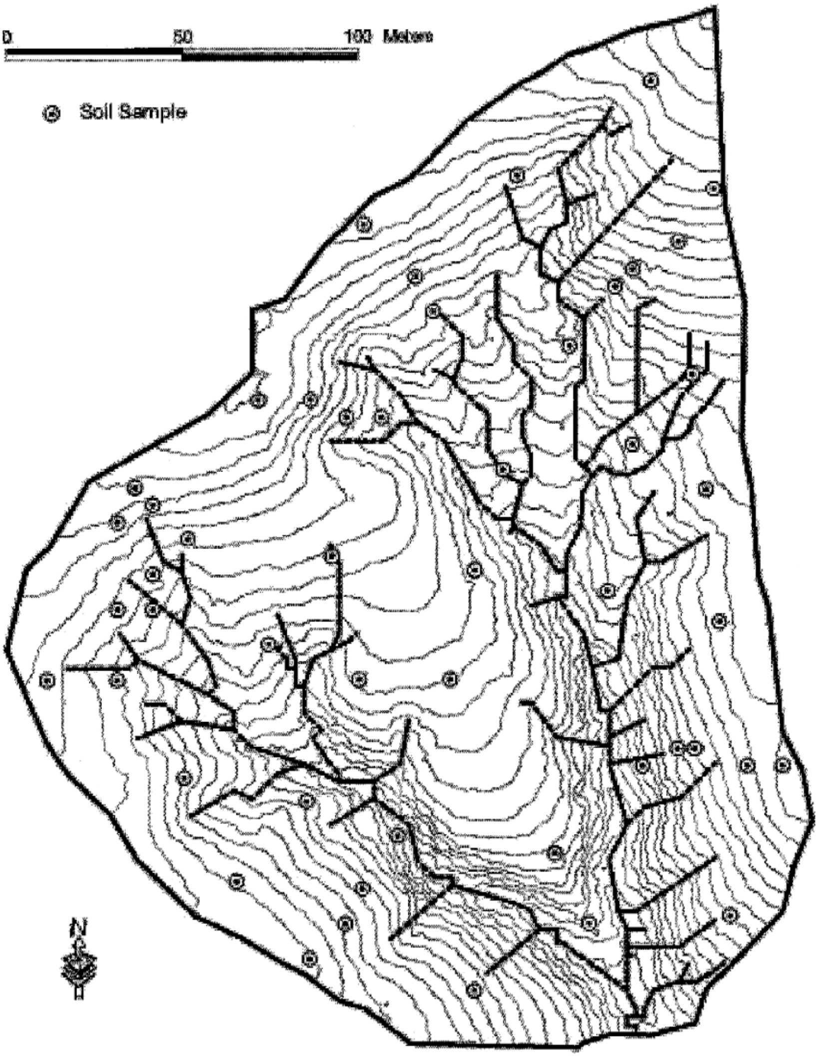

Fig. 2. Location of soil samples on the hillslopes of the watershed. Soil samples on hillslope are shown by (+). Locations were selected originally to sample on a catena to get downslope trends. Later, additional samples were collected to improve spatial estimates.

armoring could be distinguished from the underlying uneroded sediment in being slightly lighter in color due to the dominance of sand in the soil portion of the surface armoring. Typically, about half of a square meter was scraped to a depth of 0.5 cm to collect this material. The underlying sediment was sampled to a depth of about 5 cm.

While collecting bulk samples such as these may be less representative of the armoring than grid sampling methods (Wolman, 1954), grid sampling may have a bias toward larger stones (Leopold, 1970). Furthermore, grid sampling may be biased because of data conversion methods and sampling of only between 25 and 200 particles (Dunkerley, 1996). Therefore, bulk sampling allows a more complete picture of the composition of the surface armoring and a more direct means to compare the composition of the surface armoring with the underlying sediment particle distribution.

3.3. Laboratory analysis methods

Sediment samples were analyzed for particle size using sieve sizes in the phi scale classification from the −6 phi (64 mm) to +4 phi (0.063 mm) particle sizes. In addition, 30 samples were analyzed using hydrometer analysis to identify the clay (< 0.002 mm) and silt (0.063–0.002 mm) portions of the soils finer than the finest sieve. Four representative particle size samples were selected to characterize sediment variability with hillslope position.

4. Results and discussion

4.1. Correlation of surface armoring with underlying sediment

The data show a significant correlation between particle size class on the surface sediment and particle size class in the underlying sediment (Table 1). The correlation is particularly significant for the coarser particle sizes with correlation with the underlying 16–32 mm-particle size class being significantly correlated with all particle size classes in the surface armoring. In general, coarser underlying sediment tends to be associated with coarser surface armoring.

4.2. Hydrodynamic processes

Hydrodynamic processes include sediment entrainment and transport by flowing water. Fickian diffusion processes are those that can be used to describe sediment

Table 1
Pearson correlation coefficients of surface armoring to underlying sediment

Underlying sediment	64–16 mm	16–2 mm	2.0–0.5 mm	< 0.5 mm
64–16 mm	**0.665**	−**0.525**	−**0.499**	−**0.368**
16–2 mm	**0.306**	−0.060	−0.158	−**0.497**
2–0.5 mm	−**0.398**	0.247	**0.633**	0.030
< 0. 5 mm	−**0.425**	0.240	0.063	**0.596**

Bold — significant at 0.05 level.
The table shows the correlation between the particle composition of the surface armoring, and the particle size of the sediment immediately below. The coarsest particle size (64–16 mm) in the surficial armoring is positively correlated with the coarse particle sizes in the underlying sediment indicating that the surficial armoring is coarser where the underlying sediment is coarser. Likewise, the data show that the surface armoring is finer in locations where the underlying sediment is finer.

movement as a function of slope steepness such as, rainsplash, soil creep, and biological agitation. The two landscape variables that are related to these processes are:

1. **Upslope contributing area**: the upslope contributing area is a proxy for flow rate. Rainfall excess will run off, and the volume of the runoff will be proportional to the upslope contributing source area.
2. **Slope steepness**: In Fickian diffusion, diffusion rate is a function of slope steepness, so that diffusion rates should be correlated with slope steepness.

The product of slope steepness and flow rate is stream power. As such, stream power increases with increasing slope steepness and upslope contributing source area. On a hillslope, steepness will generally increase downslope until the transition to toe slope, and drainage area will also increase downslope. As such, in areas of topographic convergence with steep slopes, stream power will be greatest.

Correlations of particle size class, slope and area are summarized on Table 2.

Characteristics of the surface armoring suggest a continuum of stability against hydrodynamic processes. The coarsest particle size class (16–64 mm) is positively correlated with both drainage area and slope steepness. This suggests that these are particle sizes which tend to be stable against the stream power exerted by flowing water on hillslopes at the Lucky Hills. The fact that the finest particle size (< 0.5 mm) is negatively correlated with slope and drainage area is consistent with the process of removal of fines from armored areas by rainsplash and selective transport as described by Parsons et al. (1992).

The surface armoring is related to the underlying material which is an observation noted in other locations (Canfield et al., 1984; Poesen et al., 1998). As such, for downslope processes, it makes sense to examine both the correlation of surface armoring with hillslope variables; and the correlation of the underlying sediment with hillslope variables. In fact, the underlying sediment at the base of the slope (higher drainage area) is most likely colluvium stripped from the upper reaches of the hillslope and deposited at the base of the slope. The fact that the three coarsest particle size classes in the

Table 2
Pearson correlation coefficients of sediment and landscape characteristics

	Surface armoring		Underlying sediment	
	Contributing upslope area	Slope steepness	Contributing upslope area	Slope steepness
64–16 mm	**0.333**	0.393	0.334	0.341
16–2 mm	−**0.269**	−**0.273**	−0.079	**0.269**
2–0.5 mm	−0.175	−**0.314**	−0.018	−**0.302**
< 0.5 mm	−**0.245**	−**0.261**	−0.148	−**0.242**

Bold — significant at 0.05 level.
The table shows the correlation between the particle composition of the surface armoring, and underlying sediment with slope steepness and upslope contributing area. The statistically significant correlation of all particle size classes with slope steepness suggests that both the surficial armoring and the underlying sediment are the product of slope processes.

underlying sediment tend to increase with steeper slopes and increased drainage area supports this conclusion.

4.3. Directional processes

Since the textural composition of the surface armoring was most strongly correlated with the textural composition of the underlying sediment, the effect of hillslope variables may be masked by the effect of the underlying sediment in bivariate correlation. For this reason, the composition of the surface armoring was compared with the hillslope variables using partial correlation controlling for the effect of the underlying sediment classes (Table 3).

As indicated in Table 3, the sine of the aspect of the flow vector is more strongly correlated with particle size than any other hillslope variable when the effect of underlying soil is controlled for in partial correlation. In contrast, the cosine of the aspect of the flow vector is not well correlated with the distribution of the particles. While differences in soils have been noted with aspect (e.g. Birkeland, 1984), these have generally been associated with vegetation, which tends to be more lush on northeast-facing slopes, and more stressed on southwest-facing slopes, which receive more sun. A previous study of surficial armoring in Spain found that stone pavements were enhanced on south-facing slopes. However, as indicated in Fig. 3, the trend noted here is more clearly an east–west trend with more 16–64 mm on east-facing slopes. This is in clear contrast to other studies of spatial differences which found differences between soil composition in a northeast–southwest orientation. Possible mechanisms that might be responsible for the distribution are: deflation on east-facing slopes from easterly prevailing winds, and wind on rain in a predominantly east direction.

The predominant wind direction at the Lucky Hills 104 is from the east (Keefer, 1999, pers. comm.). However, there is a strong seasonal bias for this during the winter half year, October through March. The wind direction during the monsoon, July through

Table 3
Partial correlation of landscape variables and surface armoring controlling for the composition of underlying sediment

	Aspect of flow vector (sine)	Aspect of flow vector (cosine)	Contributing upslope area	Slope steepness
16–64 mm	**−0.32**	−0.14	0.15	0.22
2–16 mm	0.03	0.25	−0.02	−0.16
2–0.5 mm	**0.37**	0.03	−0.06	−0.13
< 0.5 mm	**0.35**	−0.03	−0.19	−0.14

Bold — significant at 0.05 level.
The table shows the partial correlation between the particle composition of the surface armoring, controlling for the effect of the underlying sediment. Only the sine of the aspect of the flow vector is significantly correlated with particle size classes when controlling for underlying particle size indicating correlation along the east–west axis. The contributing upslope area and slope steepness are not significantly correlated with particle size class when controlling for the underlying sediment. This indicates that the significant correlation of particle size class with slope steepness and contributing upslope area in bivariate correlation can largely be attributed to differences in the underlying sediment.

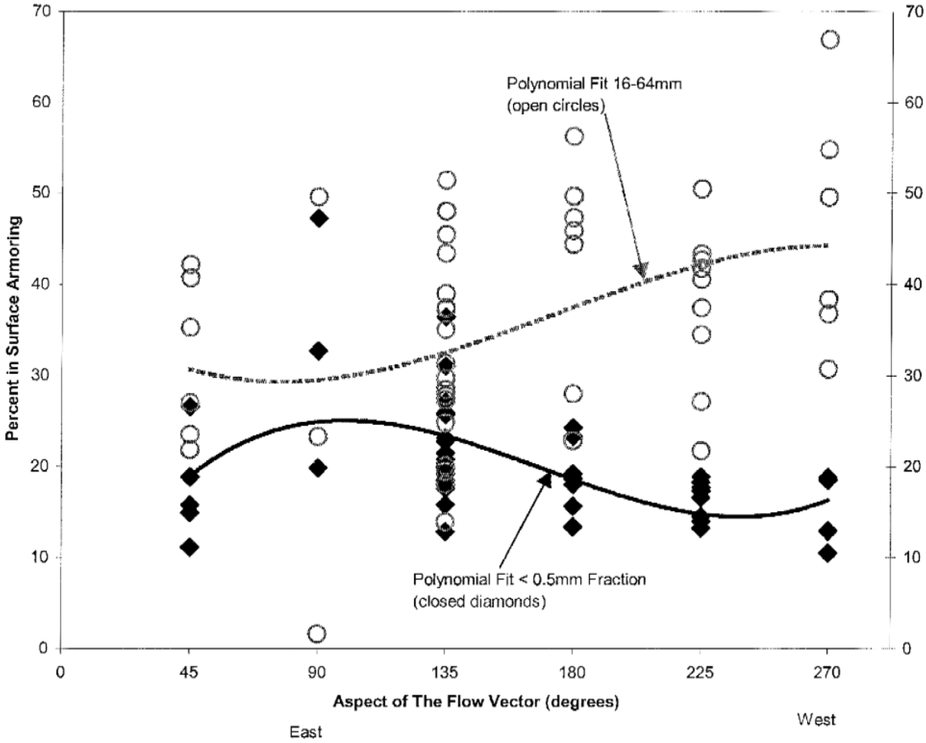

Fig. 3. Differences in particle size with aspect. Percent < 0.5 mm and percent 16–64 mm in the surface armoring plotted against the aspect of the flow vector (the direction downhill from the grid cell). Note the general sine wave trend of the regression line suggesting that the distribution of sediment is a function aspect of the flow vector, with more coarse material and less fines on west-facing slopes.

September, during which most runoff-producing events at Walnut Gulch occur, are equally from the east or west. Therefore, wind on rain and subsequent rainplash should not have a predominantly east component; but easterlies during the winter half year could deplete fines on east-facing slopes (i.e. deflation), resulting in the observed differences in east- and west-facing slopes.

5. Conclusions

Analysis of the data suggests a two-phase process for surface armoring formation as follows;

1. **Deposition of coarser underlying material on steeper slopes at higher drainage areas**. The fact that the underlying material is significantly correlated with slope steepness and drainage area (Table 2) suggests that it is a deposit resulting from downslope erosion and deposition processes. This underlying deposit could be caused by stabilization of incised areas with coarser fill and trapping of fines such

as occurs in gully gravure (Osterkamp and Toy, 1994). However, it could also be colluvium caused by soil creep or hydrodynamic mechanisms.

2. **Development of the surface armoring over this coarser deposit**. The strong correlation of the surface armoring with the underlying material (Table 1) and the lack of correlation of the surface armoring with landscape variables after correcting for the effect of the underlying material (Table 3) suggest that the surface armoring is largely developed in situ. Correlation between the surface armoring and underlying materials is an observation noted in other studies (Canfield et al., 1984; Poesen et al., 1998). The comparison of the different particle size classes suggests that rainsplash and the subsequent removal of fines by hydrodynamic processes (Parsons et al., 1992) are important surface armoring processes on the Lucky Hills. However, since the sine of the aspect of the flow vector was significantly correlated with both the finest and coarsest particle size classes, suggesting an east–west climate-related, directional component may play a role in the distribution of particle sizes in the surface armoring

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In summary, multiple processes, including hydrodynamic and climatic processes, may be responsible for spatial differences in particle size noted in the surface armoring at the Lucky Hills 104 watershed. Understanding these processes and the relationship of different particle size classes to landscape position improves the capability of researchers to parameterize process-based hydrologic models which can be used to describe and predict sediment movement on small watersheds.

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