HILLSLOPE EROSION, CHANNEL ROUTING, AND SEDIMENT YIELD IN SMALL SEMIARID WATERSHEDS, SOUTHERN CALIFORNIA

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Abstract: This paper reports first-year measurements of intrabasin erosion and sedimentation in four small semiarid watersheds on the San Dimas Experimental Forest, located in the tectonically active San Gabriel Mountains near Los Angeles, California. Three of these watersheds are covered with native chaparral vegetation (one of which had contour trenches carved into the hillsides and check dams constructed in the channels), while the fourth has been type converted to annual grass. These mechanical and vegetative treatments were established as part of an erosion control experiment following a wildfire in 1990. In 1993-94, the watersheds were instrumented with sediment collector traps, colored rock tracers, and permanent stream channel and debris basin cross sections to monitor hillslope erosion, delivery of sediment to channels, movement of channel sediment, and watershed sediment yield. Storms produced 1229 mm of precipitation over the 1994/95 hydrologic year, 172 percent of normal, generating surface runoff in the ephemeral channels not by hillslope overland flow but by soil mantle exfiltration. Hillslope erosion and sediment delivery to channels were an order of magnitude less under type converted grass vegetation than under natural chaparral plant cover. There was no relationship between painted rock tracer travel distance along the channels and rock size. Most of the tracers were too large to be entrained by the flow, however, and many were buried in fine material transported through the drainage network. Small watershed sediment yield was negligible. Most of the differences in both watershed morphology and sediment cycling appear to be related to the previous erosion control treatments.

INTRODUCTION

The USDA Forest Service, along with other agencies, is charged with responsible management of publicly owned lands. Yet, our knowledge and understanding of wildland ecosystem dynamics, including upland erosion and sedimentation, are inadequate to accurately predict the outcomes of different land management practices. Often the consequences of management treatments are poorly understood in the short term and virtually unknown in the long term. Postfire watershed rehabilitation is an especially controversial management issue with serious legal ramifications in southern California, as the urban wildland interface encroaches on adjacent steep mountain fronts. There is general agreement that watershed protection measures are necessary to reduce postfire erosion and sedimentation, but the utility and wisdom of many erosion control practices are being questioned. Ultimately, the problem reduces to the fact that there is too little quantitative information available, for either sediment dynamics or the effects of management treatments, on which land managers and policymakers can base their decisions.

The purpose of this study is to document and quantify erosion and sedimentation in four small semiarid watersheds in the tectonically active San Gabriel Mountains of southern California. Using sediment collector traps, repeated surveys of permanent cross sections, and colored rock tracers, this project monitors 1) surface sediment transport on hillsides, 2) hillslope sediment delivery to channels, 3) channel sediment movement, and 4) small watershed sediment yield. Concomitantly, this investigation may provide some indication of the long-term (35-year) effectiveness and consequences of several specific postfire emergency rehabilitation treatments (type conversion, contour trenching, and channel checks) whose persistence and influence are still apparent on the landscape. This paper reports the first-year measurements of a multi-year study that includes future burning treatments.

The results of this project should serve as fundamental building blocks for a comprehensive predictive model of small watershed sediment yield for southern California catchments subjected to several land management treatments. They will also provide benchmark data against which the performance of existing models can be evaluated. The resulting information on erosion and sedimentation behavior in small semiarid watersheds, along with the long-term effects of postfire emergency rehabilitation treatments, should aid public agencies in making land management decisions.
BACKGROUND

Semiarid geomorphic systems can exhibit extremely high rates of sediment production (Langbein and Schumm, 1958). The steep San Gabriel Mountains of southern California are an extreme example in which the high natural erosion rates are accentuated by management practices and wildfire (Sinclair, 1954; Scott and Williams, 1978). Weathered rock debris combines with organic litter to form thin, colluvial soils (DeBano, 1974). This sediment, stored on the hillslopes, is shed quasi-continuously by the processes of granular transport and mass movement (Rice, 1974), and accumulates on the banks and bed of ephemeral channels at the base of the hillsides. The stored channel sediment is then periodically scoured by surface runoff and debris flows, generated by infrequent high-magnitude storms, and routed primarily as bedload to the watershed outlet (Scott and Williams, 1978). Fire dramatically accelerates these landscape processes (Rice, 1974; Wells, 1981; Florsheim et al., 1991), prompting emergency rehabilitation treatments on the part of land managers.

Fires render the landscape susceptible to flooding and massive erosion, which endangers downstream life and property. Land management agencies strive to control the adverse impacts of accelerated erosion to both on-site environmental quality and of site resources. While many possible options for erosion control are available (USDA Forest Service, 1992), land managers have learned from experience that it is most cost-effective and realistic to attempt to reduce erosion at the source (Rice et al., 1965).

STUDY AREA

The study area is located in the San Dimas Experimental Forest (SDEF), about 45 km northeast of Los Angeles, California (Figure 1). Situated in a front range of the San Gabriel Mountains, the SDEF is a 6945-ha research preserve administered and operated by the USDA Forest Service. The SDEF has been the site of extensive hydrologic monitoring for over 60 years (Dunn et al., 1988).

The San Gabriel Mountains, part of the Transverse Ranges geomorphic province, are an upthrust crustal block resulting from the continuing regional compression associated with local tectonic plate collision (Atwater, 1970). Uplift rates in the Transverse Ranges have been estimated to be 7.6 m/1000 years, compared to a regional denudation rate of 2.3 m/1000 years (Scott and Williams, 1978). Lithologies in the study area consist exclusively of crystalline rocks, primarily Precambrian metamorphics and Mesozoic granitics (Rogers, 1967).

Topography in the SDEF consists of a highly dissected mountain front with narrow, steep-walled canyons. Elevations in the study area range from 750 to 1050 meters. Slope profiles exhibit both summit convexities and basal convexities, as the hillslopes meet the channels in an inner gorge (Wohlgemuth, 1986). Mean slope gradients in the study area are 35 degrees. The drainage network and hillslope morphology characteristics are considered to be as much a function of the tectonic activity as denudational process (Scott and Williams, 1978).

The SDEF experiences a Mediterranean climate, characterized by hot, dry summers and cool, moist winters. Precipitation, falling almost exclusively as rain, is produced by mid-latitude cyclonic winter storms and rare late summer tropical hurricanes. Mean annual precipitation for the study area is 714 mm (62-year record), but rain during individual years can range from 1595 mm to 258 mm. Over 90 percent of the annual precipitation falls between the months of November and April, with 10 percent of the storms producing over 50 percent of the total rain (Wohlgemuth, 1986).

The soils in the SDEF are poorly developed, rocky, and highly porous. Distinct soil horizons are often lacking and the boundary between soil and regolith is very gradual (DeBano, 1974). The soils are well-drained, as the underlying decomposing rock can absorb large amounts of moisture. Particle size analysis of the surface soil material reveals the average texture to be a loamy sand (Wohlgemuth, 1986).

Vegetation in the SDEF consists primarily of California chaparral. Plant cover on south-facing slopes ranges from dense stands of chamise (Adenostoma fasciculatum) and ceanothus (Ceanothus spp.) to more open stands of chamise and sage (Salvia spp.). North-facing hillsides are dominated by scrub oak (Quercus berberidifolia) and ceanothus, with occasional woodland trees—live oak (Quercus agrifolia) and California laurel (Umbellularia californica)—occurring...
Figure 1 - Location map of the San Dimas Experimental Forest showing the study area.
on the moister shaded slopes (Hellmers et al., 1955). The height of the chaparral vegetation canopy is 1-5 meters, and projected crown cover ranges from 30 to 100 percent (Wohlgemuth, 1986).

Nearly the entire SDEF burned in a wildfire in 1960, providing an opportunity to evaluate the following postfire emergency rehabilitation treatments: 1) type conversion by herbicide spraying followed by grass seeding to produce a rapid ground cover; 2) contour trenching at 12-m vertical intervals, creating platforms to interrupt overland flow and encourage onslope storage; and 3) stream channel stabilization with check dams to prevent downcutting that could undermine adjacent colluvial slopes (Rice et al., 1965). Small replicate watersheds were selected for treatment that were as similar as possible in size (0.8 to 3.6 ha), shape (elongate), aspect (south to southeast), and potential erodibility (slope, channel gradient, rockiness, and amount of colluvial soil). These watersheds were each instrumented with a debris basin to capture sediment outputs (Rice et al., 1965). Unfortunately, the subsequent winter was the driest storm season on record, so definitive results on the effects of these management treatments were never produced. Four of these small watersheds were re-activated for the current study: two in chaparral vegetation without mechanical treatments; one in type converted grass vegetation; and one in chaparral with both contour trenches and channel check dams. As only two of the watersheds are replicates of each other, the four essentially become case studies whose results are not necessarily generalizable.

METHODS

The amounts of both hillslope erosion and sediment delivery to channels were sampled using sheet metal collector traps with a 30 cm aperture on unbounded plots (Wells and Wohlgemuth, 1987). Within each of the four study watersheds, fall-line transects (from ridgecrest to channel) were established on randomly selected slope facets. Twenty five traps to document the magnitude and downslope disposition of hillslope surface sediment transport were randomly laid out en echelon along the fall-line transects with the constraint that at least two traps were deployed on each transect. Fifty traps to sample the amount of hillslope sediment delivered to channels were randomly laid out along the slope/channel interface of each watershed. The traps were installed in summer 1994 and allowed to equilibrate with the local ground surface. Trapped sediment was collected in February and May of 1995. Material was transported to the laboratory where it was dried and weighed.

Stream lengths were measured and channel patterns were mapped in the study watersheds following the near record storms of winter 1993, when the drainage networks were at their maximum extent. Permanent cross sections to document changes in channel bed elevation were established using notched rebar monuments. Ten cross sections were established in each of the four watersheds, distributed proportionately to the length of Strahler stream orders for each drainage network (Strahler, 1957). Initial surveys were performed in summer 1994 by measuring the horizontal distance and vertical relief from a reference pin to breaks in slope which define crosssection configuration using standard sag tape protocol (Ray and Megahan, -1978). The cross sections were resurveyed in March 1995, following the winter storm season.

Presence or absence of surface runoff in channels was determined by field inspection and mapped for the entire drainage network of each watershed. In most instances it was obvious whether or not runoff had occurred: scour was evident, fresh deposition was apparent, and/or organic debris marked the position of high water at crest stage. In a very few cases subjective decisions were made based on oriented vegetation on the channel bed surface.

Movement and routing of channel sediment were documented by measuring the distance moved by painted tracer rocks of various sizes (Keller, 1970). Tracers were laid out just downstream of the permanent channel cross sections, which served as reference lines to measure travel distance. Axial diameters, weights, and identification numbers were recorded for each rock. Tracer rocks ranged in intermediate axis diameter from 11.3 mm to 64 mm in five size classes according to the phi scale (Krumbein and Pettijohn, 1938). Five rocks of each size class were deployed at each channel cross section in summer 1994; rocks were located and their travel distance measured in March 1995.

Channel sediment outputs were captured in the debris basins at the bottom of the watersheds. Sediment yields were calculated using an engineering end-area formula (Eakin, 1939) based on the repeated sag tape surveys of permanent
cross sections spaced 1.5 meters apart. Debris basin cross sections were established in summer 1993, surveyed in winter 1994, and resurveyed in summer 1995.

**RESULTS**

Many of the morphological differences between these four watersheds result from the persistent effects of the management treatments following the 1960 wildfire. The vegetation in the type-converted watershed is still mostly grass, although many slopes have undergone succession to buckwheat (*Eriogonum fasciculatum*) and sage. The contour trenches persist, effectively shortening the slope lengths. These contour trench platforms continue to trap sediment, but many have been breached at channel crossings, exposing the unprotected sediment prism to the agents of erosion. Most of the channel check dams are still intact. An accretionary wedge of sediment has accumulated behind these dams, radically altering upstream channel morphology. These observations cannot be generalized, however, as the watershed treatments were not replicated.

Storms during the 1994/95 hydrologic year produced 1229 mm of rainfall, 172 percent of the long-term average and the sixth largest annual accumulation on record (the 90th percentile). Nearly half of the total rain fell in January, with a secondary peak in early March.

Preliminary analysis of the weight of trapped sediment revealed that the raw data were strongly right-skewed, but the distributions were effectively normalized using a logarithmic transformation. Summary statistics of the transformed data for both the hillslope plots and the channel interface plots for each of the four small catchments are arrayed in Table 1. T-tests confirm the tabulated results: the plots in the type converted grass watershed are very highly significantly different from the plots in the chaparral vegetation \( (p=0.000) \), but that the chaparral watersheds do not differ from each other. Because of the lack of watershed treatment replications, however, the dramatic differences between grass and chaparral vegetation types should be taken with caution. Curiously, more sediment was captured in the hillslope traps than the channel interface traps in chaparral vegetation, although this was statistically significant \( (\alpha = 0.05) \) only in watershed 0508.

Evidence of surface runoff occurred in 45 to 63 percent of drainage network lengths and four to seven of the permanent cross sections in the four study watersheds (Table 1). Continuous flow was experienced along nearly the entire mainstem and at least one tributary of each watershed. Discontinuous flow was documented in most of the tributaries, with scour apparent at the flow initiation site and deposition evident at the local flow termination site. As there was no evidence of extensive hillside surface wash or rilling, the source of the water at the initiation sites was not hillslope overland flow. Rather, evidence of sapping at the head of discontinuous gullies suggests that the source of surface runoff was exfiltration of soil mantle throughflow. However, neither violent discharge nor seepage was directly observed. Several tributaries experienced no surface water flow.

The general pattern of changes in channel bed elevation for the permanent cross sections that experienced surface flow was one of filling with fine material followed by scour through these new deposits. However, in several instances, gullies incised below the original channel level. Incision and deposition in the grass watershed were absent or very subdued. In the chaparral watersheds, local gullyning occurred in the steeper channel reaches, while deposition occurred in the flatter gradient reaches.

The patterns of painted rock tracer movement for those channel cross sections experiencing surface runoff are arrayed in Table 1. Overall, most of the rocks were located (≈ 90 percent), although several individual tracer lines had recovery rates as low as ≈ 60 percent. Many of those rocks (≈ 35 percent) were buried in fine sediments deposited during the winter storms. These were carefully excavated then re-buried. Presumably, the rocks that were not recovered are buried at some downstream location and may be unearthed in the future. Most of the rocks exhibited little or no movement, although one tracer was located 21 meters downstream from its point of origin and several others traveled more than five meters. Plots reveal no relationship between travel distance and rock size, although recovery was less complete for the smaller size classes. Fewer tracer rocks moved and fewer were buried in the type converted grass watershed than in the chaparral catchments.
## Table 1 First Year Summary Data by Watershed

<table>
<thead>
<tr>
<th>Watershed Identification Number</th>
<th>Treatment</th>
<th>Area (hectares)</th>
<th>Stream Length (meters)</th>
<th>Hillslope Sediment Traps&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Channel Interface Sediment Traps&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Surface Water Flow&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Painted Rock Tracers&lt;sup&gt;bc&lt;/sup&gt;</th>
<th>Debris Basin Sedimentation&lt;sup&gt;b&lt;/sup&gt; (meters³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0507</td>
<td>Type Chaparral Converted with Contour Grass Trenches and Treatment Check Dams</td>
<td>3.21</td>
<td>777</td>
<td>25 1.773 0.617</td>
<td>50 1.870 0.561</td>
<td>59 6 175 150</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0508</td>
<td>Chaparral with no Treatment</td>
<td>2.35</td>
<td>730</td>
<td>25 3.085 0.472</td>
<td>50 2.799 0.492</td>
<td>63 6 150</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0542</td>
<td>Chaparral with no Treatment</td>
<td>2.12</td>
<td>815</td>
<td>25 2.895 0.282</td>
<td>50 2.856 0.387</td>
<td>49 6 150</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>0560</td>
<td>Chaparral with no Treatment</td>
<td>1.32</td>
<td>446</td>
<td>25 2.894 0.341</td>
<td>50 2.744 0.480</td>
<td>45 4 100</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup> cumulative values (October 1994 - May 1995)
<sup>b</sup> winter 1995 storm season
<sup>c</sup> for channel cross sections with surface water flow
<sup>d</sup> of those located
All of the debris basins filled with water from the storm runoff, but there was little evidence of new sediment accumulation. Comparison of repeated surveys of the permanent cross sections reveals that one sediment reservoir (in watershed 0542) received ~3 m³ of new material, while the others recorded no changes (Table 1).

**DISCUSSION**

Surface sediment transport on hillslopes and sediment delivery to channels are an order of magnitude smaller in the type converted grass watershed than in catchments with chaparral vegetation. This indicates there has been a fundamental change in slope erosion behavior, presumably reflecting differences in the surface and subsurface growth habit of the dominant vegetation types, and confirms previous research findings from an adjacent watershed (Wohlgemuth, 1986). Although the hillslope erosion rates are similar in the chaparral catchments the slightly larger values in watershed 0508 may reflect the presence of the contour trenches. It is unclear why the amount of captured debris on the hillslope plots exceeds the catch for the channel delivery plots in the chaparral watersheds.

The source of surface runoff in channels was not overland flow but rather soil mantle exfiltration. The spatial distribution of channel flow may therefore reflect a limiting depth to local bedrock, forcing subsurface water above ground. The lack of local gullying in the type converted grass watershed may reflect the presence of a larger number of bedrock channel reaches. Future surveys of channel sediment storage may confirm these ideas.

Most of the painted rock tracers did not move, even though they were subjected to relatively high-magnitude runoff. The fact that many tracers were buried in fine material indicates that sediment was indeed being transported through the drainage network, but that it consisted of particles much smaller than those represented by the tracers. Fewer tracer rocks were buried in the type converted grass catchment, possibly reflecting diminished delivery of fine material from the hillslopes. The larger travel distances of tracer rocks in watershed 0560 may have been due to runoff generated on an access trail on the catchment perimeter. This ‘extra’ water was conveyed into the lower third of the mainstem via a local tributary in what amounts to an unnatural extension of the drainage network.

Despite a hydrologically active storm season, sediment yield from these watersheds was negligible. The 30 cm aperture collector traps sample a slope/channel interface that is twice the total stream length. Assuming a bulk density of 1.0 g/cm³ for the trapped debris and using the appropriate figures from Table 1, approximately 2.6 to 4.8 m³ of sediment was delivered from the hillslopes to the channels in the chaparral watersheds, compared to ~0.5 m³ in the grass catchment. Presumably, most of this newly delivered sediment filled channel storage sites flushed clean by the storms of winter 1993.

Land management treatments 35 years ago to mitigate postfire erosion and sedimentation appear to have resulted in wholesale changes in watershed morphology and perhaps sediment cycling behavior. A type converted grass watershed currently exhibits an order of magnitude less hillslope erosion and sediment delivery to channels than two comparable catchments in chaparral vegetation. A slight increase in hillslope erosion in a third chaparral watershed may stem from the presence of contour trenches. Channel morphology is dramatically different upstream of small check dams than in comparable stream sections lacking these structures. Sediment yields following the 1960 fire have long since stabilized, yet the effects of the management treatments still persist. Although these changes are not necessarily deleterious, they were certainly not anticipated. The foregoing information illuminates the consequences of several management practices in semiarid chaparral ecosystems and should aid public agencies in making more informed land management choices.

**SUMMARY**

This project has documented erosion and sedimentation in four small semiarid watersheds in southern California chaparral ecosystems during one hydrologically active storm season, using sediment collector traps, painted rock tracers, and repeated surveys of permanent cross sections. Findings based on first-year measurements are 1) type converted grass hillslopes seems to have transported and delivered less sediment to channels than comparable
chaparral hillsides, 2) sediment grains smaller than 11.3 mm in diameter were readily scoured and deposited in the channels, and 3) sediment yield to the debris basins was inconsequential. Much of the difference in intrabasin erosion and sedimentation between these watersheds appears to be related to previous management treatments.

REFERENCES


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