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A Stochastic Sediment Supply Model for a Semi-Arid Landscape

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ABSTRACT

We investigated the surficial processes that deliver sediment from hillslopes into channels in a mediterranean landscape and determined how these processes are controlled by climate and landscape characteristics (e.g. topography, vegetation). Watersheds in semi-arid regions of the United States are subject to a variety of disturbances, including grazing, fires, and vegetation cover changes and, while the consequences of sediment loading are well documented, presently our ability to predict the spatial and temporal pattern of delivery is poor. The processes that we have investigated are: shallow landslides, overland flow, dry ravel, and bioturbation. Through field experiments and monitoring, we have developed physically-based transport equations for each individual process. These transport equations are used as the governing equations for a computer model, driven by random sequences of rainstorms and fires, that predicts the spatial and temporal patterns of sediment delivery.

As downstream problems become more closely linked to watershed conditions and perturbations, this type of fundamental research is relevant to issues such as the health of riverine ecosystems and the siltation of reservoirs. We anticipate that our fieldwork and modeling results will help land managers estimate the influx of sediment from surface processes according to different land-use practices.

INTRODUCTION

Motivation

Because of the generally sparse vegetation cover, thin soils, and frequent fires, mediterranean landscapes are notoriously sensitive to disturbances and these disturbances can amplify sediment production. Sediment loading from hillslopes can have an impact on a range of concerns in Southern California and other semi-arid, mountainous environments around the U.S. and the world. First, as the urban fringe continues to climb higher into the surrounding foothills and mountains, the potential loss of life and property from geological hazards such as debris flows will escalate. Secondly, the delivery of fine-grained sediment from hillslopes is a major contributor to non-point source pollution. As population centers expand, the issue of water quality for both human consumption and riverine ecosystems will only increase through time. Finally, since dams around the world have their storage capacity reduced by sedimentation, efforts are being made to estimate and increase their useful lifespan. Therefore, because hillslopes are the main source of sediment to rivers, the ability to forecast this sediment loading is critical. The specific problem that we are addressing, then, is: *How does sediment get into channels in a mountainous semi-arid landscape?*

Background

Most of the sediment delivered from hillslopes in semi-arid environments occur during high-magnitude rainfall events and fires (Campbell, 1975; Florsheim et al., 1991; Keller et al., 1997) and the process of shallow landsliding is the primary transport mechanism for sediment issuing from small, steep watersheds (Rice and III, 1971; Scott, 1971). Research from northern California and the Pacific Northwest has identified colluvial hollows (unchanneled topographic lows on hillslopes) as the primary zone of shallow landslides (e.g. (Reneau et al., 1990). This work has led to the hypothesis that chronic erosional processes move sediment from adjacent hillslopes into colluvial hollows over hundreds to thousands of years, as well as contributing some sediment directly to channels. As the soil in a hollow thickens over time, it becomes increasingly susceptible to failure, and may fail during heavy rainfall. The colluvial hollow then begins filling up again (Figure 1a, b) and the cycle repeats itself (Dietrich and Dunne, 1978). Changes in land use, climate, and fire regime can affect the recurrence interval of evacuation by altering the rates of the various processes that fill the colluvial hollow, by changing the factors that anchor the soil (i.e. vegetation) (Rice and III, 1971; Terwilliger and Waldron, 1991), or by modifying the hillslope's hydrological response (Campbell, 1975).

In addition to shallow landslides, transport processes amplified by fire are also important contributors to sediment production in this type of landscape. Dry ravel, the downslope movement of granular material by rolling and sliding, can also deliver large amounts of sediment when plant litter that traps sediment is burnt, releasing a pulse of particles downslope. This process has been observed to fill entire channels with debris (Florsheim et al., 1991). Further, in certain types of vegetation such as sage and chaparral, the burning of the plants volatilizes waxy organic molecules that condenses near the soil surface (DeBano, 1981). This hydrophobic layer inhibits the infiltration of rainwater, increasing surface runoff and associated sediment transport.

OBJECTIVES

Understanding and predicting sediment delivery throughout a watershed and under various land-use and climatic scenarios requires both extensive fieldwork and computer modeling. Our objectives, therefore, were two-fold. First, we needed to develop and calibrate equations for the three types of processes that transport sediment down hillslopes: soil creep, overland flow, and landslides. This was accomplished through field projects such as rainfall simulation experiments and the installation of sediment traps.

Our second objective was to incorporate these equations into a computer model that would allow us to spatially and temporally 'scale-up' our field results so that we could ask questions such as: *Does conversion of coastal sage scrub to exotic grasses increase sediment production?*

PROCEDURES

Fieldwork

The fieldwork was conducted at Sedgwick Reserve, a recent addition to the U.C. Natural Reserve System. The Sedgwick Reserve landscape is typical of the region with gentle to steep hillslopes vegetated by exotic annual grasses or coastal sage scrub. Because the rates and processes of sediment transport differ by vegetation type, each of the three types of processes was studied in both grass and sage.

In the grass, the dominant soil creep process is bioturbation by pocket gophers. Rates of sediment transport for bioturbation were estimated by measuring the volumes of gopher mounds, the spatial density of mounds, and the distance from the burrow to the mound (Gabet, 2000). In agreement with current theory on soil creep processes, we found that the sediment flux (q_s, $m^3\ m^{-1}\ y^{-1}$) from gopher bioturbation is solely dependent on the hillslope gradient (dz/dx) so that

$$q_s = 0.18\left(\frac{dz}{dx}\right)^3 - 0.19\left(\frac{dz}{dx}\right)^2 + 0.07\left(\frac{dz}{dx}\right) + 0.03\left(\frac{dz}{dx}\right)^{0.4} \qquad (1).$$

The dominant creep process in the coastal sage scrub is dry ravel. To investigate this process, we installed sediment traps on hillslopes to measure rates of sediment transport (Gabet and Dunne, 2002b). Since fire can amplify dry ravel rates, traps were also set out on several hillslopes in anticipation of a prescribed burn. We found that, similar to the bioturbation, the sediment flux from dry ravel is solely dependent on hillslope angle (θ) so that

$$q_s = \frac{\kappa}{\mu \cos\theta - \sin\theta} \qquad (2)$$

where κ and μ are empirically-derived coefficients. The values for κ ($m^3\ m^{-1}\ yr^{-1}$) are 2.3 x 10^{-5} and 4.1 x 10^{-7} for background and post-fire rates, respectively. The value for μ, a friction coefficient, is 0.87.

To study the generation of overland flow and associated sediment transport, we built a mobile rainfall simulator that is capable of applying rainfall over a 15-m^2 plot. Sixty rainfall simulations were performed on plots varying by vegetation and gradient. A series of simulations were also done on coastal sage hillslopes that had been burnt in a prescribed fire and on plots that had undergone simulated cattle trampling. From these experiments, we found that, under normal conditions, the infiltration capacities are high enough in the sage to prevent any overland flow. However, with light trampling, the infiltration capacities were dramatically reduced, thus causing surface runoff and associated sediment transport (Fierer and Gabet, 2002). Other experiments and field observations demonstrated that fire, by creating a hydrophobic layer, causes decreases in infiltration that lead to the generation of thin debris flows (Gabet, 2002).

Rainfall simulations on grassland slopes revealed that overland flow could occasionally be generated under normal conditions, however the amount of sediment transported was found to be minimal due to the shielding effects of the vegetation and the flow itself (Gabet and Dunne, 2002c). Calculations based on these results indicate that, over a year, the sediment transported by overland flow in the grass is about 1000 times less than by bioturbation.

Finally, we were fortunate that our field site was in the path of a severe storm during the 1997-98 El Niño. In one evening, over 150 shallow landslides were triggered in a 10-km^2 area. This gave us the opportunity to map and survey the landslides to determine the volumes of sediment delivered to the valleys. In the coastal sage, we estimated a specific volumetric flux of 2.8 x 10^{-2} m^3 per unit width of slope for this event compared to 1.7 x 10^{-2} m^3 per unit width of slope in the grasslands. Additionally, we were able to conduct a detailed analysis of the failure mechanics which motivated us to derive a novel stability analysis equation for shallow landslides:

$$FS = \frac{C_s\left(w + \frac{2z\cos\theta}{\sin\alpha}\right) + C_{rl}\left(\frac{2z_{rd}\cos\theta}{\sin\alpha}\right) + wz\left(\gamma_s - m\gamma_w\right)\cos^2\theta\tan\phi}{wz\gamma_s\cos\theta\sin\theta} \qquad (3)$$

where C_{rl} = cohesion due to lateral root reinforcement (kPa)
C_s = soil cohesion (kPa)
m = fraction of the soil column that is saturated
w = failure width (m)
z = soil depth measured vertically (m)
z_{rd} = rooting depth measured vertically (m)
α = angle of side-scarp (°)
γ_w = unit weight of water (kN m^{-3})
γ_s = unit weight of wet soil (kN m^{-3})
θ = hillslope angle (°)
ϕ = internal angle of friction (º).

Equation (3) accounts for lateral root reinforcement along the edges of the failing soil mass and establishes a physical relationship between the width of the failure and the hillslope angle (Gabet and Dunne, 2002a). The volume of a landslide can then be predicted as the product of the soil depth (*z*) and failure width (*w*) from Equation (3) and an average length/width ratio determined from the field surveys.

Computer modeling

The sediment transport equations developed from the fieldwork were incorporated into a computer model written in C (Figure 2). The model uses a portion of Sedgwick Reserve as its topographic template and is driven by rainstorms and fires. The characteristics for each rainstorm (i.e. 1-hr rainfall intensities and storm duration) are randomly selected from exponential probability distribution functions based on historical records (Eagleson, 1972). Similarly, the size of each fire is chosen from a exponential probability distribution and the likelihood of fire ignition at any spot in the landscape is dependent on the elapsed time since the last fire.

When a rainstorm is imposed onto the model space, the rainfall is partitioned into surface and subsurface flow. Because the rainfall simulations demonstrated that the amount of sediment transported by overland flow is negligible, this process is not accounted for in the model. Subsurface flow is routed to calculate the level of soil saturation for the stability analysis (Equation 3) that triggers shallow landslides. When a fire is imposed, several different processes occur, including a pulse of sediment from dry ravel (Equation 2) and a decrease in the infiltration capacity to simulate the creation of a hydrophobic layer.

Sediment flux by bioturbation and background dry ravel are determined as annual rates (Equations 1, 2). The output of the model is a yearly prediction of the mass of sediment delivered from the hillslopes. Climate, fire regime, and vegetation type are specified before each model run. Additionally, any changes in these parameters during the model run may also be specified.

RESULTS

In Southern California and throughout the Southwest, the native scrub vegetation is often cleared and replaced by exotic grasses for grazing animals. This engenders changes such as a decrease in root strength, a different response to fire by the soil, and different habitat use by the fauna. Figure 3 presents the results from a model simulation designed to investigate the effect of vegetation conversion on sediment delivery from a 2.1 km^2 watershed. The first 2000 years of the simulation predicts the annual sediment delivery under coastal sage scrub. At year 2000, the vegetation is converted to grassland and the model is run for another 1000 years.

Three important differences in sediment delivery between the coastal sage and the grasslands can be observed in the results (Figure 3). First, the soil creep in the grassland is approximately 10 times greater than in the sage (these values form the baseline yield). This attests to the affect of changes in the faunal community caused by vegetation change because pocket gophers do not live in the sage. Second, sediment delivery events (i.e. values above the baseline) are smaller but occur more frequently in the grasslands than in the sage. In the sage, large pulses of sediment occur during and immediately after a fire from dry ravel and thin debris flows. In contrast, grasslands are relatively insensitive to fires. Indeed, the only sediment transport process in the grass that might be affected by fire is shallow landsliding and, since grass roots only provide a small amount of soil reinforcement, the loss of root strength after a fire has little effect. Further, the rapid regrowth of grass after a fire would prevent any significant soil loss by overland flow. Sediment delivery events in the grasslands, then, are solely by shallow landslides, which occur more frequently because of the weaker root strengths and the accelerated rate of hollow-filling from bioturbation. Finally, these results can be used to compare the average rate of soil erosion under each vegetation type: 0.4 mm yr^{-1} and 1.1 mm yr^{-1} for the sage and grasslands, respectively. These values suggest a nearly 3-fold increase in soil erosion under grasslands, despite the smaller sediment delivery events. These values may also be used to test the model. For example, from the sedimentation records of a nearby reservoir that drains a sage-scrub watershed similar to Sedgwick Reserve (albeit slightly steeper), we calculate a soil erosion rate of 0.6 mm yr^{-1}. We have not yet found an appropriate data source for testing the ‘grassland’ rate.

The model also predicts a spike in landslide frequency as a result of vegetation conversion (Figure 4). This is due to a decrease in the prevailing root strength as the deep-rooted sage is replaced by shallow-rooted grasses. The model prediction agrees well with observations made at Sedgwick Reserve after the 1997-98 El Niño. We found that there were nearly twice as many shallow landslides in the grasslands as in the coastal sage (Gabet and Dunne, 2002a). This landscape response to type conversion has been noted elsewhere (e.g. (Corbett and Rice, 1966; Rice et al., 1969) and is likely a common occurrence whenever root strengths are diminished over a large area.

CONCLUSIONS

This investigation has shed light on watershed-scale sediment delivery as well as on individual hillslope transport processes. From a theoretical standpoint, the transport equations developed for bioturbation and dry ravel are important contributions because, in the past, few attempts had been made to calibrate slope-dependent sediment flux equations. The rainfall simulations in the coastal sage demonstrated the importance of the biotic crust on the partitioning of rainfall between surface and subsurface flow. In the grasslands, the rainfall experiments allowed us to investigate the role of vegetation cover and flow depths in attenuating the detachment of soil particles by raindrop impact. Further, the fortuitous timing of the most recent El Niño event gave us the opportunity to study the failure mechanics of shallow landslides and motivated us to derive a novel 2-dimensional stability analysis.

The equations developed from the fieldwork were incorporated into a computer model to predict the annual delivery of sediment from a watershed. The model, driven by a stochastic climate generator, was used to investigate the effect of converting scrub vegetation to grasslands. The model makes several predictions that should be useful to land managers concerned with issues such as reservoir sedimentation, riverine ecosystems, and natural hazards. First, the reduction of the prevailing root strength will lead to a spike in landslide frequency. Second, the rates of soil creep will increase dramatically because the grasslands are much more hospitable to burrowing mammals. Third, sediment delivery events in the grasslands will occur more frequently than in the sage but the peaks will be significantly attenuated because of the relative insensitivity to fire of the grassland transport processes.

In conclusion, this study has successfully blended basic fieldwork with computer modeling to produce results that are useful to those interested in fundamental transport processes as well as those in positions to make rational land-use decisions.

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