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RUNOFF SEDIMENT PARTICLE SIZES ASSOCIATED WITH SOIL EROSION IN THE LAKE TAHOE BASIN, USA

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ABSTRACT

Runoff sediment from disturbed soils in the Lake Tahoe Basin has resulted in light scattering, accumulation of nutrients, and subsequent loss in lake clarity. Little quantified information about erosion rates and runoff particle-size distributions (PSDs) exists for determining stream and lake loading associated with land management. Building on previous studies using rainfall simulation (RS) techniques for quantifying infiltration, runoff, and erosion rates, we determine the dependence and significance of runoff sediment PSDs and sediment yield (SY, or erodibility) on slope and compare these relationships between erosion control treatments (e.g., mulch covers, compost, or woodchip incorporation, plantings) with bare and undisturbed, or 'native' forest soils. We used simulated rainfall rates of 60–100 mm h^{-1} applied over replicated 0·64 m^2 plots. Measured parameters included time to runoff (s), infiltration and runoff rates (mm h^{-1}), SY (g mm^{-1} runoff), and average sediment concentration (SC, g L^{-1}) as well as PSDs in runoff samples. In terms of significant relationships, granitic soils had larger particle sizes than volcanic soils in bulk soil and runoff samples. Consequently, runoff rates, SCs, and SYs were greater from bare volcanic as compared to that from bare granitic soils at similar slopes. Generally, runoff rates increased with increasing slope on bare soils, while infiltration rates decreased. Similarly, SY increased with slope for both soil types, though SYs from volcanic soils are three to four times larger than that from granitic soils. As SY increased, smaller particle sizes are observed in runoff for all soil conditions and particle sizes decreased with increasing slope. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: rainfall simulation; grass revegetation; sub-alpine environment; semi-arid; sediment source control

INTRODUCTION

Lake Tahoe is known for its great depth and clarity, set in the beautiful surroundings of the Sierra-Nevada and Carson Mountain Ranges, while straddling the states of California and Nevada (Schuster and Grismer, 2004). Fascination with this unique place has led to long-term monitoring data focused on the water quality and water clarity. Sediment and nutrient loading to Lake Tahoe has been indirectly measured every 12 days in at least three lake locations since July 1967 by Secchi disk (Jassby *et al*., 1999, 2000). During the past 40 years, Lake Tahoe clarity has steadily declined from approximately 30 to 20 m from inputs of suspended sediment that physically scatters light and nutrients causing algae growth. Periodic improvement in lake clarity occurs during low runoff (snowmelt) years.

Loss of clarity and tripling of algal primary productivity indicates onset of cultural eutrophication. Recently, there is an increased focus on sediment source control including on-site retention within the drainages from which they originate. Suspended particulate matter as opposed to dissolved organic matter was identified as the particulates responsible for the lake's clarity decline. Particles less than 8 μm are responsible for 85 per cent of light scattering inorganic particles in Lake Tahoe (Swift *et al*., 2006). Because small particles have a greater particle per mass ratio than large particles they are much more effective at light scattering. Therefore, small particles (<8 μm)

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have a 'higher scattering efficiency'. Fine particles are not only efficient at light scattering, but also at transporting attached nutrients. Due to the long suspension residence time in the lake of these fine particles, their high scattering efficiency, and their ability to transport attached nutrients that promote algal growth, it is imperative that fine sediment sources are managed. Schuster and Grismer (2004) identified four methods to slow or reverse lake eutrophication: control the influx of sediment and nutrients, decrease algal populations, limit sunlight available to the algae, control the nutrient distribution within the lake. The only one of those methods thought possible for Lake Tahoe, is controlling the nutrient and sediment inflow.

Using GIS assessment methods, Maholland (2002) evaluated the mixed granitic and volcanic soils environment of the Squaw Creek watershed northwest of Lake Tahoe, and found that forest roads and ski runs subject to hillslope rilling were the greatest sources of sediment. Unfortunately, despite years of work, little quantitative information exists about the performance of roadcut or hillslope erosion control measures employed in the basin from which comparative evaluations can be made. On the other hand, there are several visible examples of erosion control failures in this semi-arid, high-altitude environment especially along roadcut and ski run areas.

PREVIOUS WORK

Most literature related to erosion control involves agricultural activities and relatively humid environments and there are few scientific field evaluations of revegetation/restoration erosion control efforts in semi-arid, sub-alpine environments. What information that is available is often limited to the 'gray' literature of 'white' papers from agencies, or professional societies. For example, in the Tahoe Basin erosion control work is not new; White[Q4] and Franks (1978) documented the near 99 per cent destruction of stream benthic communities from excessive sediment discharge following development of the Rubicon Properties on the west shore of the lake. Their important 'demonstration' study of various erosion control nettings at Rubicon and Northstar-at-Tahoe was 'largely ... ignored in the erosion control literature' (Sutherland, 1998[Q5]). Their study lacked scientific rigor, but was a model study of rarely seen cooperation between agencies in limiting erosion in the basin. Examples of other studies available from societies that are relevant to erosion in the Tahoe Basin include those conducted by Fifield[Q6] *et al.* (1988) in the basin and by Fifield *et al.* (1989), Fifield and Malnor (1990), and Fifield (1992a, 1992b) in western Colorado.

Ellis (2006) reviews rainfall simulation (RS) methods and studies in the Tahoe Basin that were used in an attempt to standardize evaluation of erosion control measures through replicated rainfall events of the same intensity, or kinetic energy on multiple test plots. Grismer and Hogan (2004, 2005a, 2005b) employed the RS on disturbed roadcut and ski run granitic and volcanic soils in the Tahoe Basin to evaluate slope, cover, and surface roughness effects on infiltration and runoff rates and runoff sediment concentration (SC) and sediment yield (SY). They determined that plot micro-topography or roughness and cross-slope had no effect on runoff SCs or SYs. Grismer and Hogan (2004) found that runoff rates, SCs, and SYs were greater from volcanic soils as compared to that from granitic soils for nearly all cover conditions. RS measured runoff rates and SYs from the bare soils were significantly correlated with downslope. SYs from bare granitic soils at slopes of 28 to 78 per cent ranged from ~1 to 12 $g\,m^{-2}\,mm^{-1}$ of runoff, respectively, while from bare volcanic soils at slopes of 22–61 per cent ranged from ~3 to 31 $g\,m^{-2}\,mm^{-1}$, respectively (Grismer and Hogan, 2005a). Further, volcanic ski run soils and both types of road cut soils exhibited nearly an order of magnitude greater SY than that from the corresponding 'native', relatively undisturbed sites. Similarly, the granitic ski run soils produced nearly four times greater SC than the native areas. Revegetation, or application of pine needle mulch (PNM) covers to both soil types decreased SCs and SYs by 30–50 per cent. Soil restoration through incorporation of woodchips, or tillage and use of amendments (e.g., Biosol®, compost) and mulch covers together with plant seeding resulted in little, or no runoff (SY) from either soil regardless of rainfall intensity.

In a preliminary study, Grismer and Ellis (2006) examined the particle-size distributions (PSDs) associated with runoff sediment from the RS studies begun by Grismer and Hogan (2004). Not surprisingly, they found that granitic soils generally had larger particle sizes than volcanic soils in bulk soil and runoff samples. Similarly, as found previously runoff rates, SCs, and SYs were greater from volcanic as compared to that from granitic soils at the same

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slope. SY generally increased with slope for both soil types. Their analysis of trends lacked statistical rigor and comparisons that include more widely accepted parameters such as stream power and erodibility (K_i = SY/rainfall intensity). Moreover, with respect to lake clarity/quality concerns, more study is required to establish preliminary results such as increasing runoff particle sizes with decreasing slope.

PROJECT OBJECTIVES

The overall project objectives included evaluation of the runoff rates and SYs associated with bare and treated roadcut and ski run soils as well as undisturbed (native forest) of the Tahoe Basin in the context of the physical processes ascribed to particle detachment and transport. In addition, it is imperative to gain an understanding of the factors controlling PSDs in runoff as affected by soil type and treatment (TSC, 2007). While there are a wide variety of disturbed soil erosion control 'treatments' in the basin, they can be broadly categorized (Grismer and Hogan, 2005b) as surface treatments (e.g., hydro-seeded grasses, straw, or mulch covers), or soil restoration treatments (e.g., tillage, incorporation of woodchips, compost combined with mulch covers). This paper focuses on the determination of the significant relationships between runoff SC and SY, runoff rate and slope, and sediment PSD and slope for bare, 'treated' disturbed and native volcanic and granitic soils.

METHODOLOGY

Detailed descriptions of the RS methodology used here are provided by Battany and Grismer (2000) and Grismer and Hogan (2004). The RS consists of a needle tank, tower assembly, and associated plumbing hardware necessary to obtain the steady rainfall intensity desired. Following a preliminary land survey of a site and establishment of plots and installation of the metal plot frame (0·8 m × 0·8 m), the RS is centered over the frame and leveled. Rainfall is allowed to continue until either steady runoff is obtained, or ~60 min have elapsed. Following field measurements, collected runoff samples are taken to the laboratory for filtration and analyses. Samples were vacuum filtered first through a Whatman #541 filter followed by a 0·45 μm filter. Split samples were analyzed directly for PSDs using the laser (Coulter) counting method described by Eshel *et al.* (2004). The filter papers with sediment were dried at 105°C weighed and total sediment mass per volume of runoff was determined. SY was determined as the slope of the linear regression (R^2 values ranged from 0·90 to 0·98) between cumulative runoff sediment and cumulative runoff. SC in runoff was taken as the average of the last two to four individual SCs determined after infiltration/runoff rates stabilized.

RS test results used for this study (for precise locations see Grismer and Hogan, 2005b or Ellis, 2006) were conducted at Northstar-at-Tahoe, Juniper Mountain, and Truckee highway interchanges on the north shore of the lake (volcanic soils), in a forest mastication test site near Tahoma on the west shore, and at Heavenly Mountain Resort and State Highway 89 roadcuts on the south shore of the lake (granitic soils). At each site, RS tests were conducted on three to six plots per treatment and slope depending on the relative consistency in measured values from plot to plot at similar slopes. Slope and soil type are taken as the independent variables while SY and particle-size fraction are the response variables as affected by plot treatment (bare, treated, or native). Here, we consider particular particle-size fractions that represent the particle sizes associated with <10, 30, 60, and 90 per cent of the total sample, or D_{10}, D_{30}, D_{60}, and D_{90}, respectively.

The test plot results from each soil type were broadly categorized as summarized in Table I for subsequent statistical analyses following the observations of Grismer and Hogan (2005b). Bulk soil samples were grouped into three classes based on their location and soil survey descriptions. Volcanic soils were located on the north side of the lake and granitics on the south side. One location, in Tahoma on the west shore is considered a mixed volcanic-granitic soil, as there is volcanic soil deposition over a granitic soil base. Particle-size class differences were determined using the Tukey Standardized Range Test with an alpha of 0·05 for the bulk soil samples.

The overall statistical analysis of independent and dependent variables became quite complex due to the unbalanced design of the project and lack of true treatment replication at some test plot locations. Beginning with a large model using the full data set, the insignificant interactions and variables were removed from the model,

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Table I. Treatment groupings and titles used in regression analyses

	Treatment groupings				
	Grass	PNM combos	Woodchip combos	Fine organic cover	Coarse mulch
Treatments in each grouping	Grass Reveg.	Grass, PNM Seed, plants, PNM Amendments, plants, PNM Amendments, PNM	Woodchips Woodchips, biosol Woodchips, PNM	Compost Compost, PNM Biosol Biosol, compost	Hydromulch Straw

therefore designating them as part of the error term in the overall ANOVA. Model independent variables include soil type, location, treatment, plot, and bottle, with slope and SC as covariates. Despite manipulations such as winsorization and weighting of the data, this total data set did not satisfy basic ANOVA assumptions. As such, following Cottingham *et al.* (2005) we use regression analyses and calculated F and p-values to determine the significance of relationships between slope, runoff rate or stream power and the response variables rather than ANOVA because we have measurements across a gradient (slope) and obvious differences resulting from soil type and treatment. Table II summarizes the parameters, regression analyses, and rationale conducted here. The analysis focused on the finer particle sizes ($<8\ \mu m$, D_{10}, D_{30}, per cent clay and per cent silt) due to their impact on lake clarity from their light refracting properties and suspension times and because there is greater variability found in the larger particle-size classes (i.e., per cent sand, D_{60}, and D_{90}). Due to the small sample volumes used for laser particle-size analyses, a few larger particles can skew the results of these large size classes.

RESULTS AND DISCUSSION

As soil texture determines the particles available for erosive transport, we begin with an analysis of the PSDs of the three major soil types encountered in this study. Building on the previous study by Grismer and Hogan (2005a), we next establish the relationship between SC and SY and then consider the effects of runoff rate on SY (or SC) for bare soils. As a result of gravitational forces, infiltration and runoff rates conceptually depend in part on soil slopes, other factors being equal, so we examine this relationship next. Since stream power is the product of runoff rate and slope, we then consider these relationships between SY (or SC) and plot slope followed by that for stream power. Finally, the focus of this study of the relationships between runoff rates (slopes or stream power) and runoff PSDs and SYs is considered.

Soil textures at each location determine the range and availability of particle sizes for possible erosion. Based on the Coulter laser analysis, the soils considered here range from sands to loams and include: sand, sandy loam, loamy-sand, and loam by classification (Table III). Volcanic soils were predominantly sandy loams, while soils formed from granitic materials were almost exclusively sand. The Tahoma soil site was between the sandy loam and loamy-sand textures reflecting its mixed origin. Mean volcanic particle-size ranges are significantly lower than the granitics for all classes except D_{90}. The Tahoma mixed soil sizes were most similar to that of the volcanics, but typically fell between the granitics and volcanics. When prioritizing where restoration efforts should be directed, these results suggest it is most critical for volcanic slopes to be stabilized due to their larger proportion of fine particles in the $<8\ \mu m$ range.

SC or SY are essentially equivalent measures of erodibility (K_i) as used by in the WEPP modeling of hillslope erosion (Flanagan *et al*., 1995). In fact, as nearly all RS test plots received the same rainfall intensity (i), interrill erodibility is proportional to SY, that is $K_i = \mathrm{SY}/i$. Conceptually for bare or untreated soils, erodibility is only soil dependent, however erosion rate also depends on slope (S) and runoff rate (q_R) or stream power ($P = Sq_R$); some have suggested that soil detachment is better described by power forms of P in which S and q_R are raised to powers of approximately 2 and 1·3, respectively (Zhang *et al*., 2002, 2003). Here, we consider the effects of q_R (or

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Table II. List of parameters, definitions, and regressions analyses considered here

Parameter	Definition	Compared to	Definition	Description
SY	Least-squares regression of cumulative sediment with cumulative runoff ($g\,m^{-2}\,mm^{-1}$)	SC	Grams of sediment per liter of runoff ($g\,L^{-1}$)	To test correlation between SY and SC enabling use interchangeably
Runoff rate (q_R)	Steady runoff rate from a plot ($mm\,h^{-1}$)	SY and SC	See above	To explore the transport capacity of the runoff on different soils and treatments
Infiltration rate	Steady infiltration rate in a plot ($mm\,h^{-1}$)	Slope (S)	Downslope per cent of the individual plots	To explore effects of different soils and treatments on infiltration rates
Slope	Downslope per cent of the individual plots	q_R	Steady runoff rate from a plot ($mm\,h^{-1}$)	To test slope effects on runoff rates
Slope	Downslope per cent of the individual plots	SC	Grams of sediment per liter of runoff ($g\,L^{-1}$)	To determine if steeper slopes result in greater sediment transport
Slope	Downslope per cent of the individual plots	SY	Least-squares regression of cumulative sediment with cumulative runoff ($g\,m^{-2}\,mm^{-1}$)	To determine if steeper slopes result in greater sediment transport
Stream power (P)	Product of slope and runoff rate of the individual plots	SY	Least-squares regression of cumulative sediment with cumulative runoff ($g\,m^{-2}\,mm^{-1}$)	To determine if greater stream power results in greater sediment transport
Slope	Downslope per cent of the individual plots	D_{10}	Parameter defining diameter where 10 per cent of the particles in the sample are finer than the D_{10} (μm)	Considers runoff sediment composition with slope in terms of the smallest 10 per cent of the particles
Slope	Downslope per cent of the individual plots	D_{30}	Parameter defining diameter where 30 per cent of the particles in the sample are finer than the D_{30} (μm)	Considers runoff sediment composition with slope in terms of the smallest 30 per cent of the particles
Slope	Downslope per cent of the individual plots	Clay	Percent of particles in the sample that are $<2\,\mu m$	Compares the finest class of particles with slope
Slope	Downslope per cent of the individual plots	Silt	Percent of particles in the sample that fall in the 2–50 μm range	Compares the mid-size class of particles with slope
Slope	Downslope per cent of the individual plots	$<8\,\mu m$	Percent of particles in the sample that are $<8\,\mu m$	Considers variability in suspended particles of interest with slope
Soil D_{10}	D_{10} of the soil sample corresponding with a particular site	Runoff D_{10}	Average D_{10} from all test plot runoff	Compares the particle sizes in the soil with that of the runoff for the finest 10 per cent in the sample
Soil D_{30}	D_{30} of a soil sample corresponding with a particular site	Runoff D_{30}	Average D_{30} from all test plot runoff	Compares the particle sizes in the soil with that of the runoff for the finest 30 per cent in the sample

(*Continues*)

Table II. (Continued)

Parameter	Definition	Compared to	Definition	Description
Soil clay per cent	Percent clay in the soil sample at a site	Runoff clay per cent	Average per cent clay from all test plot runoff	To determine trends in runoff particle size compared to the *in situ* soil for <2 μm particles
Soil silt per cent	Percent silt in the soil sample at a site	Runoff silt per cent	Average per cent silt from all test plot runoff	To determine trends in runoff particle size compared to the *in situ* soil for 2–50 μm particles
Soil <8 μm per cent	Percent of soil sample particles <8 μm	Runoff <8 μm per cent	Average per cent of particles that are <8 μm from all test plot runoff	Used to determine trends in runoff particle size compared to the *in situ* soil for particles <8 μm

Table III. Summary of PSD measurements for Tahoe Basin disturbed soils (<2·0 mm)

Soil type	n	D_{10} (μm)	D_{30} (μm)	D_{60} (μm)	D_{90} (μm)	Sand (per cent)	Silt (per cent)	Clay (per cent)
Granitics—mean	16	70·4[a]	294·8[a]	785·6[a]	1589[a]	90·7[a]	7·82[a]	1·52[a]
Std dev.		30·2	91·9	146·4	83·5	3·19	2·90	0·55
Volcanics—mean	48	3·98[a]	41·3[a]	390·1[a]	1227[a]	64·9[a]	28·2[a]	6·92[a]
Std dev.		2·06	26·0	175·7	342·9	7·43	4·82	2·97
Tahoma—mean	4	8·67[a]	66·0[a]	297·8[a]	1194[a]	74·0[a]	21·8[a]	4·20[a]
Std dev.		3·06	6·39	54·2	245·6	2·11	1·45	0·85

[a]Mean values followed by different letters differed significantly ($\alpha < 0{\cdot}05$).

infiltration rate) and slope on SY independently after first examining the strength of the correlation between SC and SY for the different soils.

SC and SY correlated well for bare soil and some treatments (Table IV), though on treatment plots SY was significant (>99 per cent) in more relationships. For all bare soils combined, as well as for the individual bare soils (except mixed), the relationships between SC and SY are significant (Figure 1). For the mixed soil, this relationship is close to being significant with a large R^2 value, but the sample size is too small for a conclusive assessment. The SC versus SY relationship is also significant for the remaining treatments tested. As such, SC and SY are used interchangeably here as desired.

Table IV. F and[Q7] p-values for the summary of SC versus SY (non-zero intercepts) Q7

Soil type	Treatment	R^2	n	F	p-value
All	Bare	0·7424	21	54·758	<0·001
Granitic	Bare	0·7778	12	35·005	<0·001
Mixed	Bare	0·9890	3	89·909	0·067
Volcanic	Bare	0·9892	6	366·37	<0·001
All	All excluding bare	0·3932	112	71·279	<0·001

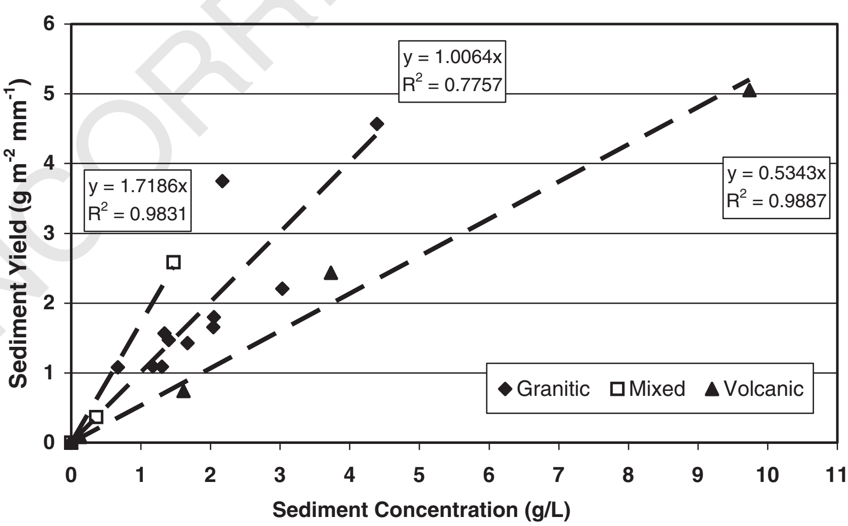

Figure 1. SY versus SC regressions for all bare soils.

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Table V. Regression F and p-values for SY and SC as they depend on q_r for bare soils (non-zero regression intercepts)

Soil type	Comparison	R^2	n	F	p-value
All	q_R versus SY	0·3586	21	10·623	0·004
Granitic	q_R versus SY	0·4262	12	7·428	0·021
Mixed	q_R versus SY	0·8925	3	8·302	0·213
Volcanic	q_R versus SY	0·9425	6	65·565	<0·001
All	q_R versus SC	0·0728	21	1·492	0·237
Granitic	q_R versus SC	0·1926	12	2·385	0·154
Mixed	q_R versus SC	0·9485	3	18·417	0·146
Volcanic	q_R versus SC	0·9071	6	39·057	0·003

Not unexpectedly as noted above in terms of P, SY and to a lesser extent, SC correlated well (>98 per cent) with q_R for the bare soils, again with the exception of the mixed soil (Table V). With the smaller p-values, it is clear that SY is better correlated with q_R than is SC for the bare soil treatment. For both SY and SC, neither relationship is significant for the mixed soil as there was only one site tested though the R^2 and F-values are as large as others in Table V that were found to be significant. As noted by Grismer and Hogan (2005a), SY or SC increased as q_R increased across all soil types and tested slopes (see Figure 2). In the granitic soil plots, runoff rates were greater than those for the volcanics due to greater rainfall intensities required to initiate runoff, and the regression slope is much smaller. Tests on volcanic soils usually resulted in a smaller q_R, though their SYs are among the largest. More readily transported fine particles are more abundant in the volcanic soils.

Slope effects on q_R and SY (or SC) were surprisingly difficult to characterize, though Grismer and Hogan (2005a) also obtained mixed results in comparing SY (or SC) to slope, despite the rather direct concept indicating that increased slope will result in greater runoff and erosion rates for a given rainfall intensity on bare soils. Very few of such regression comparisons were found to be significant at >95 per cent (Table VI). Bare soil plot slopes ranged from 15 to 55 per cent and on the granitic plots, counter-intuitively q_R tended to decrease with increasing slope; this

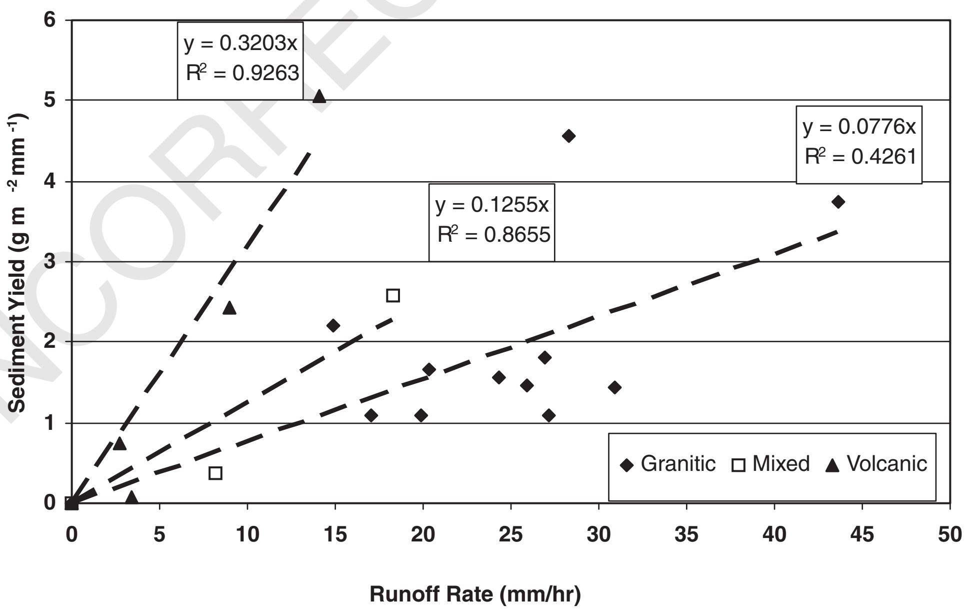

Figure 2. SY versus runoff rates for each bare soil type.

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Table VI. Summary of regression F and p-values for dependence of runoff rate, SC, and SY on bare soil plot slopes

Soil type	Comparison	R^2	n	F	p-value
All	Slope versus q_R	0·014	21	0·266	0·612
Granitic	Slope versus q_R	0·391	12	6·420	0·030[a]
Mixed	Slope versus q_R	0·699	3	2·319	0·370
Volcanic	Slope versus q_R	0·469	6	3·526	0·134
All	Slope versus SC	0·118	21	2·542	0·127
Granitic	Slope versus SC	0·056	12	0·592	0·459
Mixed	Slope versus SC	0·475	3	0·906	0·516
Volcanic	Slope versus SC	0·623	6	6·613	0·062[a]
All	Slope versus SY	0·009	21	0·165	0·689
Granitic	Slope versus SY	0·221	12	2·834	0·123
Mixed	Slope versus SY	0·372	3	0·592	0·583
Volcanic	Slope versus SY	0·631	6	6·834	0·059[A]

[a]Correlations >94 per cent significance.

was the only significant regression for slope relationships on bare soils. In contrast, as expected, q_R increased with plot slopes for the volcanic soils (Figure 3). Similarly, near significant regressions (~94 per cent) and the largest R^2 values between slope and SC or SY occurred for the volcanic soils.

With constant rainfall intensities, steady infiltration rates were expected to decrease with increasing slope as a result of increasing runoff rates. However, the conflicting results of the runoff rate versus slope comparisons, the relationship between infiltration rate and slope was considered. For the granitic soils, significant relationships (>99 per cent) between infiltration rate and slope were only detected when aggregating all the 'treated' plot data (with and without the no-runoff plots) and using inverse infiltration rates (Table VII). No significant relationships were found between infiltration rates and slopes for the granitic bare and native soils. In contrast, no infiltration rate

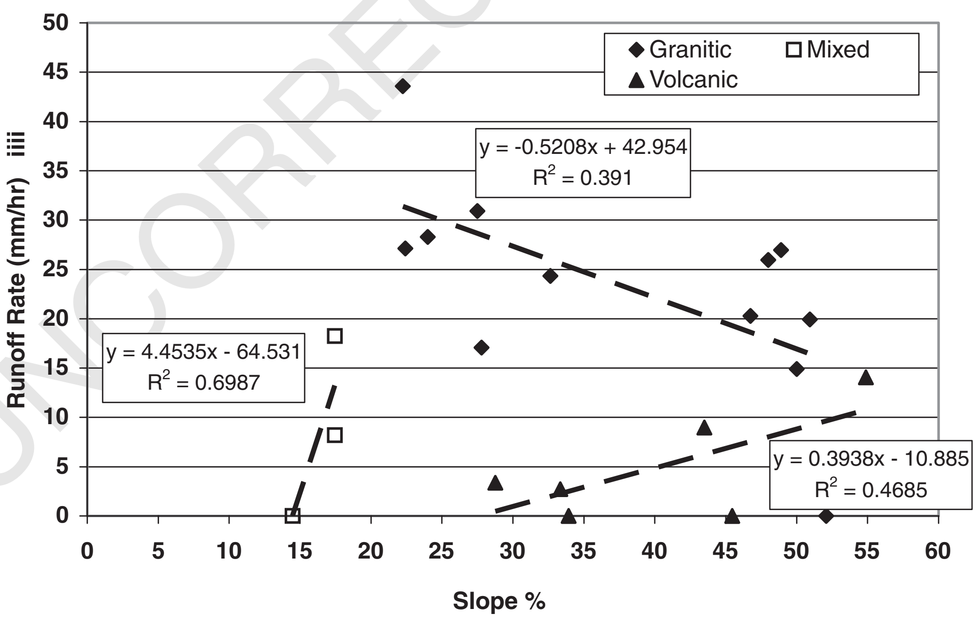

Figure 3. Runoff rate as it depends on slope for all bare plots.

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Table VII. Summary of significant (>99 per cent) regressions for dependence of infiltration rate on plot slopes

Soil	Condition	Comparison	n	R^2	Slope	Intercept	p-value
Granitic	All-treated	Slope versus 1/inf. rate	32	0·747	0·0003	0·0031	<0·0001
	Treated w/runoff	Slope versus 1/inf. rate	15	0·663	0·0004	0·0019	0·0002
Volcanic	All bare	Slope versus inf. rate	6	0·306	−1·053	103·76	0·0116
	Truckee treated	Slope versus inf. rate	7	0·883	−0·149	67·247	0·0017

transform was required for the volcanic bare or Truckee Exit treated soils to obtain significant relationships. The Truckee Exit treated soils were largely freshly surface covered mulches across a range of slopes resulting in the significant relationship. In both cases, infiltration rates decline with increasing slope, but this may require further scrutiny with focused testing for infiltration rates as a function of slope and treatment.

While it appears that for the bare soil plots considered here, slope effects on runoff and erosion rates is small when compared to that of q_R on SY, the product of slope and runoff rate (stream power, P) is expected to have a significant effect; as was in fact observed for bare and PNM covered soils (Table VIII). A linear relationship with a near perfect R^2 between SY and P was observed for the bare volcanic soils while log transforms were required to obtain significant relationships for the granitic soils. That q_R has a greater effect on SY (or SC) has been noted earlier when fitting multivariate power equations to experimental data that result in exponents of approximately two on runoff rate as compared to just greater than one for slope.

Soil and/or cover treatment effects on controlling runoff and erosion rates are the primary design factors employed in limited soil losses from disturbed hillslopes. Runoff rates for some treatments considered here were greater than those from the bare volcanic soil, however, SC and SY values remained lower. Compared to that from bare soils, SYs were lower for all treatments, though there were some large SCs associated with very little runoff. For example, SCs of nearly 20 g L^{-1} resulted from a plot with the fine organic cover treatment and 12 g L^{-1} for a plot with woodchips, but SYs for both were less than 1·0 g m^{-2} mm^{-1} as a result of the minimal runoff. While many treatments resulted in no runoff after 30 or more minutes of rainfall (Table IX), this was rarely observed for the bare

Table VIII. Summary of significant (>99 per cent except granitic bare) regression results for dependence of SY on stream power (P)

Soil type	Treatment	Comparison	R^2	n	Slope	Intercept	p-value
Volcanic	Bare	SY versus P	0·983	4	683·20	−228·29	0·0085
Granitic	Bare	SY versus ln(P)	0·591	6	640·71	−2876·9	0·074
Granitic	PNM combo	SY versus ln(P)	0·751	8	185·79	−371·79	0·0054

Table IX. Summary of non-runoff treatment plot characteristics

Soil type	Treatment	Slope range (per cent)	No-runoff plots (#)
Volcanic	Soil restoration and revegetation	33–80	15
	Grass and PNM covers	24–42	3
	Tilled compost, amendments, and PNM	24–42	17
	Incorporated woodchips	25–56	7
	Natives	35–75	10
Mixed	Grass cover	9–15	3
	Natives	9–15	1
	Surface woodchips	9–15	1
Granitic	Tilled compost, amendments, grass, and PNM	27–35	6

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Table X. Summary of regression F and p-values for dependence of SC and SY on runoff rates from treated and native plots

Soil type	Treatment	Comparison	R^2	n	F	p-value
Volcanic	Coarse mulch	q_R versus SY	0·3838	5	1·869	0·265
Volcanic	Coarse mulch	q_R versus SC	0·2307	5	0·900	0·413
Mixed	Control till	q_R versus SY	0·5065	9	7·184	0·032[a]
Mixed	Control till	q_R versus SC	0·0285	9	0·205	0·664
Mixed	Fine organic cover	q_R versus SY	0·457	27	21·041	<0·0001[a]
Granitic	Fine organic cover	q_R versus SY	0·4685	12	8·815	0·014[a]
Volcanic	Fine organic cover	q_R versus SY	0·4874	15	12·361	0·004[a]
Mixed	Fine organic cover	q_R versus SC	0·0307	27	0·792	0·382
Granitic	Fine organic cover	q_R versus SC	0·9215	12	117·389	<0·0001[a]
Volcanic	Fine organic cover	q_R versus SC	0·3767	15	7·857	0·015[a]
All	Grass	q_R versus SY	0·1991	30	6·961	0·013[a]
Volcanic	Grass	q_R versus SY	0·2467	24	7·205	0·014[a]
All	Grass	q_R versus SC	0·2015	30	7·066	0·013[a]
Volcanic	Grass	q_R versus SC	0·2648	24	7·924	0·010[a]
All	Native	q_R versus SY	0·2557	9	2·405	0·165
Granitic	Native	q_R versus SY	0·015	5	0·046	0·844
All	Native	q_R versus SC	0·4276	9	5·229	0·056
Granitic	Native	q_R versus SC	0·1668	5	0·601	0·495
Mixed	PNM combos	q_R versus SY	0·4151	17	10·645	0·005[a]
Granitic	PNM combos	q_R versus SY	0·0018	9	0·013	0·914
Volcanic	PNM combos	q_R versus SY	0·9332	8	83·820	<0·001[a]
Mixed	PNM combos	q_R versus SC	0·5184	17	16·146	0·001[a]
Granitic	PNM combos	q_R versus SC	0·152	9	1·255	0·300
Volcanic	PNM combos	q_R versus SC	0·064	8	0·410	0·546
All	Woodchip combos	q_R versus SY	0·1091	15	1·592	0·229
All	Woodchip combos	q_R versus SC	0·2473	15	4·271	0·059

[a]Correlations >97 per cent significance.

soils. Unfortunately, while enhanced infiltration with no runoff is beneficial in terms of erosion control, such plot treatments generate no results for statistical analyses. Therefore, in some cases regressions are analyzed for all plots and then without the non-runoff values.

Of particular interest here are the results of regression analyses (Table X) between SY (or SC) and q_R associated with the various erosion control treatments and native soils. Non-significant regressions occur from all of the more intensively treated (e.g., woodchip, compost, or mulch incorporation) or native soils. Significant regressions are found between SY and q_R for the various cover treatments (fine organic matter, grass, or PNM), but in many cases R^2 values are less than 0·50. On volcanic soils, grasses alone as well as light organic or PNM covers result in erosion rates and processes similar to that of the bare soils though at smaller SYs hence the >98 per cent significance of SY, or SC correlation with q_R as found in bare soils.

SYs for most of the other more intensive erosion control treatments were relatively small. For example, in the thick fine organic cover treatment SYs $<0{\cdot}5\,\mathrm{g\,m^{-2}\,mm^{-1}}$, and regressions of the runoff and sediment loads were significant for volcanic and granitic soils together as well as separately. The PNM combined treatments resulted in average q_R and average SCs and SYs of $0{\cdot}5\,\mathrm{g\,L^{-1}}$ and $0{\cdot}5\,\mathrm{g\,m^{-2}\,mm^{-1}}$, respectively. Regression lines best fit the data when both soil types were included in the data set. Runoff occurred from all the granitic soil plots with PNM treatments, ranging from 5 to $20\,\mathrm{mm\,h^{-1}}$, however SYs were within a narrow range of 0·7 and $0{\cdot}95\,\mathrm{g\,m^{-2}\,mm^{-1}}$ resulting in non-significant regressions. Runoff produced from native plots carried little, if any sediment, as in all plots SCs and SYs remained below $0{\cdot}75\,\mathrm{g\,L^{-1}}$ and $0{\cdot}75\,\mathrm{g\,m^{-2}\,mm^{-1}}$, respectively. For native soils, like some other treatments, SY was slightly better correlated with q_R than SC, though neither relationship is significant.

Lake Tahoe clarity is declining as a result of primary production from nutrient input as well as light scattering effects associated with suspension of fine particles in the water column (Swift *et al*., 2006). It is likely, that these same fine particles also transport adsorbed nutrients including dissolved reactive phosphorous, the nutrient

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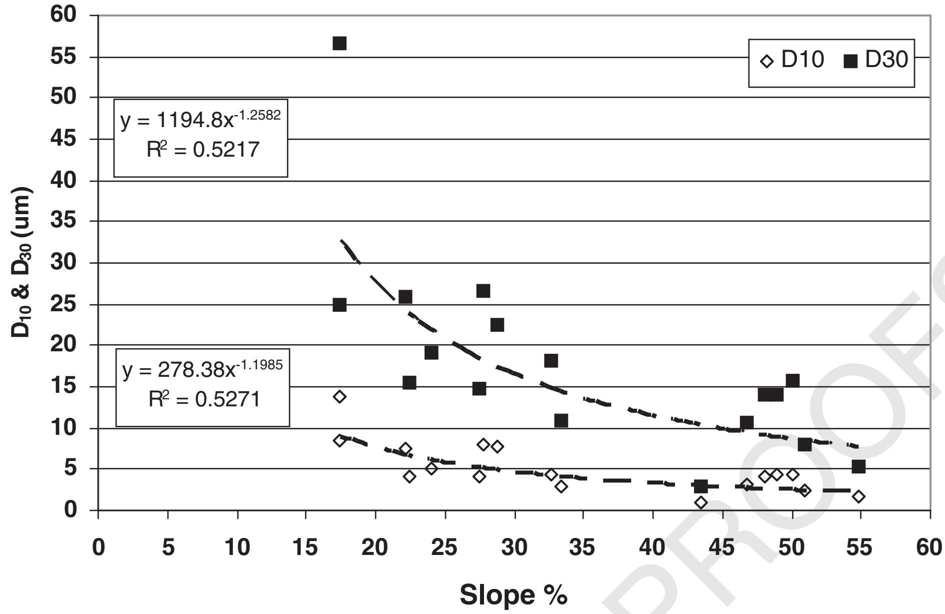

Figure 4. Slope versus D_{10} and D_{30} particle sizes (μm) for all bare soils.

presently limiting algal production in the lake. As suggested by Grismer and Ellis (2006), we found a significant relationship for decreasing D_{10} and D_{30} particle sizes with increasing slopes on bare soils (Figure 4). Interestingly, a log transform of the D_{10} and D_{30} particle-sizes' data improves the R^2 values of the regressions by 0·07–0·08 (Figure 5[Q8]). Similarly, slope effect results in terms of percent silt, clay, and <8 μm particle sizes in the runoff Q8

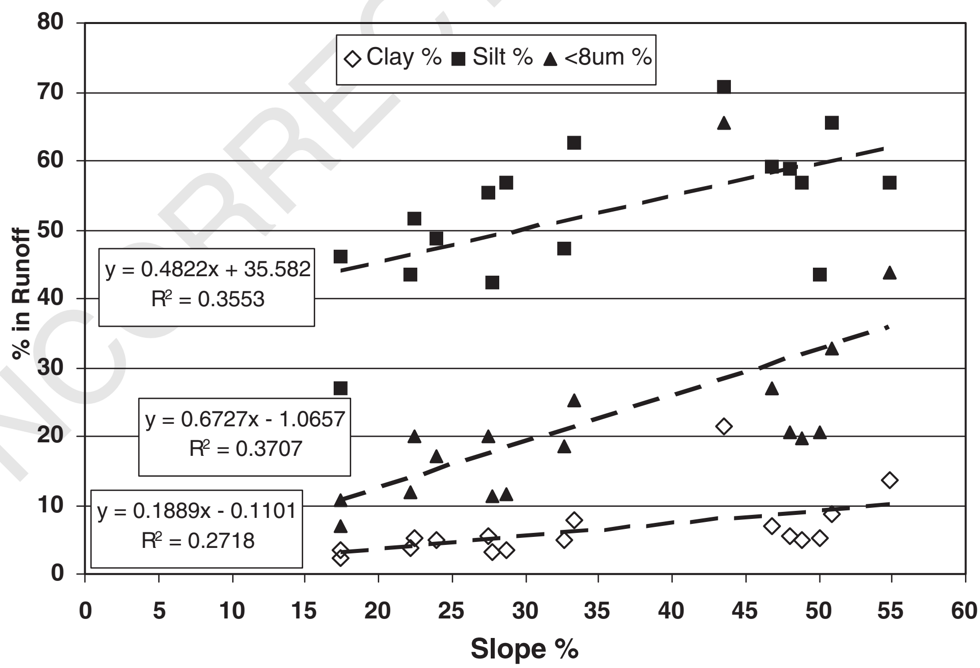

Figure 5. Slope versus per cent clay, per cent silt, and <8 μm for all bare soils.

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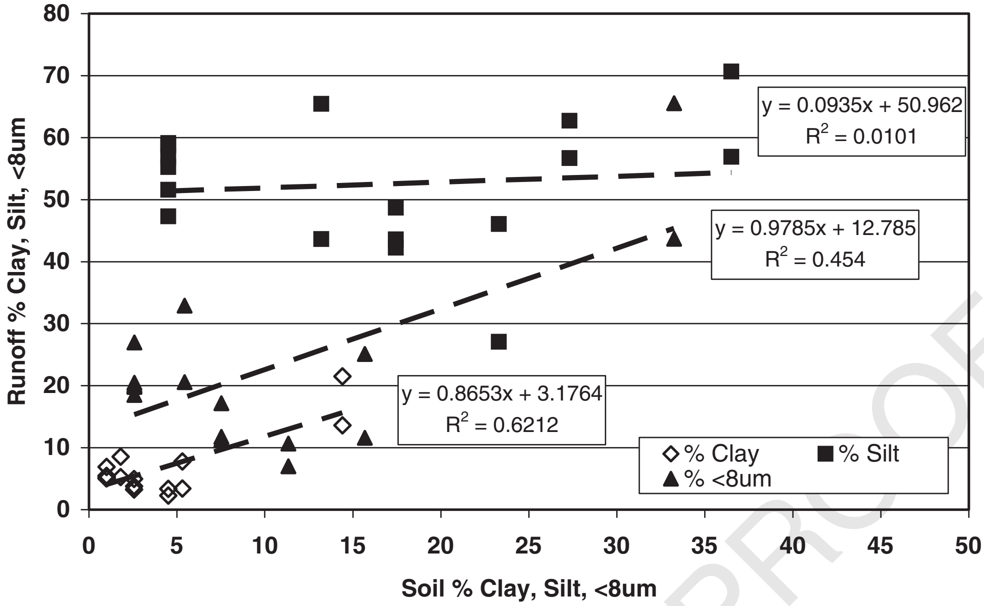

Figure 6. Soil versus runoff particle sizes for all bare soils.

complement the D_{10} and D_{30} trend with these parameter values increasing with greater slopes (Figure 6). Not surprisingly, significant regressions (>95 per cent) were obtained for all particle size versus slope data from all bare plots with runoff considered together (Table XI). Runoff from granitic soils showed significant correlations (>95 per cent) between slope and particle-size classes, with the exception of per cent silt. Runoff from volcanic soils had no significant regressions between slope and particle size. Unlike the SY versus *P* relationships, including q_R with the particle-size regressions did not largely improve the regression statistics, perhaps as a result of the contrasting dependence of q_R on slope between granitic and volcanic soils. Apparently as slopes increase, greater proportions

Table XI. Regression *F* and *p*-values for slope and runoff particle-size comparisons for bare soils

Soil type	Comparison	R^2	*n*	*F*	*p*-value
All	Slope versus D_{10}	0·4957	17	14·7442	0·0016[a]
Granitic	Slope versus D_{10}	0·3506	11	4·8589	0·0550[a]
Volcanic	Slope versus D_{10}	0·5656	4	2·6041	0·2479
All	Slope versus D_{30}	0·4650	17	13·0374	0·0026[a]
Granitic	Slope versus D_{30}	0·4787	11	8·2645	0·0183[a]
volcanic	Slope versus D_{30}	0·6221	4	3·2924	0·2113
All	Slope versus clay per cent	0·2718	17	5·5987	0·0319[a]
Granitic	Slope versus clay per cent	0·3668	11	5·2135	0·0483[a]
Volcanic	Slope versus clay per cent	0·4451	4	1·6043	0·3328
All	Slope versus silt per cent	0·3553	17	8·2666	0·0116[a]
Granitic	Slope versus silt per cent	0·3240	11	4·3136	0·0676
Volcanic	Slope versus silt per cent	0·0015	4	0·0030	0·9613
All	Slope versus <8 μm per cent	0·3707	17	8·8360	0·0095[a]
Granitic	Slope versus <8 μm per cent	0·4509	11	7·3905	0·0237[a]
Volcanic	Slope versus <8 μm per cent	0·4769	4	1·8234	0·3094

[a]Correlations >95 per cent significance.

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of finer sediment comprise runoff sediment, despite the possible expectation of there to be a predominance of larger particles running off at higher slopes due to greater stream power. However, this conclusion warrants further study. Variability naturally occurring from the different soils resulted in D_{10} ranges from 1·59 to 13·88 μm and D_{30} from 2·86 to 56·60 μm across a slope range of 14·5–54·9 per cent.

Comparisons of the PSDs of bulk soil samples with that of the runoff sediment did not lead to many significant regressions, though there were strong and consistent trends found in all soil types and treatments (Ellis, 2006). This may have been a result of aggregating many of the bulk soil samples for a site rather than using analyses of individual plot bulk soil samples. The five values of D_{10}, D_{30}, and per cent clay, per cent silt, and <8 μm in the bulk soil samples were plotted against these same parameters for the tested plots with measurable runoff. Consistently, there were a greater proportion of fine particles in the runoff versus that of the bulk soil. This trend was confirmed by all of the measured parameters with D_{10}s and D_{30}s being smaller and higher percentages of clay, silt, and <8 μm particles in the runoff.

Of the regressions that are significant between the bulk soil and runoff sediment particle sizes, there are no relationships that were consistently significant. For all bare soils, the per cent clay and <8 μm particles were the only significant regressions between runoff and bulk soil sediment (Table XII and Figure 6). In these bare soils, the per cent clay in the runoff versus that of the bulk soil results in a nearly 1:1 regression slope (0·98) though a small positive intercept. Similarly, comparing the <8 μm runoff particle sizes with that of the bulk soil samples, the regression slope is somewhat less (0·87) with a larger positive intercept. In contrast, somewhat surprisingly, there is no relationship or trend between the silt fraction in the runoff and that in the bulk soil.

PSDs in the runoff from the erosion control treatment plots were notably different than that from either bare soil runoff, or bulk soils (Ellis, 2006). It should be noted, however, that there smaller data sets are available for runoff from the erosion treatments. The control till treatment was the only one with three of five significant regressions between the soil and sediment in runoff; they are D_{10}, D_{30}, and per cent silt (Table XIII). Differences between the soil and sediment in runoff are more distinct for this treatment than that from the bare soil as regression slopes are <1·0 for all but the silt-size fraction (Figure 7). While tillage often has the effect of decreasing soil compaction and increasing infiltration rates, the average runoff rate of 25·5 mm h^{-1} for control till is greater than that for the bare soil at 19·7 mm h^{-1}. The runoff sediment is four to five times finer than in the soil based on D_{10} and D_{30} particle-size fractions, though smaller per cent clay and <8 μm particle-size fractions occur in the runoff from the control till plots. Perhaps, tillage is breaking aggregates and increasing the availability of fine particles for detachment and transport.

Table XII. Regression *F* and *p*-values for bulk soil and bare soil runoff particle-size comparisons

Soil type	Comparison	R^2	*n*	*F*	*p*-value
All	Soil D_{10} versus runoff D_{10}	0·0706	17	1·139	0·3026
All	Soil D_{30} versus runoff D_{30}	0·0342	17	0·531	0·4773
All	Soil per cent clay versus runoff per cent clay	0·6212	17	24·599	0·0002[a]
All	Soil per cent silt versus runoff per cent silt	0·0101	17	0·153	0·7011
All	Soil per cent <8 μm versus runoff per cent <8 μm	0·454	17	12·472	0·0030[a]
Granitic	Soil D_{10} versus runoff D_{10}	0·2418	11	2·870	0·1245
Granitic	Soil D_{30} versus runoff D_{30}	0·2381	11	2·812	0·1278
Granitic	Soil per cent clay versus runoff per cent clay	0·1476	11	1·558	0·2434
Granitic	Soil per cent silt versus runoff per cent silt	0·2627	11	3·207	0·1069
Granitic	Soil per cent <8 μm versus runoff per cent <8 μm	0·1817	11	1·998	0·1911
Volcanic	Soil D_{10} versus runoff D_{10}	0·5634	4	2·581	0·2494
Volcanic	Soil D_{30} versus runoff D_{30}	0·691	4	4·473	0·1687
Volcanic	Soil per cent clay versus runoff per cent clay	0·778	4	7·009	0·1180
Volcanic	Soil per cent silt versus runoff per cent silt	0·1281	4	0·294	0·6421
Volcanic	Soil per cent <8 μm versus runoff per cent <8 μm	0·7986	4	7·931	0·1064

[a]Correlations >99 per cent significance.

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Table XIII. Regression F and p-values for bulk (granitic and volcanic) soil and runoff particle-size comparisons from control till and fine organic cover treatments

Treatment	Comparison	R^2	n	F	p-value
Control till	Soil D_{10} versus runoff D_{10}	0·8314	6	19·724	0·0113[a]
Control till	Soil D_{30} versus runoff D_{30}	0·7959	6	15·598	0·0168[a]
Control till	Soil per cent clay versus runoff per cent clay	0·4172	6	2·863	0·1659
Control till	Soil per cent silt versus runoff per cent silt	0·9738	6	148·67	0·0003[a]
Control till	Soil per cent <8um versus runoff per cent <8 μm	0·5034	6	4·055	0·1143
Fine organic cover	Soil D_{10} versus runoff D_{10}	0·6253	6	6·675	0·0611
Fine organic cover	Soil D_{30} versus runoff D_{30}	0·788	6	14·868	0·0182[a]
Fine organic cover	Soil per cent clay versus runoff per cent clay	0·5215	6	4·360	0·1051
Fine organic cover	Soil per cent silt versus runoff per cent silt	0·414	6	2·826	0·1680
Fine organic cover	Soil per cent <8 μm versus runoff per cent <8 μm	0·696	6	9·158	0·0389[a]

[a]Correlations >96 per cent significance.

The last treatment with significant soil to runoff particle-size comparisons is D_{30} and <8 μm particle sizes for fine organic cover on granitic and volcanic soils (Table XIII). Fine organic cover consisted of composts and Biosol (a proprietary 'slow release' amendment). For coarser granitic soils, the D_{10} and D_{30} particle sizes are ten times finer in the runoff than in the bulk soil (Figure 8). The variation between sediment in the runoff and bulk soil is less distinct for the percent size classes, especially for the per cent clay (Figure 9). For the <8 μm percent particle sizes the difference between that in the soil and in the runoff is significant, with approximately 1·5 times more particles in this size class in found in the runoff samples. In both of these treatments, 'excess' fine particles in the runoff may be a result of the application of the surface amendment; though when considered in the overall context of the relationships between slope and PSDs and PSDs and SYs, this result may not be unusual.

While there were few significant relationships between runoff PSDs and that of the bulk soil PSDs, there were similar significant power relationships between PSDs and soil slope or SY regardless of erosion control treatment. Generally, as plot slope (Figure 4 for bare soils and Figures 10 and 11 for all treatments) or SY (Figures 12 and 13)

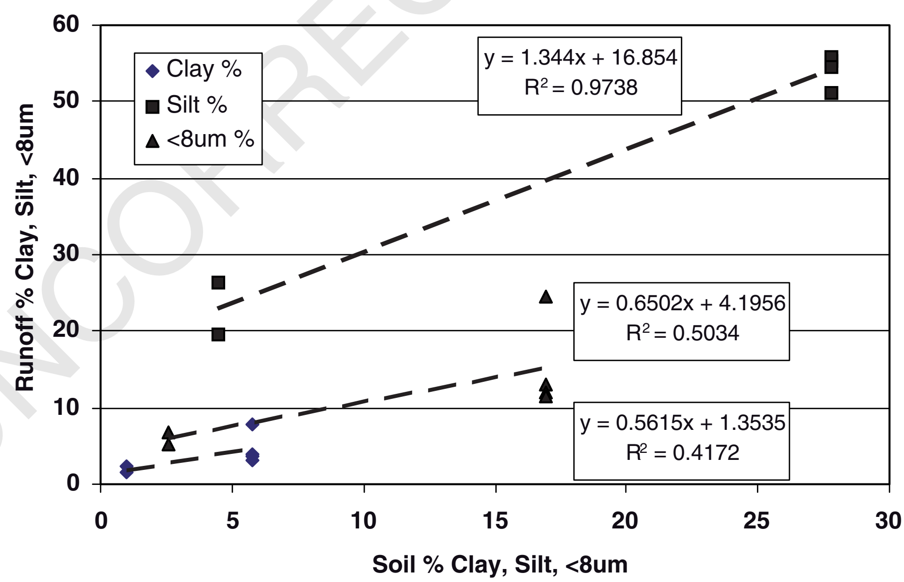

Figure 7. Runoff versus soil per cent clay, per cent silt, and <8 μm particle-size fractions from the control till treatment on granitic and volcanic soils. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

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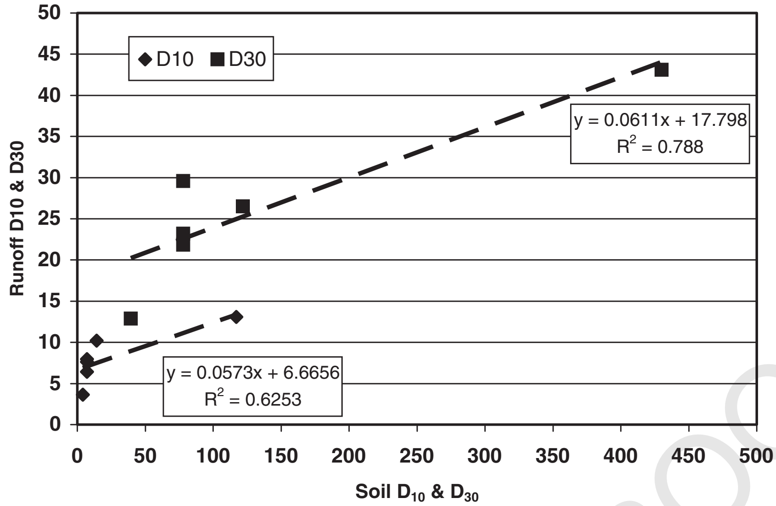

Figure 8. Runoff versus soil D_{10} and D_{30} particle sizes (μm) for granitic and volcanic soils with fine organic cover treatment.

increased, particle sizes decreased regardless of erosion control treatment. [Note scale changes between figures for volcanic and granitic soils; the particle-size scale increases by a factor of two and the SY scale decreases by a factor of three for the granitic soils reflecting the distinct differences in material available for detachment and transport (Table III).] Presumably, finer particle sizes would be expected at the smaller slopes from previously deposited finer particles, but this was not observed here.

SYs (erodibilities) were generally zero or very small for the erosion control soil treatments that involved soil rehabilitation, or restoration of soil hydrologic function. Small SY values were also associated with larger PSDs in runoff reflecting the effects of the soil rehabilitation in changing the soil texture characteristics (Figures 12 and 13). It appears that the mixed soil results (Figures 11 and 13) fit best with the granitic soils data reflecting the granitic soils basis of the Tahoma site. Combining the results shown in Figures 11–14[Q17] may be an approach to estimating particle sizes in runoff from the two soil types irrespective of soil treatment. Q17

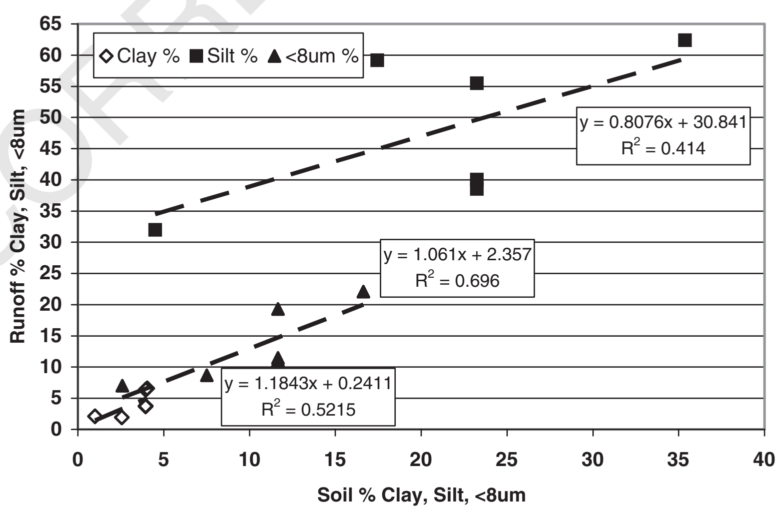

Figure 9. Runoff versus soil per cent clay, per cent silt, and <8 μm particle sizes (μm) for granitic and volcanic soils with fine organic cover treatment.

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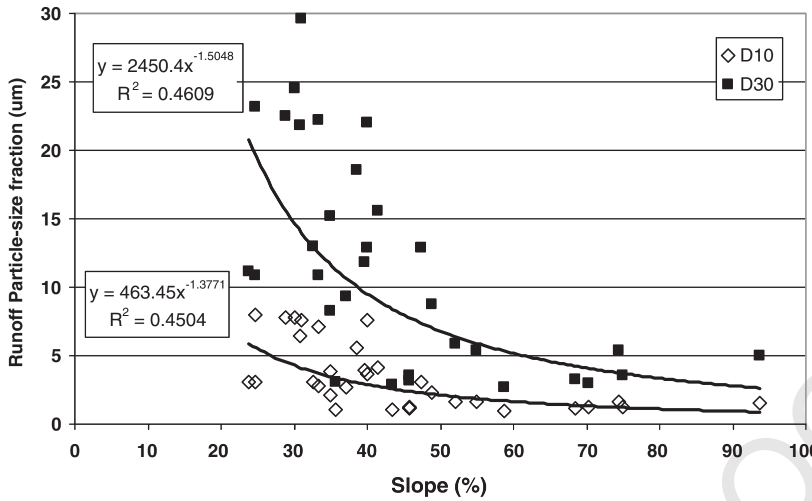

Figure 10. Effect of plot slope on PSDs for all volcanic soils.

SUMMARY AND CONCLUSIONS

Analysis of treatments and results of this study relied on distinguishing between volcanic and granitic soil types and textures. The textural analysis of the Tahoe soils tested confirmed their separation into three groupings: volcanic, granitic, and mixed soils; volcanics tended to be sandy loam, granitic soils tended to have a sand texture, and the one mixed soil site split between sandy loam and loamy-sand. Mean separation tests showed that for D_{10}, D_{30}, and D_{60} particle sizes, the mixed soil is not significantly different from the average volcanic soil, though in terms of runoff, results from the Tahoma site fit better with the granitic soils. There was no significant difference among the three

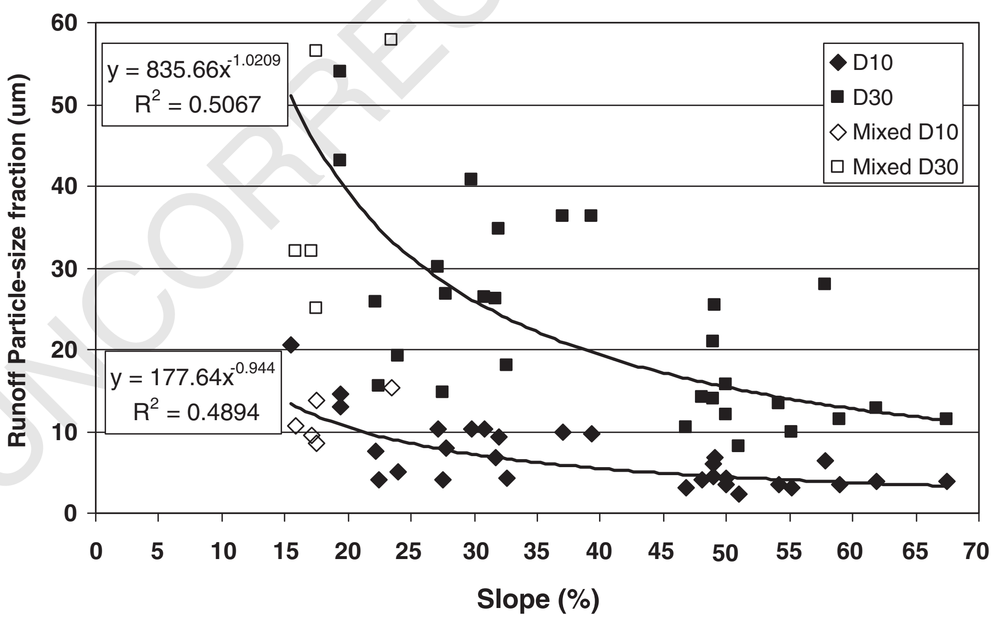

Figure 11. Effect of plot slope on PSDs for all granitic soils.

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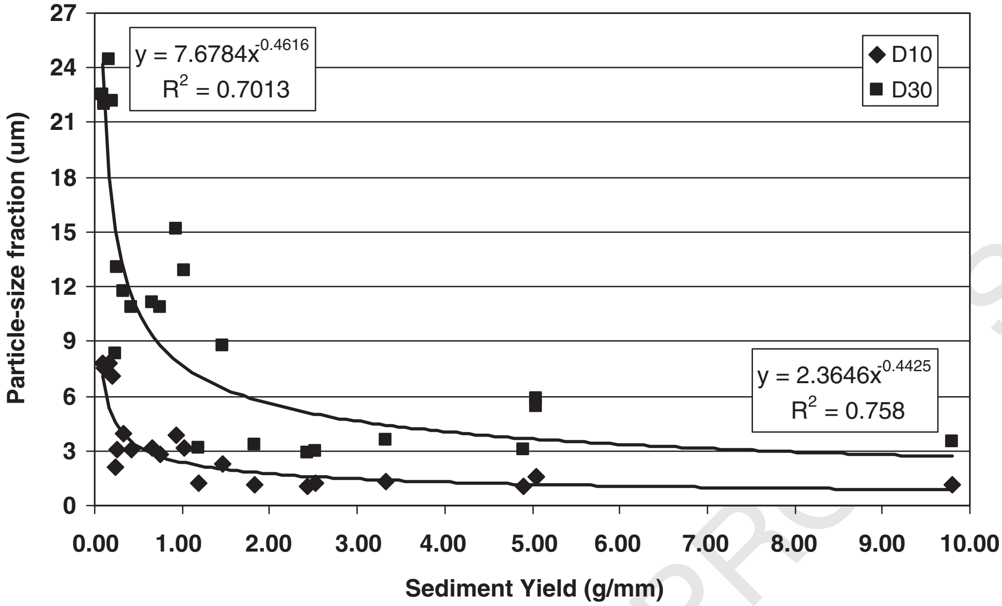

Figure 12. Effect of SY on PSDs for all volcanic soils.

soils groups for D_{90}. Percent sand, silt, and clay were more distinct among the groups. Volcanic and granitic soils per cent clay were significantly different, while the clay content in the mixed soil was not significantly different from either of the other soils.

The different erosion control treatments tested had a range of effects on SC, SY, and q_R. Considering all bare soil plots, there was a trend of increasing SC and SY with increasing q_R. This suggests greater runoff is linked to high

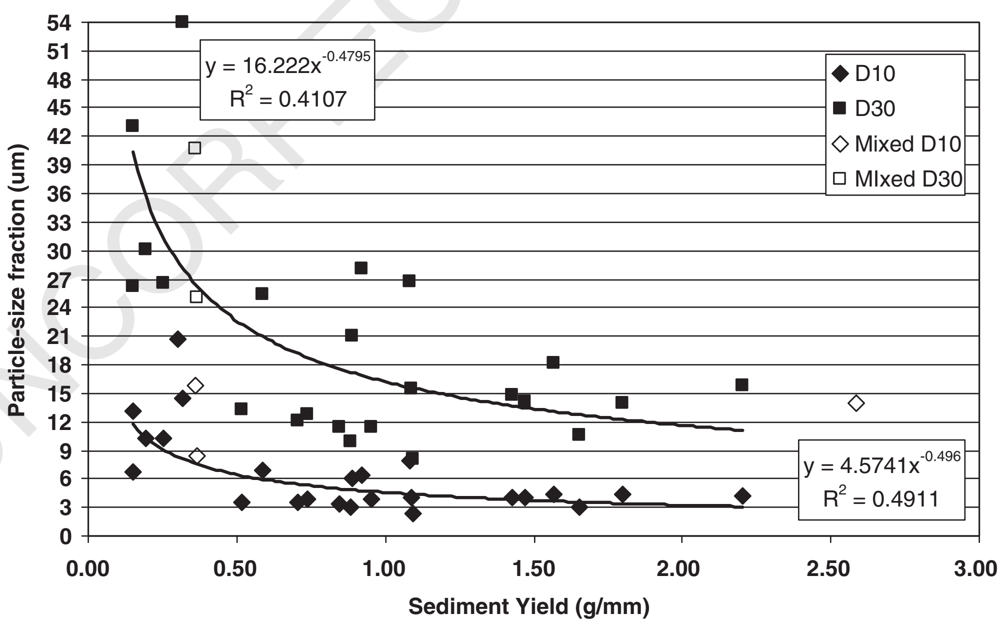

Figure 13. Effect of SY on PSDs for all granitic soils.

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sediment transport capacity. For the bare soils, SY was more strongly correlated with runoff rate than was SC. Coarse mulch treatment, hydromulch, and straw, improved plot infiltration but had sediment loads similar to that from bare plots. The control till treatment led to high runoff rates, up to 40 mm h^{-1}, though SYs and SCs remained less than 0·45 g m^{-2} mm^{-1} or g L^{-1}, respectively for this treatment. PNM plots had a wide range of runoff rates, but SYs and SCs remained below 1·2 g m^{-2} mm^{-1} or g L^{-1}. Grass treatments had variable success in reducing either runoff rate or sediment loads, which was, in part, due to the poor grass coverage over some plots. A stronger relationship between SY and q_R was found for the volcanic soils, though for all soils greater variability in the data occurred with higher runoff rates. Two treatments, fine organic cover and woodchip combinations were most effective at increasing infiltration and reducing runoff. Of the 27 plots tested with fine organic cover, 81 per cent had no runoff. Those plots with runoff had SYs below 0·5 g m^{-2} mm^{-1}. Woodchip combination plots had 73 per cent of the plots with no runoff and SYs below 0·4 g m^{-2} mm^{-1}. Lastly, the native treatment resulted in no runoff on the volcanic soil plots. On the granitic native plots, the highest q_R of 42 mm h^{-1} had the lowest sediment load at 0·2 g m^{-2} mm^{-1} or g L^{-1}.

Slope affected infiltration and runoff rates and sediment loads differently for the two major soil types. Generally, infiltration rates declined with increasing slope for both soils, however, runoff rate decreased with increasing slope on granitic soils and increased on steeper slopes for volcanic soils. SC and SY followed the same trend as q_R for each of soil. This suggests that within each soil type q_R determined the sediment transport capacity, though slope was not a significant factor in most cases.

Treatment performance was assessed in terms of q_R, sediment movement, and fraction of fine sediment in the runoff. Bare soil was considered the baseline, with comparatively the highest runoff rates, consistently elevated SCs and SYs, and two to four times greater small diameter particles in the runoff. Runoff did not occur on native plots with volcanic soils. Granitic and mixed soil native treatments did have some plots with runoff, however all sediment loads remained below 0·8 g m^{-2} mm^{-1} or g L^{-1}. With native soil, runoff particle size was not statistically analyzed due to the lack of plot runoff on different soils. However, particle size continued to be finer in the runoff than the *in situ* soils. PSDs generally fined with increasing slope. Results comparing bulk soil and runoff particle sizes were not found to have many significant relationships. The tillage treatment was ineffective for reducing runoff or reducing the transport of fine sediment. This treatment maintained high runoff rates, though tilling was expected to have increased infiltration, it also produced runoff with four to five times the proportion of fines as the *in situ* soils. Grass treatment produced variable results, which can be attributed to differences in grass growth and coverage over the plots. There were many grass treatment plots with no runoff, and those with runoff averaged between 10 and 25 mm h. Sediment loads varied with q_R. At higher runoff rates, SC and SY were less than 1·0 g L^{-1} and g m^{-2} mm^{-1}, and at low q_R SYs ranged from 2 to 5 g m^{-2} mm^{-1}. particle size tended to be two to four times finer in the runoff than the *in situ* soil for grassed plots. Overall, these results suggest that woodchips and fine organic cover were the two treatments that are most suitable for erosion control on Lake Tahoe soils in terms of runoff rates, sediment loads, and generation of fine particles. Most plots with these treatments had no runoff and had percentages of fine particles closest to the bulk soil. SC and SY for the woodchip treatments remained below 1 g m^{-2} mm^{-1} and 1 g L^{-1}, respectively, and under 0·35 g m^{-2} mm^{-1} and 0·35 g L^{-1} for the fine organic cover.

PSDs, in terms of D_{10}, D_{30}, and <8 μm particle sizes, showed significant log relationships with slope and SY for all plots having runoff. Small SYs, regardless of plot slope, resulted in larger particle sizes, similarly smaller plot slopes resulted in larger particle sizes as well. This combination of measured slope and SY relationships may be useful towards assessing sediment loads expected from watersheds in the basin for which these parameters are known.

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