LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **15**: 1–16 (2004)

Published online in Wiley InterScience (www.interscience.wiley.com). **DOI**: 10.1002/ldr.640

SIMULATED RAINFALL EVALUATION OF REVEGETATION/MULCH EROSION CONTROL IN THE LAKE TAHOE BASIN—1: METHOD ASSESSMENT

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Received 11 November 2003; Revised 23 March 2004; Accepted 15 April 2004

ABSTRACT

Revegetation of road cuts and fills is intended to stabilize those drastically disturbed areas so that sediment is not transported to adjacent waterways. Sediment has resulted in water quality degradation, an extremely critical issue in the Lake Tahoe Basin. Many revegetation efforts in this semiarid, subalpine environment have resulted in low levels of plant cover, thus failing to meet project goals. Further, no adequate physical method of assessing project effectiveness has been developed, relative to runoff or sediment movement. This paper describes the use of a portable rainfall simulator (RS) to conduct a preliminary assessment of the effectiveness of a variety of erosion-control treatments and treatment effects on hydrologic parameters and erosion. The particular goal of this paper is to determine whether the RS method can measure revegetation treatment effects on infiltration and erosion. The RS-plot studies were used to determine slope, cover (mulch and vegetation) and surface roughness effects on infiltration, runoff and erosion rates at several roadcuts across the basin. A rainfall rate of $\approx$60 mm h^{-1}, approximating the 100-yr, 15-min design storm, was applied over replicated 0·64 m^2 plots in each treatment type and over bare-soil plots for comparison. Simulated rainfall had a mean drop size of $\approx$2·1 mm and approximately 70% of 'natural' kinetic energy. Measured parameters included time to runoff, infiltration, runoff/infiltration rate, sediment discharge rate and average sediment concentration as well as analysis of total Kjeldahl nitrogen (TKN) and dissolved phosphorus (TDP) from filtered (0·45 µm) runoff samples. Runoff rates, sediment concentrations and yields were greater from volcanic soils as compared to that from granitic soils for nearly all cover conditions. For example, bare soil sediment yields from volcanic soils ranged from 2–12 as compared to 0·3–3 g m^{-2} mm^{-1} for granitic soils. Pine-needle mulch cover treatments substantially reduced sediment yields from all plots. Plot microtopography or roughness and cross-slope had no effect on sediment concentrations in runoff or sediment yield. RS measurements showed discernible differences in runoff, infiltration, and sediment yields between treatments. Runoff nutrient concentrations were not distinguishable from that in the rainwater used. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: rainfall simulation; grass revegetation; subalpine environment; semiarid; sediment source control

INTRODUCTION

Development during the past 50 years in the Lake Tahoe Basin, USA, has caused an increased flux of sediments and nutrients into the Lake. Algal primary productivity has more than tripled and clarity has decreased by 25 per cent from approximately 30 to 21 m indicating onset of cultural eutrophication (Goldman *et al.*, 1989; TRG, 2002). Efforts attempting to slow nutrient input to the Lake have taken many forms, most of which focus on sediment source control including on-site retention, or within the drainages from which they originate. Using GIS assessment methods, Maholland (2004)[Q1] evaluated the sediment sources and geomorphic conditions in the Squaw Creek watershed northwest of Lake Tahoe, a mixed granitic and volcanic soils environment, and found that forest roads ski runs[Q2] subject to hillslope rilling were the greatest sources of sediment. Unfortunately, despite years of work, little scientific information exists about the performance of roadcut or hillslope erosion control measures

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employed in the Basin (Schuster and Grismer, 2004). However, there are several examples of visible failures in erosion control in this semiarid, high-altitude environment especially along road-cut and ski-run areas.

Construction in the basin often removes nutrient-containing topsoil essential for plant growth while exposing compacted, readily erodible andesitic decomposed granite (DG), or volcanic subsoils to erosion. As the physicochemical soil quality declines, vegetation growth is limited. That vegetation and its supporting soil stabilizes and covers the slope (Lal, 1997), thus minimizing erosion. The thin, poorly developed soils in the basin combined with subalpine elevations and dry summers, make abiotic factors and anthropogenic influences particularly damaging to soil quality (Claassen and Hogan, 2002). As a result, above and below ground vegetative growth is restricted (Claassen and Zasoski, 1998). The low nitrogen availability of volcanic and DG subsoils also limits microbial activity, a critical element in nutrient cycling, soil aggregation and native grass reestablishment. Compounding soil degradation and subsequent lack of plant establishment is the influence of continued erosion on persistent nitrogen-deficient soil conditions (Claassen *et al*., 1995).

PREVIOUS WORK

While there is an enormous amount of literature related to erosion control in agricultural and relatively humid environments, there are few statistically validated field evaluations of the performance of revegetation/restoration-type erosion control efforts in semiarid, subalpine environments. Information that is available is often limited to the 'grey' literature of 'white' papers from agencies, or professional societies. For example, in the Tahoe Basin erosion control work is not new; White 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 Lake Tahoe. Their important 'demonstration' study of various erosion control nettings at Rubicon and Northstar-at-Tahoe was 'largely . . . ignored in the erosion control literature' (Sutherland, 1998a). The 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 of Fifield *et al.* (1988) in the basin and Fifield *et al.* (1989), Fifield and Malnor (1990), and Fifield (1992a,b) in western Colorado. In these studies, the workers evaluated the need for irrigation and runoff and erosion from plots 'treated' with a variety of 'natural' and geotextile covers on 33 per cent to 67 per cent slopes. The 'natural' treatments included hydroseeding, seed blankets, wood and paper hydromulches, straw, coconut and jute materials. Sediment yields and runoff were measured following natural rainfall events using collection troughs at the base of 24 to 36 m^2 plots. Generally, both runoff and sediment yields dramatically decreased as compared to bare-soil conditions; sediment yields ranged approximately two orders of magnitude, from 1·0 to 87 $g\,m^{-2}\,mm^{-1}$ runoff. The established, 2–3 year old dryland grasses on 33 per cent slopes resulted in a midrange sediment yield of 21 $g\,m^{-2}\,mm^{-1}$. Standardized or 'head-to-head' comparisons of treatment methods were difficult as differing rainfall intensities (energies) occurred, so averages of collected runoff and erosion values were reported. Not surprisingly, the greatest sediment yield reductions were associated with the largest surface cover biomasses. What remains unknown are the long-term benefits of these erosion control strategies in the field, their transferability to other locations and the effects that they have on infiltration rates and soil-quality restoration.

More recently, other efforts at assessing hydrologic effects of erosion control treatments at higher elevations or in nutrient-deficient soils have been reported. Montoro *et al.* (2000) described efforts to control erosion from anthropic soils on 40 per cent slopes using 30 m^2 plots treated with vegetal mulch (VM), hydroseeding with added humic acids (HA) and hydroseeding with VM and HA. Runoff and erosion from natural rainfall events of 2–34 $mm\,h^{-1}$ were significantly reduced from all treatments as a result of 'protection against raindrop impact' and 'general improvement in soil structure'. Development of grasslands on volcanic ash soils in northern Ecuador resulted in significant soil losses. Poulenard *et al.* (2001) used simulated rainfall at intensities of 20–120 $mm\,h^{-1}$ for 15 minutes on 1 m^2 plots to evaluate effects of grassland development, or conversion on soil crusting, infiltration, runoff and erosion rates.

In comprehensive reviews of rolled erosion control systems for hillslope stabilization, Sutherland (1998a,b) noted that the 'formative years' prior to ~1990 resulted in a mass of information that lacked scientifically creditable, standardized data in actual applications, a matter that has only been slightly addressed in subsequent studies. He argues for standardized evaluation methods that have field applicability and greater emphasis on study of surface, or near-surface, processes controlling erosion. Perhaps better still, would be a greater emphasis on restoration of soil quality adequate to support hillslope vegetation.

Rainfall simulation studies provide a means by which to standardize evaluation of erosion control measures through replicated rainfall events of the same intensity, or kinetic energy on multiple plots enabling statistical evaluation of treatment effects on hydrologic parameters of interest. Battany and Grismer (2000a) review efforts to develop rainfall simulators and describe development of a portable rainfall simulator (RS) that provided consistent rainfall intensities with acceptable rainfall energy. They employed the RS on hillslope vineyards to evaluate slope, cover and surface roughness effects on runoff and erosion (Battany and Grismer, 2000b). The RS method yielded data from the vineyard studies comparable to that obtained from other field studies for plot sizes in the order of $10\,m^2$ and larger in some cases. The primary advantages of the RS were the ability to bring it to a variety of field locations and evaluate a sufficient number of plots at any one location with statistical significance.

PROJECT OBJECTIVES

We hypothesized that native-grass revegetation will be reflected in greater infiltration rates and less runoff or sediment yield in successfully restored sites and that these changes can be measured directly in the field using RS techniques. The overall project objectives include evaluation of the runoff and sediment yields associated with bare soils and a variety of revegetation treatments on road-cuts and ski-runs. The specific objective of this paper is simply to evaluate whether the RS method is capable of distinguishing differences in infiltration rates and sediment yields associated with erosion-control treatments on road-cuts that have occurred historically in the Tahoe Basin on disturbed granitic and volcanic soils.

METHODOLOGY

Following a preliminary land survey of a site and establishment of plots and installation of the plot frame ($0{\cdot}8\,m \times 0{\cdot}8\,m$), the RS is centered over the frame and leveled. Detailed descriptions of the RS and plot frame are provided by Battany and Grismer (2000a); only slight modifications to their RS were employed here including replacement of the Bosch fuel pump with a more reliable (and less expensive) recreational vehicle sink pump and use of a more accurate and durable flowmeter. The plot frames were also constructed of heavier gage aluminum than originally used due to the compacted, rocky soils encountered in the Tahoe basin. The front adjustable legs of the RS tower were lengthened to access steeper slopes and a combination of two ladders with ladder jacks laid on the slope were used to support the front legs with minimal disturbance to the site. Three soil samples were collected from around the plot frame and later dried for 48 h at 105°C to determine antecedent soil moisture at each plot. A plexiglass sheet was placed on the simulator structure above the plot frame and the rainfall rate established at $60\,mm\,h^{-1}$ after which the sheet was quickly removed and rainfall initiated. While this rainfall rate is high, it corresponds to the estimated 100-year 15-min storm for the basin. Preliminary studies indicated that little, if any, runoff occurred at rainfall intensities less than $\sim 40\,mm\,h^{-1}$. (As will be discussed in a subsequent paper considering new revegetation treatment effects on infiltration, rainfall intensities of as much as $180\,mm\,h^{-1}$ of 30 minutes duration were sometimes required to initiate runoff at all.) Rainfall was allowed to continue until either steady runoff was obtained, or ~ 60 minutes have elapsed. The RS was removed and the surface microtopography, or surface 'roughness' of the plot soil (after removing any cover) was measured as well as the visible wetting front depth. Figure 1 illustrates the RS needle tanks (a) and the simulator in use (b) on a road-cut along the Lake Tahoe west shore (Rubicon).

The number of plot tests conducted at each site ranged from 3 to 6 depending on the relative consistency in measured values from plot to plot. Average values of infiltration, runoff and sediment yield are compared here between treatments and locations. Following Battany and Grismer (2000b), a one-way ANOVA was used to

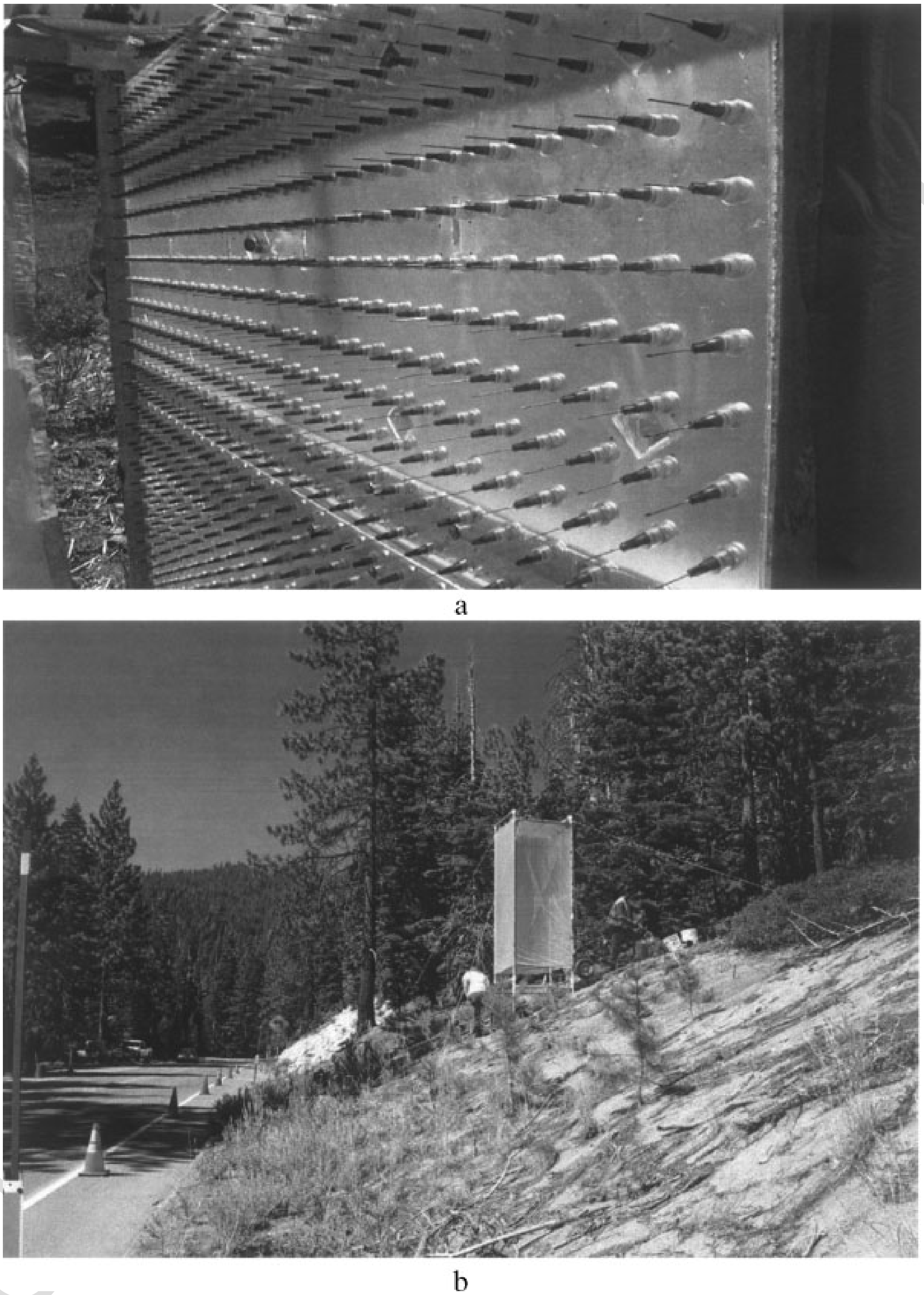

Figure 1. Rainfall simulator needle tanks (a) in use along lake west shore (b).

Table I. Summary of soil characteristics at Tahoe Basin road-cut sites (NRCS, 1974)

Site	Soil series	Taxonomic classification	Surface texture	Basin soils (%)	Area of basin soils (ha)	pH	Permeability ($mm\,hr^{-1}$)	AWC ($cm\,cm^{-1}$)
Blackwood Canyon	Waca	Medial–skeletal, amorphic, frigid Humic Vitrixerands	Cobbly coarse sandy loam	0·3	288	5·6–6·5	5·1–16	0·06–0·08
Bliss and Rubicon	Meeks	Sandy–skeletal, mixed, frigid Humic Dystroxerepts	Very stony loamy coarse sand	1·2	1020	6·1–6·5	16–51	0·03–0·05
Brockway and Dollar Hill	Jorge-Tahoma	Fine–loamy, isotic, frigid Ultic or amorphic, frigid Ultic Haploxeralfs	Very stony sandy loam	0·3	288	5·1–6·0	5·1–16	0·10–0·12
Incline Village and Cave Rock	Umpa	Loamy–skeletal, isotic, frigid Andic Dystroxerepts	Very stony sandy loam	3·3	2735		ND	

determine significant differences between infiltration rates and sediment yields from bare-soil plots (having downslopes within ~5 per cent) and treatments at particular locations and then between comparable slopes/treatments at different locations.

Following field measurements, collected runoff samples are taken to the laboratory for filtration and chemical analyses. Samples were vacuum filtered, first through a Whatman #1 filter followed by a 0·45 μm filter. The filtrate was later analyzed for total Kjeldahl nitrogen and total soluble phosphorous (TKN and TDP) by the DANR Lab at UC Davis. The filter papers with sediment were dried at 105°C weighed and total sediment mass per volume of runoff was determined.

Rainfall simulation tests for this study were conducted during the summer of 2001 at volcanic-soil sites along the north shore (Dollar Hill and Brockway) of the Lake and granitic-soil sites on the west (Rubicon and Bliss), northeast (Incline Village) and east shores (Cave Rock) of the Lake. The site at Blackwood Canyon has a granitic base with volcanic soil cover located along the west shore roughly equidistant between the Dollar Hill and Rubicon sites. Table I summarizes reported soil-survey characteristics of the soils at the road-cut sites (NRCS, 1974). Though overall basin area soil-type fractions are small, they represent some of the largest in the basin after the rock complexes. Generally, the soils could be divided into granitic- (andesitic) or volcanic-type soils, though at the Blackwood Canyon site, the soil classification was mixed. Volcanic-soil sites were represented by road-cuts at Dollar Hill (State Hwy 28 east of Tahoe City), Brockway Summit (State Hwy 267 north of Kings Beach) and bare soil in Blackwood Canyon (along access road 4 km west from Hwy 89 and ~6·4 km south of Tahoe City, 1950 m elevation with N aspect) all in California. Granitic soils sites were represented by road-cuts at mileposts 22·8 (Rubicon) and 18·5 (Bliss) along State Hwy 89 south of Tahoe City in California, as well as smaller road-cuts at Incline Village (no treatment information was available) and Cave Rock Estates in Nevada. Cation exchange capacities (CEC) were generally very small for DG soils (2–5 meq $100\,g^{-1}$), while the remaining soils ranged from 5–10 meq $100\,g^{-1}$. Table II summarizes the known treatment characteristics and elevation/aspects of the sites at which RS tests were conducted.

Soil-cover conditions varied from site to site, though an effort was made to obtain runoff measurements from bare soil, standardized pine-needle covers of 38–76 mm depths, and various combinations of pine-needle mulches, composts, duff and grass covers. Revegetation treatments also ranged from site to site and were in various stages of decay. Generally, revegetation treatments tested consisted of application of grass seed mixtures with either organic fertilizer (OF) or compost amendments (tilled into the soil in some cases) and with or without pine needle (PN), or pine-needle mulch (shredded needles) covers. In some cases, forest-duff cover conditions were available, either naturally (e.g. Blackwood Canyon), or 'tilled in' as part of a treatment (see Table I). Detailed information about

Table II. Summary of site treatment/physical characteristics at Tahoe Basin road-cut sites

Site	Seed mix	Amends	Fertilizer	Mulch		Tillage depth (mm)	Treatment year	Elevation (m)/aspect
Granitic soils				Type	Depth (mm)			
Bliss	None	Duff	None	Pine needle (PN)	25	100	2000	2010/E
Cave Rock	Br ca/El el* ($100\,kg\,ha^{-1}$)	Compost	Biosol	PN over straw	50	100	2000	2000/NW
Rubicon	Caltrans Type B grasses–planted	Compost	16–16–16	Straw and PN	∼25	None	1998	2000/E
Volcanic soils								
Dollar Hill (yarrow sites)	Native grasses over standard reveg. mix	No	Biosol	Ground PN	50	None	1998?	1950/SSE
Dollar Hill (other sites)	Various bunchgrass (BG) mixes	??	Biosol	PN, hand applied	30	None	1999	1950/SE
Brockway	Various grass mixes (unknown)	Compost	Biosol	PN	10	None	1998?	2085/SW

**Bromus carinatus*/*Elymus elymoides*.

Table III. RS test measurements considered in subsequent analyses of RS test results

Measurement	Units	Description
Downslope	%	Average ratio of change in depth from a level plane to horizontal distance across the plot frame perpendicular to hillslope contours based on 25–30 point measurements
Cross-slope	%	Average ratio of change in depth from a level plane to horizontal distance across opposite corners of the plot frame, or at a 45 degree angle to the hillslope contours based on 40–45 point measurements
Roughness	mm	Average absolute deviation from a plane passing through each of the three slope measurements
Soil moisture	w/w	Average of three soil-moisture samples taken adjacent to each side of the plot frame prior to simulated rainfall
Time-to-runoff	s	Elapsed time from the start of simulated rainfall at which runoff was observed to cross the plot frame lower lip and into collection channel
Steady runoff	$mm\,h^{-1}$	Ratio of measured runoff sample volume and elapsed time per sample divided by plot-frame area after runoff rate stabilized, or average few rates determined when there was little runoff
Steady infiltration	$mm\,h^{-1}$	Difference between rainfall rate and steady runoff rate
Steady sediment concentration	$g\,L^{-1}$	Sediment mass in runoff samples collected after runoff rate stabilized, or average of few samples collected when little runoff
Cumulative runoff	mm	Measured, or interpolated runoff depth occurring after 15 minutes of simulated rainfall
Cumulative sediment	g	Measured, or interpolated eroded material in runoff water occurring after 15 minutes of simulated rainfall
Sediment yield	$g\,m^{-2}\,mm^{-1}$	Slope of linear regression between cumulative sediment mass in runoff water and cumulative runoff depth

specific treatment 'as-builts' at a site was generally unavailable from the responsible agencies (USFS or CA Transportation Department) and no effort was made here in this first phase of the study to determine mass or extent of vegetative cover, or soil-treatment conditions. Soil treatment and vegetative cover conditions of more recently revegetated sites and their effects on infiltration and sediment yields will be considered in a subsequent paper of this series. Table III lists the measurements discussed here determined in each RS test.

RESULTS AND DISCUSSION

We first consider the performance of the RS on four bare-soil plots at the Dollar Hill site to illustrate the type of raw data generated and its reproducibility between randomly selected plots at the first site examined in this study. Next, we expand discussion of results from RS tests at both granitic and volcanic bare-soil plots. As RS test results on granitic soils generally differed from those taken on volcanic soils, we then consider RS test results from these two soil types separately in terms of revegetation treatment effects on measured infiltration rates and sediment yields. Finally, we consider bare soil and treatment effects in aggregate for both soil types.

Bare-soil Plot Assessment

As may be expected from bare-soil plots, concentration in the runoff decreases with time to a relatively constant value reflective of the available sediment source. However, initially high infiltration rates increase the elapsed time required for each increment of runoff to occur such that the sediment mass recovered with each increment of runoff remains more-or-less constant. Figure 2 shows measured infiltration and runoff rates as well as sediment concentrations as a function of time since initiating rainfall on a typical bare-soil plot at the Dollar Hill site. Figure 3 illustrates the relationship between cumulative sediment collected in the runoff and cumulative runoff from the four bare-soil plots at this site while Table IV summarizes the bare-soil data obtained from these plots. It also provides some insight into the reproducibility of the method in our initial trials. (In fact, with greater experience and an improved pump and flowmeter on the RS, some variability seen in the infiltration and runoff

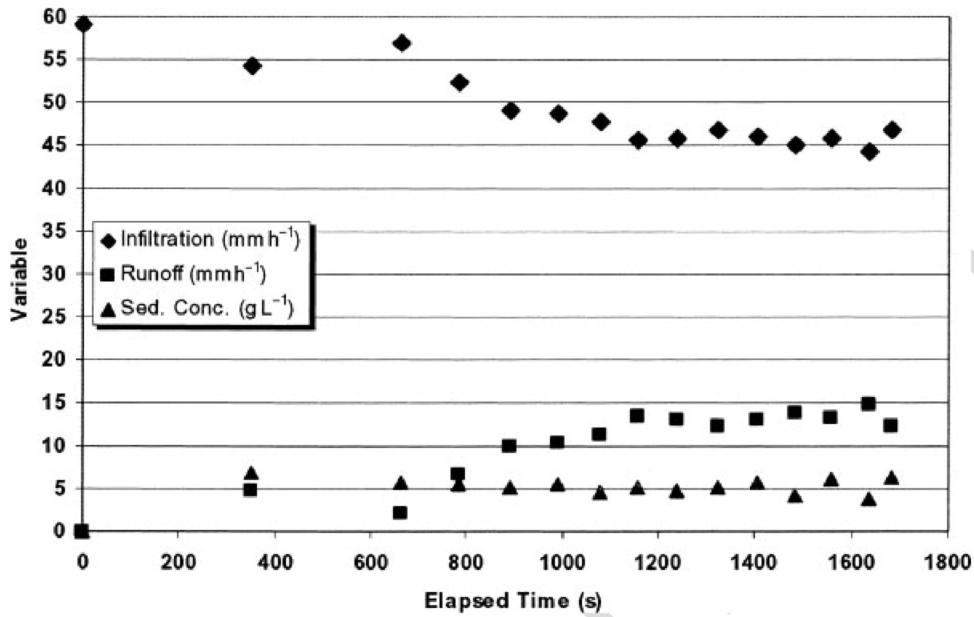

Figure 2. Runoff and sediment concentration data from bare-soil plot (1D) at Dollar Hill site.

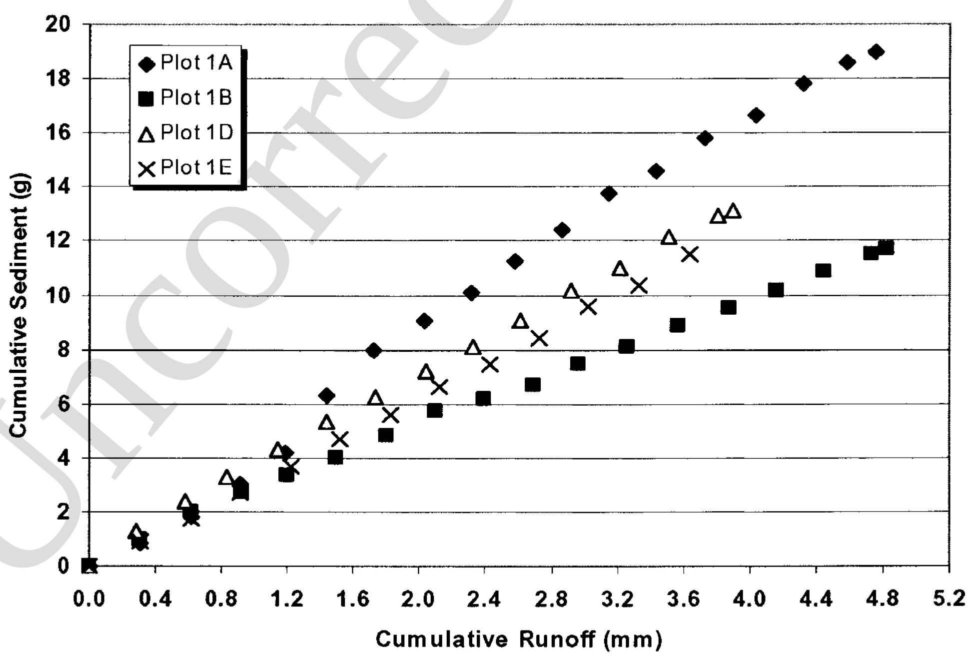

Figure 3. Variation of cumulative sediment discharge with cumulative runoff from bare-soil plots at Dollar Hill site.

Table IV. Summary of Dollar Hill bare-soil plot runoff and sediment yield results from RS method

Plot	Slopes (%)			Average		Init. soil moisture	Time to runoff	Cum. @ 15 minutes		Steady			Sediment yield	R^2	n
	Down	Cross	Cross	Rough. (mm)	Rainfall (mm h^{-1})	(w/w %)	(s)	Runoff (mm)	Sedim. (g)	Infilt. (mm h^{-1})	Runoff (mm h^{-1})	Sedim. (g L^{-1})	(g m^{-2} mm^{-1})	(%)*	
1A	49·5	39·6	24·7	8·3	60	9·44	509	1·24	3·85	44·5	15·5	5·95	6·52	99·2	18
1B	49·8	39·1	27·3	14·8	60	11·08	225	1·36	3·66	44·5	15·5	3·65	3·88	99·5	18
1D	54·0	38·8	36·8	8·9	59	9·87	218	0·73	2·93	46·5	12·8	5·25	5·39	99·7	15
1E	55·5	37·5	39·2	8·0	64	15·46	236	2·11	6·61	44·5	19·5	4·51	4·88	99·9	13

*Linear regression coefficient between cumulative sediment and runoff as in Figure 3 where 'n' is the number of samples in regression.

Table V. Summary of RS test variable averages for bare-soil plots at all road-cut sites

Location	Soil type	Average Slope (%)	Average Rough. (mm)	Cumul. @ 15 min Runoff (mm)	Cumul. @ 15 min Sediment (g)	Steady Runoff ($mm\,h^{-1}$)	Steady Sed. conc ($g\,L^{-1}$)	Sediment yield ($g\,m^{-2}\,mm^{-1}$)
Blackwood	Mix	61·4[a]	10·6	0·06[a]	0·03[a]	0·47[a]	1·89[a]	1·9[a]
Brockway	Volcanic	51·5	10·6	2·35[a]	16·0[a]	23·5[a]	11·3[a]	12·3[a]
Dollar Hill	Volcanic	48·5	10·2	0·86[a]	2·66[a]	12·8[a]	4·19[a]	4·3[a]
Bliss	Granitic	72·3[a]	6·3	1·64[a]	12·7[a]	14·3	14·6[a]	12·6[a]
Bliss	Granitic	56·3	6·7	1·00	2·40	11·5	2·43	3·4[a]
Cave Rock	Granitic	59·6	7·4	0·56	1·39	13·7	5·29[a]	2·1
Rubicon-cut	Granitic	52·4	6·2	0·05[a]	0·02[a]	1·14[a]	0·29[a]	0·3[a]
Rubicon-fill	Granitic	58·1	11·0[a]	1·70	2·17	17·1	1·32	2·0

[a]Tukey test on means significantly different from that for other sites of the same soil type ($p < 0{\cdot}05$).

rates of Figure 2 was eliminated.) Steady infiltration rates were practically identical from three of the plots, but differed from the fourth by 2 mm h^{-1} or by about 4 per cent. Similarly, the time to runoff was similar between three of the plots, but averaged less than half that estimated for plot 1A, our first plot over which there was some confusion about what constituted 'runoff'. Down-slopes spanned a 6 per cent range and while cross-slope variation was somewhat greater across the four plots it had no effect on infiltration rates and sediment yields. Soil surface roughness values were quite similar with the exception of plot 1B, which was $\sim$50 per cent greater. This greater roughness in plot 1B may have resulted in lower sediment yield as compared to that from other plots, however, sediment yields from the four plots ranged only $\pm$25 per cent from the average of the four plots. Steady sediment concentrations from the four plots were also similar, ranging 23 per cent about the mean value.

With the exception of the Incline Village site, from which very few plots tests were conducted on a revegetation treatment, RS tests were conducted on bare soils at all sites. As noted in the example results above for Dollar Hill, cross-slope was not a significant factor affecting runoff or sediment yields so is not included in further analyses. Table V summarizes the averages of RS test results for bare-soil plots. Down-slopes at the Blackwood Canyon and one of the Bliss sites were significantly greater than those from all the other sites and resulted in much greater sediment yield at the Bliss site as compared to other granitic-soil sites. Roughness values were practically identical in all of the volcanic soil sites and the Rubicon-fill site, but these were much larger than those for the other granitic sites. Roughness was not a significant variable with respect to sediment yield. Runoff and sediment variables were all significantly different between sites in the volcanic soils while less variability was observed for these parameters at the granitic-soil sites having down-slopes between 50 and 60 per cent. RS tests at the Rubicon-cut site resulted in the lowest sediment concentration and yield and the second lowest runoff value. The overall runoff and sediment yield average values for the volcanic-soil sites of 12 mm h^{-1} and 6·2 g m^{-2} mm^{-1}, respectively, were greater than comparable (50–60 per cent slopes) averages for the granitic soil sites of 11 mm h^{-1} and 2·0 g m^{-2} mm^{-1}, respectively. This difference in runoff and sediment variables between soil types is even more apparent when comparing respective averages of volcanic and granitic 15-min cumulative runoff and sediment values (1·07 mm and 6·2 g m^{-2} mm^{-1}, respectively versus 0·8 mm and 1·5 g m^{-2} mm^{-1}, respectively). Presumably, increased sediment yield from the volcanic soils reflects a smaller average grain size than that for the granitic soils.

Volcanic Soil Plot Assessment

Revegetation treatments generally improved erosion control on the volcanic roadcut soils. Table VI summarizes the average results of RS test plots on revegetated volcanic soils at Brockway and Dollar Hill. Newer pine-needle mulch (PNM) covers reduced sediment concentrations and yields to similar values of roughly 0·65 g L^{-1} and 1 g m^{-2} mm^{-1}, respectively, from the very different bare-soil values at both the Brockway and Dollar Hill sites. However, runoff from the Brockway site was greater than that at Dollar Hill site. Past additional amendments

Table VI. Summary of RS test-variable averages for treatment plots at volcanic road-cut sites

Location	Treatment	Average Slope (%)	Average Rough. (mm)	Cumul. @ 15 min Runoff (mm)	Cumul. @ 15 min Sediment (g)	Steady Runoff (mm h^{-1})	Steady Sed. conc (g L^{-1})	Sediment yield (g m^{-2} mm^{-1})
Brockway	New PN mulch	55·2	15·3[b]	2·33	1·73[b]	16·4	0·63[b]	1·1[b]
Brockway	PNM+compost	50·3	14·3[b]	0·44[b]	0·40[b]	9·5[b]	0·74[b]	1·0[b]
Brockway	Deep duff	48·0	12·3	0·43[b]	6·33	6·3[b]	17·3	21·0[b]
Dollar Hill	New PN mulch	54·3	11·9	0·71	0·43[b]	7·7	0·66[b]	0·8[b]
Dollar Hill	PNM+Bunch grass	55·8	14·3[b]	1·73[b]	3·14	15·4	2·10	2·3
Dollar Hill	PNM+BG+duff	54·6	14·2[b]	0·11[b]	0·19[b]	2·8[b]	1·70[b]	1·7[b]
Dollar Hill	PNM+yarrow	49·8	9·33	1·86[b]	8·73[b]	20·0	7·76[b]	8·8[b]

[b]Means significantly different than that for bare-soil plots at the same site ($p < 0{\cdot}05$).

including incorporation of compost or duff or use of plant plugs or seeding provided no further erosion control at either site in terms of sediment concentrations or yields, but did reduce runoff rates and hence, net sediment output from the site for a given storm. Deep duff and old mulches resulted in greater sediment yield at both sites, but resulted in greater runoff at the Dollar Hill Yarrow site. The Yarrow site yielded seemingly anomalous results in many ways suggesting that further investigation at the site is needed to better understand the runoff and erosion processes occurring there.

Granitic Soil Plot Assessment

Revegetation and pine-needle cover treatments on the granitic soils had conflicting results in terms of erosion control of the road-cut soils. Table VII summarizes the average results of RS test plots on revegetated granitic soils at Bliss, Cave Rock, Incline Village and Rubicon-cut and fill sites. At Bliss and Cave Rock, pine-needle mulch covers reduced sediment concentrations and yields and runoff rates as compared to that from bare soils, while at the Rubicon-cut site the pine-needle cover had little effect on already very small sediment concentrations and yields and runoff rates. Incorporation of compost or duff and addition of plants appears to reduce sediment concentrations and yields and runoff rates further as compared to bare-soil conditions at the Cave Rock and Incline Village sites. Variability from site to site in treatment plot runoff sediment concentrations is less than that from the volcanic soils as the overall average value is also much less.

Table VII. Summary of RS test variable averages for treatment plots at granitic road-cut sites

Location	Treatment	Average Slope (%)	Average Rough. (mm)	Cumul. @ 15 min Runoff (mm)	Cumul. @ 15 min Sediment (g)	Steady Runoff (mm h^{-1})	Steady Sed. Conc (g L^{-1})	Sediment Yield (g m^{-2} mm^{-1})
Bliss	PN cover	58·1	6·87	0·64	1·27[b]	8·41	1·21	2·3
Bliss	Tilled in duff	58·4	10·4[b]	0·03[b]	0·02[b]	1·07[b]	0·34[b]	0·4[b]
Bliss	Tilled duff+PN	56·0	7·06	0·07[b]	0·05[b]	1·60[b]	0·42[b]	0·6[b]
Cave Rock	OM+PN cover	64·5[a]	6·22	0·07[b]	0·27[b]	3·91[b]	0·37[b]	0·6[b]
Cave Rock	Grass reveg.	60·2	15·7[a,b]	2·44[b]	0·57[b]	17·9	0·25[b]	0·4[b]
Incline Village	Grass reveg.	48·3	13·6	0·27	0·07	6·87	0·22	0·3
Rubicon	PN cover	53·7	5·87	0·12	0·06	2·72	0·30	0·4
Rubicon	Tilled in duff	53·1	7·08	0·08	0·03	1·96	0·50	0·6
Rubicon	Tilled duff+PN	57·3	6·06	0·22	0·09	2·82	0·23	0·3
Rubicon	Fill PN cover	61·9	10·2	1·35	0·89[b]	16·97	1·19	1·1[b]

[a]Tukey test on means significantly different from that for other sites of the same soil type ($p < 0{\cdot}05$).
[b]Means significantly different than that for bare-soil plots at the same site ($p < 0{\cdot}05$).

Table VIII. Filtered runoff water nutrient analyses for Bliss, Dollar Hill and Rubicon sites

Location	No. of samples	Nutrient	Mean conc. (mg L^{-1})	*SD* (mg L^{-1})	Detection limit (mg L^{-1})
Bliss	100	TKN	1·5	1·3	0·1
Dollar Hill	300	TKN	2·2	1·0	0·1
Rubicon	200	TKN	1·8	1·4	0·1
Rainwater	10	TKN	1·8	1·2	0·1
Bliss–Rubicon	150	TDP	0·2	0·1	0·1
Dollar Hill	100	TDP	0·09	0·08	0·01*
Rainwater	10	TDP	0·1	0·1	0·1

*New analytic method with lower detection limit.

Rainfall and Runoff Water Quality Assessment

Soil and runoff water quality are of particular interest in the Lake Tahoe Basin due to nutrient impacts on lake-water clarity. While analysis of soil-nutrient conditions was beyond the scope of this RS method assessment objective, some preliminary evaluations have been conducted (e.g., Claassen and Hogan, 2002), which generally indicate that disturbed soil nutrient concentrations are extremely low. This observation was also born out in results of chemical analyses (TKN and TDP) of the runoff water. Analyses of more than 300 samples, yielded nutrient concentrations indistinguishable from the rainwater (resident groundwater) used in the simulations (see Table VIII). Analyses of several unfiltered runoff samples yielded average TKN and TDP concentrations slightly greater than the means for the filtered samples, but well within the standard deviation of the measurements. Work underway suggests that initially greater nutrient concentrations occur in simulated runoff from very recently amended or treated granitic soils, but that this elevated nutrient concentration is absent within a year after treatment occurs.

Table IX. Least to greatest ranking of treatment effects on *granitic* and volcanic soils by cumulative runoff and sediment after 15 minutes of 60 mm hr^{-1} rainfall and overall sediment yield

Rank	15-minute cumulative runoff		15-minute cumulative sediment		Sediment yield	
1	*Bliss*	Tilled in duff	*Bliss*	Tilled in duff	*Incline Village*	Grass reveg.
2	*Rubicon*	Bare soil	*Rubicon*	Bare soil	*Rubicon*	Bare soil
3	Blackwood	Bare soil	*Rubicon*	Tilled in duff	*Rubicon*	Tilled in duff+PN
4	*Cave Rock*	OM+PN cover	Blackwood	Bare soil	*Rubicon*	PN cover
5	*Bliss*	Tilled in duff+PN	*Bliss*	Tilled in duff+PN	*Cave Rock*	Grass reveg.
6	*Rubicon*	Tilled in duff	*Rubicon*	PN cover	*Bliss*	Tilled in duff
7	Dollar Hill	PNM+BG+duff	*Incline Village*	Grass reveg.	*Rubicon*	Tilled in duff
8	*Rubicon*	PN cover	*Rubicon*	Tilled in duff+PN	*Bliss*	Tilled in duff+PN
9	*Rubicon*	Tilled in duff+PN	Dollar Hill	PNM+BG+duff	*Cave Rock*	OM+PN cover
10	*Incline Village*	Grass reveg.	*Cave Rock*	OM+PN cover	Dollar Hill	PN mulch
11	Brockway	Deep duff	Brockway	PNM+compost	Brockway	PNM+compost
12	Brockway	PNM+compost	Dollar Hill	PN mulch	*Rubicon*	Fill PN cover
13	*Cave Rock*	Bare soil	*Cave Rock*	Grass reveg.	Brockway	PN mulch
14	*Bliss*	PN cover	*Rubicon*	Fill PN cover	Dollar Hill	PNM+BG+duff
15	Dollar Hill	PN mulch	*Bliss*	PN cover	Blackwood	Bare soil
16	Dollar Hill	Bare soil	*Cave Rock*	Bare soil	*Rubicon*	Fill bare soil
17	*Bliss*	Bare soil	Brockway	PN mulch	*Cave Rock*	Bare soil
18	*Rubicon*	Fill PN cover	*Rubicon*	Fill bare soil	Dollar Hill	PNM+bunchgrass
19	*Bliss*	Bare soil (72%)	*Bliss*	Bare soil	*Bliss*	PN cover
20	*Rubicon*	Fill bare soil	Dollar Hill	Bare soil	*Bliss*	Bare soil
21	Dollar Hill	PNM+bunchgrass	Dollar Hill	PNM+bunchgrass	Dollar Hill	Bare soil
22	Dollar Hill	Old PNM+yarrow	Brockway	Deep duff	Dollar Hill	Old PNM+yarrow
23	Brockway	PN mulch	Dollar Hill	Old PNM+yarrow	Brockway	Bare soil
24	Brockway	Bare soil	*Bliss*	Bare soil (72%)	*Bliss*	Bare soil (72%)
25	*Cave Rock*	Grass reveg.	Brockway	Bare soil	Brockway	Deep duff

Ranking of RS Results from Bare Soil and Treatment Plots

All RS plot average results from the various treatments and both soil types were combined and ranked from least to greatest in terms of cumulative 15-minute runoff, cumulative 15-minute sediment output and overall sediment yield to evaluate the treatments most effective in reducing runoff and sediment output (see Table IX). We use the 15-minute cumulative values as a means of standardizing the comparisons and because it is a commonly used design storm duration (100-year return period) in the Tahoe Basin. This ranking helps to highlight some of the apparent anomalies observed in the field and provides direction towards sites requiring additional testing.

Soil conditions that resulted in large infiltration capacities and the least runoff included amended soils (tilled in duff or compost), or naturally deep duff (e.g., Blackwood) and high infiltration capacity, coarse, decomposed granite soils (e.g., Rubicon bare soil). Addition of pine-needle mulches or covers reduced the rainfall kinetic energy of impact at the ground surface, or cumulative sediment in the runoff that did occur. Finally, sediment availability for erosion is reflected in rankings by sediment yield reflecting mostly granitic soils in the top ten rank followed by the volcanics, that is, presumed dominance of the smaller size particle fraction of volcanic soils appears as greater cumulative sediment outputs or yields. Illustrating the relative importance of these three elements in revegetation practices is the dramatic shift in rank of the Cave Rock 'grass reveg.' treatment from greatest runoff (25th rank) due to shallow bedrock conditions, to 13th in terms of sediment load (due to PNM + grass cover) to 5th in terms of sediment yield in Table IX. The effect of soil slope is also apparent in the Bliss bare-soil treatment (72% vs. ~55%) located near the bottom of all rankings. Overall, the rankings underscore the importance of both elements in revegetation efforts, that is, the need to improve the infiltration capacity of the soil and stabilize, or restrain sediment delivery through adequate cover. It should be noted that the excessively shredded, decomposed, or 'old' (>3 years) pine-needle covers/mulches provided little, if any, erosion control (e.g., Dollar Hill PNM + yarrow).

SUMMARY AND CONCLUSIONS

There has been little hydrologic evaluation of revegetation/restoration efforts on steeply sloping degraded soils. Such an analysis/assessment is critical in evaluating and improving BMPs for sediment source (erosion) control along roadcuts and other hillslope disturbances in the Tahoe Basin region. A portable rainfall simulator developed for steep slopes has enabled preliminary assessment of revegetation effects on soil infiltration, runoff, and sediment yields from disturbed road-cut soils. In the road-cut revegetation treatments considered here, efforts were made to improve surface cover and infiltration conditions on engineered soil slopes having nearly uniform slopes of approximately 50 per cent. In this first year of evaluation, it was found that treatments combining improved infiltration capacity with sediment control at the surface were the two primary factors affecting runoff rates, sediment concentrations and sediment yields after soil type (granitics vs. volcanics). Overall, the significance of measured or determined variables from the RS tests is considered individually below.

Down-slope (%)

With the exception of three plot averages that had significantly greater down-slopes than the others in the range from 48–62 per cent, only one plot average down-slope at 72 per cent (Bliss) showed a significant effect between down- or cross-slopes and runoff rates or sediment yields.

Cross-slope (%)

Though having a greater range than down-slopes, average cross-slopes had no significant correlation with runoff rates or sediment yields.

Roughness (mm)

Though some plot average roughness values were significantly different than that for other sites or the corresponding bare-plot values, average roughness values were small, ranging from only 6–15 mm. Greater average roughness values were generally associated with increased tillage or addition of amendments that altered the soil surface. Nonetheless, no significant correlations were found between average roughness and runoff rates or sediment yields.

Time-to-runoff (s)

Time-to-runoff is a qualitative field judgement that generally increased with decreasing antecedent soil moisture, but the correlation was weak and the variability was quite large. In some cases, no runoff occurred and in others, only a few minutes were required. Runoff rates and sediment yields were not significantly correlated with time-to-runoff.

Steady infiltration and runoff rates (mm h^{-1})

Infiltration and runoff rates were largely controlled by soil type, soil tillage, or cover treatment. Runoff rates ranged from 0–23 mm hr^{-1} with the higher values associated with bare volcanic soils. Addition of pine-needle mulch and incorporation of organic matter, or duff, significantly increased infiltration, or decreased runoff rates as compared to bare-soil conditions in each subsoil type, though there were anomalies in this regard at Dollar Hill for the bunchgrass and yarrow plots.

Steady sediment concentration (g L^{-1})

Sediment concentrations of runoff samples collected after runoff rate stabilized ranged from 0·2–15 g L^{-1}, and were largely controlled by soil type, soil tillage, or cover conditions. Again, addition of pine-needle mulch and/or incorporation of duff significantly decreased runoff rates in general as compared to corresponding bare soils. However, at the Dollar Hill yarrow site, decomposed mulches appeared to be ineffective and a significantly greater average sediment concentration was observed.

Cumulative runoff @ 15 minutes (mm)

Runoff depth occurring after 15 minutes of simulated rainfall ranged from 0–2·4 mm, and was largely controlled by soil type, soil tillage, or cover. Interestingly, cumulative runoff depth was not significantly correlated with cumulative sediment @ 15 minutes or sediment yield, but rather with the presence of an intact pine-needle mulch cover, or granitic subsoil. Again, presence of pine-needle mulch significantly reduced cumulative runoff depths in general, however, unexpectedly, at the Dollar Hill yarrow and bunchgrass sites, cumulative runoff depths increased.

Cumulative sediment @ 15 minutes (g)

Sediment output in runoff occurring after 15 minutes of simulated rainfall ranged from 0–16 gm, and was largely controlled by soil type, soil tillage, or cover. The greatest values were associated with bare volcanic soils, with the exception of the deep duff-like soil at Blackwood where both cumulative runoff and sediment at 15 minutes were minimal. Again, pine-needle mulches and incorporation of organic matter or duff resulted in significantly lower cumulative sediment values as compared to corresponding bare soils, with the exception of the Dollar Hill yarrow site.

Sediment yield (g m^{-2} mm^{-1})

The slope of a linear regression between cumulative sediment discharge and cumulative runoff depth ranged from 0·2–16 g mm^{-1} runoff (0–20 g m^{-2} mm^{-1} runoff), and were largely controlled by soil type, soil tillage, or cover. The high-end sediment yield values of 20 g m^{-2} mm^{-1} are equivalent to what Fifield (1992a,b) reported from much larger plots of dryland grass revegetation sites on similar slopes in eastern Colorado. Here, high sediment yields were associated with bare volcanic soils. These high-end values found here for bare soils are comparable to the ECPS (2000) reported values from much larger RS plots for gypsum, curled wood fiber blanket and paper or wood mulches w/polymer treatments, while the low sediment yields are comparable to straw, straw-coconut and wood fiber blankets, or incorporated wheat straw. Again, pine-needle mulches and incorporation of organic matter or duff resulted in significantly lower sediment yields as compared to corresponding bare soils, with the exception of the Dollar Hill bunchgrass and yarrow sites.

Several uncertainties requiring further study remain, however. Here, the variability associated with runoff from some of the granitic soils requires additional testing to better understand the role of DG grain size and depth on infiltration rates and sediment yield. Simultaneous measurements following rainfall simulation using a cone penetrometer in the field as well as grain-size distribution and permeameter measurements in the laboratory will shed some light on this apparent anomaly (e.g. Rubicon vs. Bliss and Cave Rock bare-soil tests). Initial investigation into native site hydrologic function (e.g., Blackwood Canyon) suggests that less-disturbed 'native' soils (including forest soils) be used for comparison with revegetation treatments rather than simply bare-soil plots. Similarly, disturbed slopes of far greater size and possible magnitude of watershed runoff and erosion impacts that require further evaluation include former mining areas and skiruns in the Tahoe Basin. Finally, before any revegetation can be truly evaluated, longterm analyses of the role of mulches, OM, composts and other amendments in the field *vis-à-vis* whether, and for how long, they provide enhanced infiltration capacity and erosion control in the field is essential. From this first-year study, intact pine-needle mulches appear to provide erosion control, while soil amendments enhance infiltration capacity. Ultimately, restoration should include combined treatments that provide a soil environment conducive to sustained plant growth as well as soil retention. This combination seems evident in the revegetation at Incline Village and Cave Rock estates. As to how long these treatments remain effective in the field is unknown. Additional simulation studies will be required to determine the long-term hydrologic and restoration trajectory of these sites.

REFERENCES

Battany MC, Grismer ME. 2000a. Development of a portable field rainfall simulator system for use in hillside vineyard runoff and erosion studies. *Hydrological Proceedings* **14**: 1119–1129.

Battany MC, Grismer ME. 2000b. Rainfall runoff, infiltration and erosion in hillside vineyards: effects of slope, cover and surface roughness. *Hydrological Proceedings* **14**: 1289–1304. Q3

[Q3]Claassen VP, Marler M. 1998. Annual and perennial grass growth on nitrogen-depleted decomposed granite. *Restoration Ecology* **6**(2): 175–180.

[Q3]Claassen VP, Zasoski RJ. 1998. A comparison of plant available nutrients on decomposed granite cut slopes and adjacent natural soils. *Land Degradation & Development* **9**(1): 35–46. Q3

Claassen VP, Hogan MP. 2002. Soil nitrogen pools associated with revegetation of disturbed sites in the Lake Tahoe area. *Restoration Ecology* **10**(2): 195–203.

Claassen VP, Zasoski RJ, Southard RJ. 1995. Soil conditions and mycorrhizal infection associated with revegetation of decomposed granite slopes. Soil & Biogeochemistry Section; Department of Land, Air and Water Resources. UC Davis, Davis, CA.

[Q4]ECPS. 2000. Comparison of erosion control products. CA Department of Transportation Report. Q4

Fifield JS. 1992a. Comparative evaluation of erosion control products. Proceedings of the High Altitude Revegetation Workshop, Colorado [Q5]St. Univ. CO Water Resources Research Institute Informatic Series No. 71. pp. 133–148. Q5

[Q4]Fifield JS. 1992b. How effective are erosion control products in assisting with dry land grass establishment with no irrigation? Proceedings of the International Erosion Control Association Conference XXIII. pp. 321–333. Q4

Fifield JS, Malnor LK. 1990. Erosion control materials vs. a seimarid environment—What has been learned from three years of testing? Proceedings of the International Erosion Control Association Conference XXI. pp. 233–248.

Fifield JS, Malnor LK, Dezman LE. 1989. Effectiveness of erosion control products on steep slopes to control sediment and to establish dry land grasses. Proceedings of the International Erosion Control Association Conference XX. 10 pages.

Fifield JS, Malnor LK, Richter B, Dezman LE. 1988. Field testing of erosion control products to control sediment and to establish dry land grass under arid conditions. Proceedings of the International Erosion Control Association Conference XIX. 17 pages.

Goldman CR, Jassby AP, Powell T. 1989. Interannual fluctuations in primary productivity: meterological forcing in two subalpine lakes. *Limnology & Oceanography* **34**: 310–323.

Lal R. 1997. Degradation and resilience of soils. *Philosophical Transactions: Biological Sciences* **352**(1356): 997–1010. Q6

[Q6]Montoro JA, Rogel JA, Querejeta J, Diaz E, Castillo V. 2000. Three hydro-seeding revegetation techniques for soil erosion control on anthropic steep slopes. *Land Degradation & Development* **11**: 315–325. Q4

[Q4]NRCS. 1974. Soil survey of the Tahoe Basin area, California and Nevada. US Department of Agriculture–Natural Resource Conservation Service. March.

Poulenard J, Podwojewski P, Janeau J-L, Collinet J. 2001. Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian *Paramo: Effect of tillage and burning. Catena* **45**: 185–207.

Schuster S, Grismer ME. 2004. Evaluation of water quality projects in the Lake Tahoe Basin. *Environmental Monitoring & Assessment* **90**(1–3): 225–242.

Sutherland RA. 1998a. Rolled erosion control systems for hillslope surface protection: a critical review, synthesis and analysis of available data. I. Background and formative years. *Land Degradation & Development* **9**: 465–486.

Sutherland RA. 1998b. Rolled erosion control systems for hillslope surface protection: a critical review, synthesis and analysis of available data. II. The post-1990 period. *Land Degradation & Development* **9**: 487–511.

TRG (Tahoe Research Group). 2002. *Annual Lake Tahoe Report*. UC Davis: Davis, CA.

White CA, Franks AL. 1978. Demonstration of erosion and sediment control technology: Lake Tahoe Region of CA. Municipal Environment Research Lab, Office of Research & Development. USEPA Demonstration Grant No. S803181, Cincinnati, OH.

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