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## **Improving Erosion Modeling on Forest Roads in the Lake Tahoe Basin: Small Plot Rainfall Simulations to Determine Saturated Hydraulic Conductivity and Interrill Erodibility**

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**Abstract.** *Lake Tahoe is renowned for its beauty and exceptionally clear water. The Tahoe basin economy is dependent upon the protection of this beauty and the continued availability of recreational opportunities in the area; however, scientists estimate that the continued increase in fine sediment and nutrient transport to the lake threatens to diminish this clarity in as little as 30 years.*

*The Lake Tahoe Basin Management Unit (LTBMU) is the largest land management agency in the basin. The LTBMU plans to employ WEPP: Road as a predictive tool for land planning in the basin. WEPP: Road was developed by the Rocky Mountain Research Station as an interface to the Water Erosion Prediction Project (WEPP) model. WEPP: Road allows users to quantify sediment production from road surfaces and to assess the effectiveness of best management practices on those surfaces. Model accuracy may be improved through use of site-specific parameters. The purpose of this study was to obtain estimates of hydrologic parameters for native surface roads comprised of soils derived from the two predominant parent materials in the Lake Tahoe basin.*

*Rainfall simulations were conducted on four unpaved roads to determine the saturated hydraulic conductivity and interrill erodibility. The average measured saturated hydraulic conductivity was 16 mm hr<sup>-1</sup> and the average measured interrill erodibility was 1.0 x 10<sup>6</sup> kg s<sup>-1</sup> m<sup>-4</sup>. The roads measured*

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*in this study typically produced sustained and relatively high sediment concentrations throughout the simulation period. Sustained sediment concentrations may have been due to soil water repellency.*

**Keywords.** Saturated hydraulic conductivity; Interrill erodibility; WEPP; Erosion modeling; Forest roads

## Introduction

Accurate erosion modeling of unpaved forest roads is an important tool for land managers in their efforts in preserving Lake Tahoe water quality and, more broadly, toward sustaining the basin economy. The clarity for which Lake Tahoe is renowned is threatened by sediment and nutrient transport into the lake. Land managers in the basin want to identify non-point pollution sources and implement best management practices (BMPs) to reduce the amount of fine sediment and nutrients entering the streams which feed the lake. Unpaved roads may be the greatest single source of sediment delivered to stream networks (La Marche and Lettenmaier, 2001; Wemple et al., 1996; Ziegler and Giambelluca, 1997). A model that accurately predicts erosion from unpaved forest roads can be used to identify erosional “hot spots” and forecast the efficacy of proposed roadway BMPs.

WEPP: Road, which is an internet interface for the Water Erosion Prediction Project (WEPP) model, has been used by Tahoe basin land managers since 2003 to estimate sediment delivery from forest road segments in the basin (Elliot, 2004; USDA Forest Service LTBMU, 2005). Accuracy of model predictions could be improved by parameterization for local conditions. Improved accuracy will increase utility of WEPP: Road as a planning tool in the basin. If model predictions are significantly different when local, rather than generic parameters are used, then efforts in parameterization may be worthwhile. This study uses rainfall simulation on native surface roads in the Tahoe basin to determine saturated hydraulic conductivity and interrill erodibility parameters for use in the WEPP:Road model.

### ***The WEPP Model: Infiltration and Erosion***

WEPP is a physically-based soil erosion model that provides estimates of soil erosion, sediment yield, and sediment particle size distribution of the runoff for various combinations of soil, climate, ground cover, and topographic conditions (Flanagan and Livingston, 1995). WEPP uses the Green-Ampt Mein-Larson equation for infiltration as presented by Chu (1978)

$$f = K_e \left( 1 + \frac{(\phi_e - \theta_i)\Psi}{F} \right) \quad (1)$$

where  $f$  is the infiltration rate ( $\text{mm h}^{-1}$ ),  $K_e$  is the effective hydraulic conductivity ( $\text{mm h}^{-1}$ ),  $\phi_e$  is the effective soil porosity ( $\text{mm}^3 \text{mm}^{-3}$ ),  $\theta_i$  is the initial soil water content ( $\text{mm mm}^{-1}$ ),  $\Psi$  is the average wetting front capillary potential (mm), and  $F$  is the cumulative infiltration depth (mm). The erosion process in WEPP is based on the steady-state continuity equation

$$\frac{dG}{dx} = D_i + D_f \quad (2)$$

where  $x$  is the distance downslope (m),  $G$  is sediment load ( $\text{kg s}^{-1} \text{m}^{-1}$ ),  $D_i$  is interrill erosion rate ( $\text{kg s}^{-1} \text{m}^{-2}$ ), and  $D_f$  is the rill erosion rate ( $\text{kg s}^{-1} \text{m}^{-2}$ ) (Flanagan and Nearing, 1995). Interrill erosion is determined in WEPP by

$$D_i = K_i I Q \quad (3)$$

where  $D_i$  is the interrill detachment rate ( $\text{kg s}^{-1} \text{m}^{-2}$ ),  $K_i$  is interrill erodibility ( $\text{kg s m}^{-4}$ ),  $I$  is rainfall intensity ( $\text{m s}^{-1}$ ), and  $Q$  is interrill runoff rate ( $\text{m s}^{-1}$ ). Rill erosion is an important sediment source and delivery mechanism, but is beyond the scope of this study. In the absence of concentrated flow, interrill erosion is the driving erosive mechanism, and is the focus of this study.

### The WEPP: Road Interface

The WEPP: Road interface was developed to facilitate use of WEPP for erosion and sediment delivery prediction specifically from forest roadways. The interface utilizes html screens for input and output and accepts input for road-specific variables including road design, geometry, surface characteristics, and traffic level (Fig. 1) (Elliot, 2004). Climate and soil texture can be specified from a pick list on the input screen.

Fig. 1. WEPP:Road html input screen.

WEPP: Road assumes that runoff and sediment generated by the road traveled way are routed over a fill slope and forested buffer to the stream system (Fig. 2). The length and slope of the forested buffer and fill slope can also be altered on the input screen.

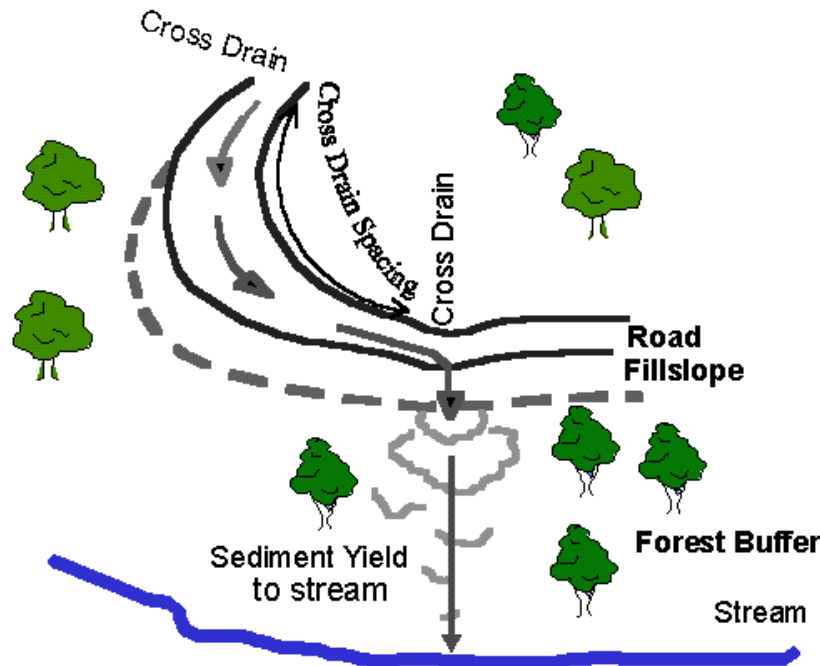


Fig. 2. Schematic of WEPP:Road conceptual model (Elliot, 2004).

Output from WEPP:Road includes average precipitation, average annual runoff from the buffer, and the sediment delivered from both the eroding section of the road prism and the bottom of the buffer. WEPP:Road offers the option to view additional output parameters including the distribution of erosion and deposition along the road, fill, and buffer, the presence of a sediment plume in the buffer, and the particle size distribution on the hillslope and in the delivered sediment (Elliot, 2004).

The current version of WEPP:Road uses hydrologic model parameters determined for native surface roadways derived from decomposed granite and volcanic parent material in central Idaho. While these Idaho-derived parameters serve as reasonable estimates, parameterization on Lake Tahoe roadway soils could improve accuracy of runoff and sediment production estimates for the basin. Higher accuracy may be warranted for evaluating effectiveness of BMPs, as differences among various BMPs are typically small compared to the difference between a given BMP and no management practice.

In the absence of concentrated flow, process-based erosion modeling of forest roads requires knowledge of the following site-specific parameters: infiltration, soil erodibility, and ground cover. Infiltration rate determines the amount of runoff from the road running surface and forest buffer. Saturated hydraulic conductivity is one of the input parameters used by the WEPP model to determine infiltration. Due to difficulties in measuring saturated hydraulic conductivity directly, steady-state infiltration rate at saturation is often used as an approximation (Foltz et al., 2009; Ziegler and Giambelluca 1997). Soil erodibility is the model input parameter which dictates how susceptible a soil is to particle detachment and erosion. In the absence of concentrated flow, interrill erosion, which is the combination of splash and sheet erosion, is the driving soil detachment mechanism. Interrill erodibility is the soil parameter which controls this process in the WEPP model. Ground cover is another important parameter, which may change due to natural variations, such as litter cover, or due to management practices, such as gravel amendments to the road running surface. Ground cover may be easily changed in the

WEPP:Road interface, following simple observation of road conditions; however, saturated hydraulic conductivity and interrill erodibility cannot be determined by simple observation, and consequently, are not readily changeable by the end-user of the model interface.

## Methods

We used rainfall simulation on small plots to derive the saturated hydraulic conductivity and interrill erodibility parameters for native surface forest roads in the Lake Tahoe basin. Simulations were performed on four roads in the basin (Fig. 3).

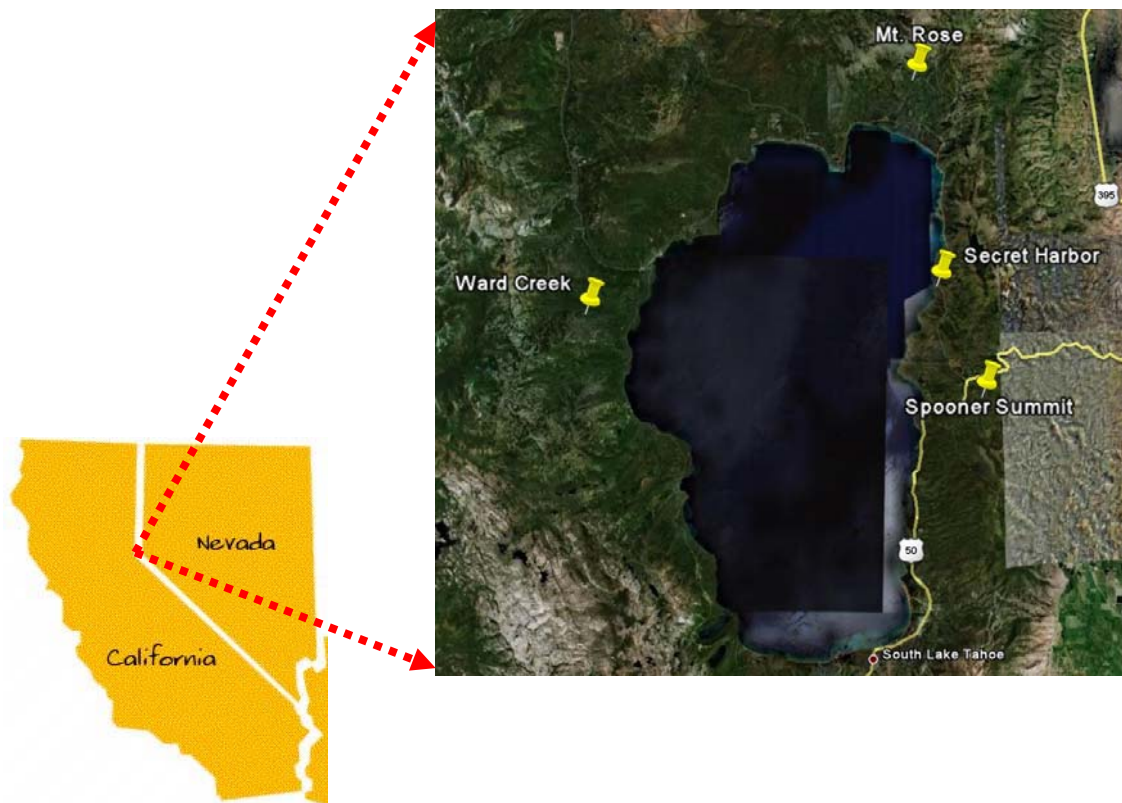


Fig. 3. Site locations for simulated rain events in the Lake Tahoe Basin, USA.

The Spooner Summit and Ward Creek roads were composed of soils derived from volcanic parent material and the Secret Harbor and Mt. Rose roads were composed of soils derived from granitic parent material. Soil water repellency was assessed on each road using the water drop penetration time (WDPT) test (Doerr, 1998; Krammes and DeBano, 1965). Six rainfall simulation plots were installed on each road, for a total of 24 plots. Plot locations were randomly chosen on each road and were typically spread within a one mile section of the road. The one-meter-square bounded plots were constructed from three sheet metal borders with a collection tray and runoff apron at the downhill edge of the plot (Fig 4). The borders and collection tray were driven 50 mm into the soil surface and sealed with bentonite to prevent seepage. Plots were installed in the tire tracks of the road running surfaces. Plot slopes ranged from 2–10% with an average of 5.6% (Table 1).





Fig. 4. One-meter-square bounded plot installed on a native surface road for rainfall simulation in the Lake Tahoe basin, USA.

A single simulated rain event was delivered to each of the bounded plots. Rainfall was simulated with a Spraying Systems Veejet 80100 nozzle affixed to a telescoping tripod that leveled the nozzle at a height of 3 m above the ground (Fig 5). A windscreen protected the plot from wind effects on rainfall distribution.



Fig. 5. Setup of rainfall simulator with wind screen on a native surface road in the Lake Tahoe basin, USA.

A storm with an intensity of  $86 \text{ mm hr}^{-1}$  and duration of 50 min was delivered to each plot. The rainfall rate was measured during a series of calibration runs prior to rainfall simulations. Simulations were conducted under antecedent moisture conditions which ranged from 0.1–2.5% gravimetric water content (Table 1). The goal of the simulations was to achieve steady-state runoff and not indented to be representative of any particular design storm. This design was used to ensure soil saturation, such that saturated hydraulic conductivity could be determined

based on infiltration. Timed grab samples were taken during every minute of the runoff period and used to calculate runoff rates and sediment concentrations.

Steady-state runoff rates were used to determine saturated hydraulic conductivity. The saturated hydraulic conductivity was estimated as the rainfall rate minus the steady-state runoff rate. Rearranging Eq (3), interrill erodibility ( $K_i$ ) was estimated from

$$K_i = \frac{D_i}{IQ} \quad (4)$$

where  $D_i$  is the sediment delivery rate averaged over the entire runoff interval ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $I$  is the rainfall intensity ( $\text{m s}^{-1}$ ), and  $Q$  is the runoff rate averaged over the entire runoff interval ( $\text{m s}^{-1}$ ) (Fangmeier et al., 2006).

## Results and Discussion

The average runoff hydrograph for each road is shown in Fig. 6a. The four roads exhibited similar trends in evolution of runoff, characterized by a steep rising limb, followed by a steady-state runoff rate approaching  $18 \text{ mL s}^{-1}$  (Fig. 6a). The Mt. Rose hydrograph appeared to have a somewhat slower rising limb, although it did eventually reach a steady-state runoff rate comparable to those measured on the other roads (Fig. 6a). Mt. Rose also had the smallest slope, at 4% (Table 1), and although variability in slope among the roads was low, this lower slope may have influenced the shape of the hydrograph.

Table 1. Saturated hydraulic conductivity and interrill erodibility parameters measured from four native surface roads in the Lake Tahoe basin, USA.

Road	Parent Material	Slope (%)	Soil Moisture (%)	Textural Class	$K_s$ ( $\text{mm hr}^{-1}$ )		$K_i$ ( $\text{kg s m}^{-4}$ ) $\times 10^6$	
					Average	s	Average	s
Spooner Summit	Volcanic	5	1.1	Sand	13	3.7	1.1	0.4
Secret Harbor	Granitic	9	0.1	Gravelly sand	19	6.8	0.7	0.2
Mt. Rose	Granitic	4	0.2	Sand	16	6.7	1.1	0.3
Ward Creek	Volcanic	5	2.5	Gravelly loamy sand	16	3.6	1.2	0.2

$K_s$  = saturated hydraulic conductivity

$K_i$  = interrill erodibility

s = sample standard deviation



Trends in sediment concentrations were somewhat more variable than those in runoff rates among the four roads (Fig. 6). Most notably, Spooner Summit and Ward Creek (both of which are derived from volcanic parent material) exhibited peaks in sediment concentration at the beginning of the rainfall simulation and then followed a decreasing trend to reach steady-state sediment concentrations between minutes five and ten (Fig. 6b). Previous studies have reported similar trends in sediment concentrations (Foltz et al., 2009; Ziegler et al., 2001). In contrast, Secret Harbor and Mt. Rose had relatively low sediment concentrations at the beginning of the run and followed increasing trends to steady-state (Fig. 6b). All roads, regardless of initial trend, reached a steady-state sediment concentration approaching  $15 \text{ g L}^{-1}$ . The steady-state concentration was sustained throughout the remainder of the simulation period and did not drop off with time as described in previous studies (Foltz et al., 2009; Ziegler et al., 2001).

One possible cause for the sustained sediment concentrations is the moderate to strong water repellency measured on these roads (Table 2). There was a high degree of spatial variability in the WDPT, and although we did not measure any soil water repellency on the Mt. Rose road during the WDPT tests, we did observe hydrophobic conditions during the rainfall simulation, characterized by “beading” of runoff from the plot. DeBano (2000) reported on the mechanisms for increased erosion via raindrop splash under hydrophobic soil conditions. Hydrophobicity limits surface sealing during a rainfall event, as hydrophobic soil particles tend to remain dry, non-cohesive, and thus, susceptible to detachment by raindrop splash (DeBano 2000).

We did not observe a marked difference in sediment production between the volcanic and granitic-based soils as reported in Grismer and Hogan (2005) from slopes ranging between 30–70% in the Tahoe basin.

Table 2. Range in water drop penetration time (WDPT) and corresponding water repellency classes measured on four roads in the Lake Tahoe basin

Road	WDPT (s)	Water Repellency Class
Spooner Summit	0–420	Wettable–strongly repellent
Secret Harbor	0–63	Wettable–strongly repellent
Mt. Rose	0–1	Wettable
Ward Creek	0–140	Wettable–strongly repellent

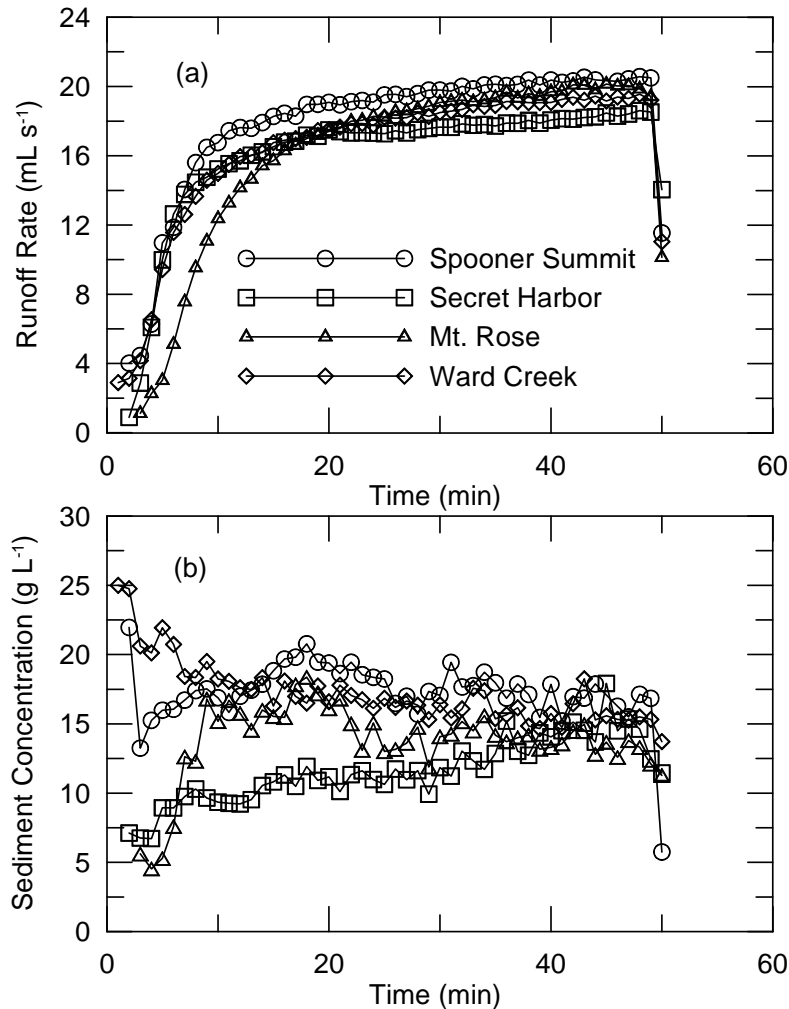


Fig. 6. Average (a) runoff rate and (b) sediment concentration measured each minute throughout the runoff periods of simulated rain events on four native surface roads in the Lake Tahoe basin.

Average saturated hydraulic conductivity ranged from 13–19 mm hr<sup>-1</sup> (Table 1). The standard deviation in saturated hydraulic conductivity within each road was approximately equal to the range of the measured average values (Table 1); this high variability precludes discussion of differences among road averages. Interrill erodibility ranged from 0.7–1.2 × 10<sup>6</sup> kg s m<sup>-4</sup> (Table 1). Again, high variability obscured any potential differences in interrill erodibility among the roads.

## Conclusions

Measured runoff and sediment concentration during simulated rainfall events were used to determine saturated hydraulic conductivity and interrill erodibility of four native surface roads in the Lake Tahoe basin.

The runoff rates measured on these roads followed trends typical of native surface forest road runoff hydrographs (Foltz et al., 2009; Sheridan et al., 2008). The two granitic-based roads demonstrated sediment concentration trends similar to those reported in other studies; however

the volcanic-based roads followed a slightly different trend, as they started out with relatively low sediment concentrations at the beginning of the rain events and gradually increased to steady-state concentrations. Soil water repellency on the road running surfaces may have caused the sustained sediment concentrations measured during the rainfall events. The shapes of the hydrographs and sedigraphs indicate differences in the hydrologic responses of the roads; however they do not necessarily affect the model parameters, saturated hydraulic conductivity and interrill erodibility.

Average saturated hydraulic conductivity ranged from 13–19 mm hr<sup>-1</sup> and average interrill erodibility ranged from 0.7–1.2 x 10<sup>6</sup> kg s m<sup>-4</sup>. High variability in the measured parameters precluded assessment of differences among the roads or parent materials.

Future work will involve combining rainfall simulation data from over 25 roads in Idaho, Montana, Colorado, Nevada, and California. This synthesis of data will allow us to more adequately assess variability in saturated hydraulic conductivity and interrill erodibility on native surface roads in the inter-mountain northwest.

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