SOIL EROSION MODEL PREDICTIONS USING PARENT MATERIAL/SOIL TEXTURE-BASED PARAMETERS COMPARED TO USING SITE-SPECIFIC PARAMETERS

R. B. Foltz, W. J. Elliot, N. S. Wagenbrenner

ABSTRACT. *Forested areas disturbed by access roads produce large amounts of sediment. One method to predict erosion and, hence, manage forest roads is the use of physically based soil erosion models. A perceived advantage of a physically based model is that it can be parameterized at one location and applied at another location with similar soil texture or geological parent material. To test this perception, a two-part study was conducted to compare soil erosion model predictions using parent material/soil texture-based parameters to predictions using site-specific parameters. The first step was to determine site-specific erosion parameters using rainfall simulation. The second step was to compare erosion model results for a typical road network using the two parameter sets. Lake Tahoe was chosen for the study because it had parent materials similar to sites where parameterization had been performed. The coefficient of variation in runoff and sediment mass from the Lake Tahoe rainfall simulations varied from 8% to 36%. These values, although smaller than those reported from natural rainfall studies, are an indication of the inherent variability of erosion measurements. Effective hydraulic conductivity determined by rainfall simulation for a granitic parent material at Lake Tahoe was greater than that for the similar parent material. A volcanic parent material from Lake Tahoe also had higher effective hydraulic conductivity than that for another volcanic parent material. Soil interrill erodibility values for granitic parent material were similar, while values for volcanic parent material were slightly greater for the Lake Tahoe soil. Only the effective hydraulic conductivity of the granitic parent material was statistically different at the 95% confidence level from the parent material/soil texture-based values. Process-based WEPP model predictions of runoff from a typical Lake Tahoe road network were 82% and 73% less for granitic and volcanic soils, respectively, when using the site-specific Lake Tahoe values compared to similar parent material values. Corresponding differences between sediment yields were 85% and 78% less. Most of the decrease was due to fewer snowmelt runoff events. The inherent variability in soil erosion measurements results in a corresponding variability in erosion model parameters derived from those measurements. As a result, model predictions have an inherent accuracy range. In this Lake Tahoe study, the erosion measurement variability resulted in a WEPP model prediction range of approximately ±75% of the mean for both runoff and sediment mass.*

Keywords. *Forest roads, Lake Tahoe, Parameterization, Process-based models, Soil erosion, WEPP.*

Forest disturbances that remove protective vegetation cover such as wildfires or access roads have the potential to produce large amounts of sediment annually. Vegetation recovery from wildfires often occurs in three to five years depending on location (Robichaud et al., 2000). Conversely, vegetation recovery on access roads does not occur as long as traffic is present. This lack of vegetation recovery on access roads contributes to making them the greatest single source of sediment in forest environments (Megahan and King, 2004; Ziegler et al., 2004). The USDA Forest Service manages over 600,000 km of low-volume forest roads. Typically, a combination of physical, site-specific characteristics result in a small percentage of roads contributing the majority of sediment (Gucinski et al., 2001; Megahan and King, 2004). Although access roads can contribute significant amounts of sediment, these road networks are necessary for forest management as well as recreational opportunities (Gucinski et al., 2001; USFS, 2011). When roads are properly maintained and strategically located, road-generated sediment contributions can be minimized. The challenge is to identify and quantify those particular site-specific road attributes that result in high erosion locations.

Sediment production from unpaved roads is dominated by five factors: climate, infiltration, raindrop splash, concentrated flow, and vegetative cover. Process-based soil erosion models explicitly simulate these processes at the hillslope and watershed scale using numerical solutions of the governing equations. The Water Erosion Prediction Project (WEPP) and the Kinematic Erosion Model (KINEROS2) are two models that have been adapted to predict erosion on forest roads (Elliot et al., 1995; Laflen et at., 1997; Ziegler et al., 2001). The WEPP model includes components for the five dominate road erosion factors.

Climate addresses the timing of rain, snow, and snowmelt events during the year. The climate component of WEPP generates mean daily precipitation, daily maximum and mini-

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mum temperature, mean daily solar radiation, and mean daily wind direction and speed.

Infiltration is a measure of the rate at which water is absorbed by the road surface. WEPP uses the Green-Ampt Mein-Larson equation for infiltration, as presented by Chu (1978):

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

where f is the infiltration rate (mm h^{-1}), K_e is the effective hydraulic conductivity (mm h^{-1}), φ_e is the effective soil porosity (mm^3 mm^{-3}), θ_i is the initial soil water content (mm mm^{-1}), Ψ is the average wetting front capillary potential (mm), and F is the cumulative infiltration depth (mm). Effective hydraulic conductivity is the term used in the WEPP technical documentation (Alberts et al., 1995), which states that effective hydraulic conductivity "is related to the saturated hydraulic conductivity of the soil, but it is important to note that it is not the same as or equal in value to the saturated hydraulic conductivity of the soil." We will use the term "effective hydraulic conductivity" to describe hydraulic conductivity calculated from the WEPP model. The average wetting front capillary potential is calculated in WEPP as a function of soil texture, soil water content, and soil bulk density (Alberts et al., 1995). Rainfall simulation is generally used to determine effective hydraulic conductivity for unpaved roads (Foltz et al., 2007).

Raindrop splash is the result of rain impacting the road surface and dislodging soil particles. These dislodged soil particles are transported from the road surface by shallow overland flow. The WEPP model describes raindrop splash erosion as:

$$D_i = K_i \times I \times q \tag{2}$$

where D_i is the interrill detachment rate (kg s^{-1} m^{-2}), K_i is the interrill erodibility coefficient (kg s m^{-4}), I is the rainfall intensity (m s^{-1}), and q is the interrill runoff rate (m s^{-1}). Rainfall simulation is also used to determine the interrill erodibility coefficient (Foltz et al., 2007). Both the effective hydraulic conductivity and the interrill erodibility coefficient can be determined from the same rainfall simulation.

Concentrated flow occurs on roads in wheel ruts and in the adjacent ditches. This type of flow causes several times greater erosion than raindrop splash and should be minimized in a well designed and maintained road. Concentrated flow simulations on roads are important but beyond the scope of this study.

Vegetative cover is another of the factors influencing road erosion. The undisturbed forest floor typically has greater than 80% ground cover due to duff and plants that protect the bare soil from raindrop splash and reduce the velocity of concentrated flow. Roads that are open to traffic have little to no vegetative cover to protect the surface. Previous studies conducted by our group have shown that roads closed to traffic revegetate naturally, with three to five years being enough to reestablish a thin duff layer and vegetative cover. Decades are required for substantial return of the tree canopy (Foltz et al., 2009; Froehlich et al., 1985; Wert and Thomas, 1981).

While process-based models are based on physical processes, development of appropriate input parameters is still a challenge and has resulted in years of field studies with both simulated and natural rainfall to parameterize the models under different conditions and for different locations. WEPP has been parameterized for various land use and management conditions, including crop, range, and forest lands; roads; and prescribed and natural fires. Our group has conducted numerous rainfall simulation studies over the years to derive road-specific infiltration and sediment detachment parameters for the WEPP model (Elliot et al., 1995; Foltz and Elliot, 2001; Foltz and Truebe, 2003; Foltz et al., 2008; Foltz et al., 2009). WEPP:Road, an on-line interface to the WEPP model, uses the results of these studies to estimate long-term soil erosion and sediment delivery from forest roads.

Elliot et al. (1993) used the WEPP cropland soil relationship to predict effective hydraulic conductivity for five native-surface roads with soil textures of loamy sand, sandy loam, loam, and gravelly loamy sand. The cropland soil relationship predicted effective hydraulic conductivities ranging from 0.002 mm h^{-1} for a sandy loam to 0.24 mm h^{-1} for a loam. Elliot et al. (1993) also compared the WEPP-predicted total runoff to observed total runoff from rainfall simulation studies and concluded that the predicted value of 0.029 mm h^{-1} for gravelly loamy sand needed to be increased to 2.87 mm h^{-1} in order to achieve differences in predicted and observed total runoff of "seldom greater than 10%." No optimization of effective hydraulic conductivity was performed in their study. In this context, we mean optimization to be iteratively running a model while changing certain model parameters until a predefined objective is achieved or minimized.

Luce and Cundy (1994) used Philip's infiltration equation coupled to a kinematic wave overland flow equation to determine four parameters to model the processes of infiltration, depression storage, and overland flow from rainfall simulation studies. Using an optimization routine, they determined the best combination of the four parameters for six native-surface roads with soil textures of loamy sand, sandy loam, and silt loam. They reported hydraulic conductivities ranging from 5×10^{-5} to 8.82 mm h^{-1}. Philip's equation uses time as an independent variable, while the Green-Ampt equation uses cumulative infiltration as an independent variable. Direct comparison of "hydraulic conductivity" determined by these two equations is, therefore, problematic.

Foltz et al. (2009) reported an average saturated hydraulic conductivity of 11 mm h^{-1} for a re-opened native-surface road with sandy loam texture. The road had been allowed to revegetate for 30 years and then reopened and used for a small timber sale prior to the rainfall simulation. In this study, the same effective hydraulic conductivity optimization method as used in the current study was used and is, therefore, directly comparable.

Foltz et al. (2009) reported an interrill erosion coefficient range of 1.0×10^6 to 1.8×10^6 kg s m^{-4} from the same road that had been closed for 30 years. In a study of an obliterated road, Foltz et al. (2008) found interrill erodibility coefficients ranging from 1.2×10^6 to 6.1×10^6 kg s m^{-4}.

These studies have led to better estimates of erosion parameters for forest roads and have given an indication of the variability in these parameters among forest roads with different traffic use histories and in various conditions (i.e., new, old, bladed, abandoned, or decommissioned). The erosion parameters of infiltration and interrill and rill erodibility have historically been reported as a function of either geological parent material or soil texture. In this article, we will refer to these parameter sets as parent material/soil texture-based.

While soil texture is used to estimate erosion parameters for forest roads (Elliot et al., 1999) and has long been accepted in agricultural settings, beginning with the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), the accuracy of model predictions for forest roads might be improved by determining site-specific parameters rather than using a parent material/soil texture-based parameter set. Welsh (2008) observed road erosion rates much greater than those predicted using a parent material/soil texture-based granitic soil parameter set for roads in the Pike's Peak batholith located in central Colorado. Conversely, WEPP-predicted post-fire erosion rates using a parent material/soil texture-based granitic soil parameter set from sites in California, Colorado, Montana, and Washington (W. Elliot, unpublished data, 2010, USDA Forest Service, Rocky Mountain Research Station) resulted in overprediction of sediment rather than under prediction, as in the Welsh study. These examples of widely varying erosion parameters from granitic parent material locations suggest that erosion parameters may not be consistent within similar geologies. If model predictions are sufficiently different when site-specific parameters are used, rather than parent material/soil texture-based parameters, then efforts in site-specific parameterization may be worthwhile.

The goal of this study was to compare WEPP model predictions where infiltration and interrill erosion model parameters were based on either similar parent material/soil texture values or parameters determined from on-site rainfall simulation. The objectives were: (1) to determine effective hydraulic conductivity and the interrill erodibility coefficient for two parent materials, and (2) to compare long-term WEPP erosion predictions for a typical network of roads based on the site-specific parameters to predictions based on parent material/soil texture parameters.

The Lake Tahoe basin was selected for determination of site-specific parameters. Lake Tahoe is renowned for its beauty and exceptionally clear water. However, the lake has been losing clarity over the past 30 years at a rate of approximately 30 cm per year due primarily to phosphorus and fine particulate matter (Bachand et al., 2010). The Lake Tahoe basin economy is dependent upon the protection of this beauty and the continued availability of recreational opportunities in the area. The basin contains large areas of both granitic and volcanic parent material derived soils that compare favorably with similar parent material soils that have had WEPP parameters determined by the Rocky Mountain Research Station. The USDA Forest Service Lake Tahoe Basin Management Unit (LTBMU) is the largest land management agency in the basin and uses WEPP:Road as a predictive tool for land planning.

METHODS

The study sites were located on four native-surface roads in the Lake Tahoe basin (fig. 1). The Spooner Summit and Ward Creek roads were composed of soils derived from volcanic parent material. The Secret Harbor and Mt. Rose roads were composed of soils derived from granitic parent material. Road surface soil texture was determined by wet sieving (ASTM, 2007).

RAINFALL SIMULATION

Six rainfall simulation plots per road segment were installed in the Spooner Summit, Ward Creek, Secret Harbor, and Mt. Rose watersheds, resulting in a total of 24 plots. Plot locations were randomly chosen on each road and were typically located within a one-mile section of road. One-meter-square bounded plots were constructed from three sheet metal borders plus a collection tray and runoff apron at the downhill edge of the plot. The borders were driven 50 mm into the soil surface. The runoff apron was sealed with bentonite to prevent water seepage under the runoff apron. Plots were installed in the tire tracks of the running surface. Plot slopes ranged from 2% to 10% with an average of 5.6%.

A backpackable rainfall simulator designed and constructed by the Rocky Mountain Research Station was

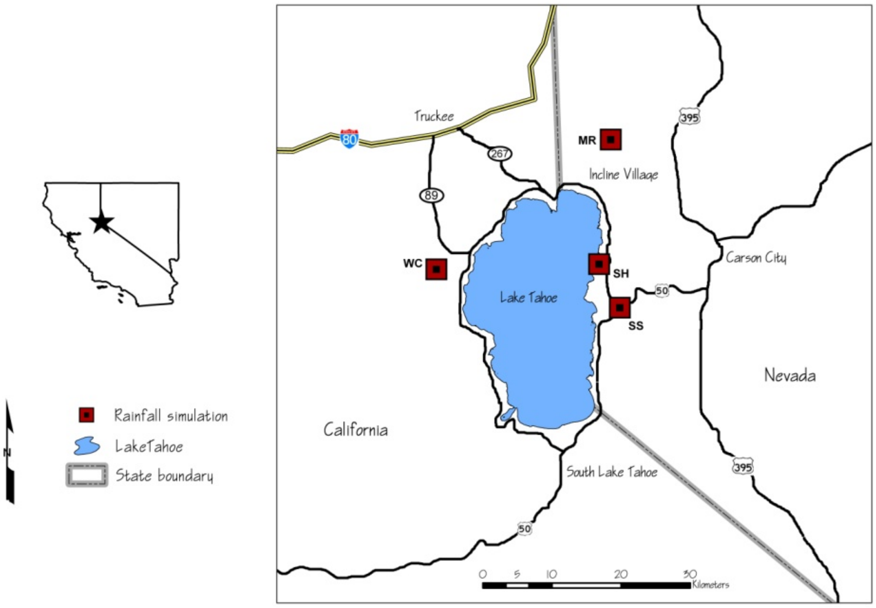

Figure 1. Location of the rainfall simulation sites at Mt. Rose (MR), Secret Harbor (SH), Spooner Summit (SS), and Ward Creek (WC).

used (Foltz et al., 2007). This simulator has a single VeeJet 80100 nozzle in a spray-down configuration and when operated at 41 kPa produces drops with a kinetic energy of 200 kJ ha^{-1} mm^{-1} (Meyer and Harmon, 1979).

A simulated rainfall with an intensity of 86 mm h^{-1} and a target duration of 50 min was delivered to each plot. The duration was extended to 60 min for two of the simulations to achieve steady-state runoff. The rainfall rate was measured during a series of calibration runs prior to rainfall simulations. Timed grab samples were taken during every minute of the runoff period and used to calculate runoff rates and sediment concentrations. Simulations were conducted under antecedent moisture conditions that ranged from 0.1% to 2.5% gravimetric water content.

The goal of the simulations was to achieve steady-state runoff, and the simulations were not intended to be representative of any particular design storm. The intensity was chosen to ensure that the entire plot contributed runoff and to exceed the expected steady-state infiltration rate. Both of these conditions are necessary to calculate effective hydraulic conductivity from equation 1 and the interrill erosion coefficient from equation 2.

EFFECTIVE HYDRAULIC CONDUCTIVITY

Soil hydraulic conductivity can be calculated by at least two different methods. One method is to calculate the difference between the rainfall rate and the steady-state runoff (Rawls et al., 1990; Foltz et al., 2009; Ward and Bolton, 2010). A second method is to use the WEPP model to determine effective hydraulic conductivity (Nearing et al. 1989; Foltz et al., 2007; Foltz et al., 2009). Since the focus of the study was the WEPP model, we chose to use WEPP to determine effective hydraulic conductivity by comparing predicted values from the WEPP model with measured values from the rainfall simulations.

When the WEPP model is run for a single storm, a runoff hydrograph is generated and the peak flow and total runoff volume are predicted. The optimized fit for effective hydraulic conductivity was found by iteratively changing the assumed effective hydraulic conductivity value until the differences between the corresponding predicted and observed runoff volumes, and between the predicted and observed peak runoff rates, were minimized, i.e., minimizing the objective function (eq. 3):

$$OBJ = \left(RO_{obs} - RO_{WEPP}\right)^2 + \left(Peak_{obs} - Peak_{WEPP}\right)^2 \quad (3)$$

where RO_{obs} is the observed runoff (mm), RO_{WEPP} is the WEPP-predicted runoff (mm), $Peak_{obs}$ is the observed peak runoff (mm h^{-1}), and $Peak_{WEPP}$ is the WEPP-predicted peak runoff (mm h^{-1}).

We used the objective function (eq. 3) to match both the runoff volume and the peak runoff rate. It is possible to predict a hydrograph that matches the runoff volume, but not the peak flow. For example, a hydrograph that begins at minute 15, peaks at 40 mm h^{-1}, and ends at minute 50 has a runoff volume of 23.3 mm. A hydrograph that begins at minute 2, peaks at 29 mm h^{-1}, and ends at minute 50 also has a runoff volume of 23.3 mm. Matching only the peak flow or only the total volume does not replicate the hydrograph. Our choice of the objective function attempts to satisfy both criteria and closely approximate the shape of the hydrograph.

To estimate how well the predicted hydrograph matched the observed hydrograph, we used the Nash-Sutcliffe coefficient (Moriasi et al., 2007). Values range from negative infinity to 1, with a value of 1 representing perfect agreement between observed and predicted data. A value of 0 indicates that there is no difference between using the mean of the observed data and the model predictions. Values less than 0 indicate that the mean of the observed data is a better estimate than the model data.

INTERRILL ERODIBILITY COEFFICIENT

The interrill erodibility coefficient in equation 2 can be determined either by direct solution (Elliot et al., 1989) or by using the WEPP model (Nearing et al., 1989; Foltz et al., 2009). Similar to our selection of the WEPP model for effective hydraulic conductivity, we chose to use the WEPP model to determine the interrill erodibility coefficient. Once the effective hydraulic conductivity was found, the value of the interrill erodibility coefficient required for the WEPP-predicted erosion to match the observed erosion was determined.

STATISTICAL COMPARISON OF HYDRAULIC CONDUCTIVITY AND INTERRILL ERODIBILITY

The WEPP:Road documentation (Elliot et al., 1999) recommends an effective hydraulic conductivity of 3.8 mm h^{-1} for granitic parent material. The recommended interrill erodibility coefficient value is 2×10^6 kg s m^{-4}. There is no recommendation for a volcanic parent material soil. For sandy loam soil texture, which is the nearest soil texture to sand (granitic) and loamy sand (volcanic), the WEPP:Road documentation recommends an effective hydraulic conductivity of 3.8 mm h^{-1} and an interrill erodibility coefficient of 2×10^6 kg s m^{-4}.

To statistically compare the effective hydraulic conductivity and interrill erodibility coefficient determined by the rainfall simulation to the WEPP:Road recommended values, we used a t-test of the difference between the rainfall simulation values and the WEPP:Road recommended values. A confidence level of 95% was used. The values of effective hydraulic conductivity and interrill erodibility coefficient from each rainfall simulation within a watershed were repeated measures; therefore, we used the average values for each watershed in the t-test. Granitic and volcanic parent material soils were tested separately.

WEPP PREDICTIONS USING PARENT MATERIAL / SOIL TEXTURE-BASED PARAMETERS COMPARED TO SITE-SPECIFIC PARAMETERS

The parent material/soil texture-based parameter set used all of the approximately 400 WEPP input parameters recommended by Elliot et al. (1999). The site-specific parameter set substituted only the rainfall-determined effective hydraulic conductivity and interrill erodibility coefficient for the Lake Tahoe basin. We chose to illustrate the differences between the parent material/soil texture-based parameter set and the site-specific parameter set by using the WEPP model to make predictions from a network of typical roads in the Glenbrook Creek watershed at Lake Tahoe. The average annual runoff depth, average annual sediment yield, and number of runoff events from rainfall and snowmelt for 30 years of simulated Lake Tahoe climate were compared. Within these 30 years of daily weather values would be a range of precipitation and snow melt intensities typical of the local climate, with high-intensity storms and snow melt events dominating the predicted erosion rates.

The climate file was developed by Tetra Tech, Inc., for the Dynamic Lake Model (Schladow et al., 2004) used to determine the total maximum daily load (TMDL) for sediment into Lake Tahoe (Tetra Tech, 2007). Tetra Tech developed the climate file using locally observed weather data, customization of observed data to local influences, and a high-resolution, grid-based synthetic data set based on the Fifth-Generation Mesoscale Model (MM5). We chose a combination of roads to illustrate the range of differences between the parameter sets. This combination of roads was not an attempt to model results from the rainfall simulations but rather to model a typical road in the Glenbrook Creek watershed. A 4 m wide, outsloped, rutted road with a road gradient of either 2% or 8% on either granitic or volcanic parent materials was chosen. Based on a road culvert inventory in the Glenbrook Creek watershed (Efta, 2009), runoff and erosion from road segments with a culvert spacing of either 25 m or 105 m were predicted. These lengths represented the 25th and 90th percentile of culverts in the watershed. This combination of eight roads represents the range from a short culvert spacing (25 m), low gradient (2%) to a long culvert spacing (105 m), steep gradient (8%) road typical of the Glenbrook Creek watershed.

RESULTS AND DISCUSSION

The soil texture of the granitic locations was sand, while the texture of the volcanic locations was loamy sand (table 1). The mean particle diameters (d_{50}) for the two soils were similar at 0.33 and 0.39 mm. On Lake Tahoe cut slope and ski area soils, Grismer and Hogan (2005a) reported that the d_{50} of granitic soils was approximately twice that of volcanic soils. Our road surface soils did not exhibit this wide difference in mean diameters. Foltz and Truebe (1995) reported that the logging truck traffic from a 4.3 million board feet timber sale caused considerable breakdown of an aggregate surface road. Reid and Dunne (1984) mentioned two processes to generate fine sediments and, hence, change the mean diameter on road surfaces: (1) crushing of the surface materials and (2) forcing upward of fine-grained sediment from the road bed. Rhee (2006) investigated how traffic changed the physical properties of forest road aggregate. He found that crushing due to traffic was the dominant process producing fine particles. Based on these studies, we postulate that traffic on our road surfaces was sufficient to mechanically break or grind the soils to similar mean diameters.

Table 1. Soil characteristics for Lake Tahoe basin rainfall simulation locations with matching Elliot et al. (1999) soils.

Parent Material	Soil Texture	Rock (%)	Sand (%)	Clay (%)	d_{50} (mm)	Pre-Rain Water Content (%)
Granitic	Sand	9	89	0.4	0.33	0.16
Volcanic	Loamy sand	18	85	0.7	0.39	1.81
	Sandy loam (Elliot et al., 1999)	20	60	5	--	--

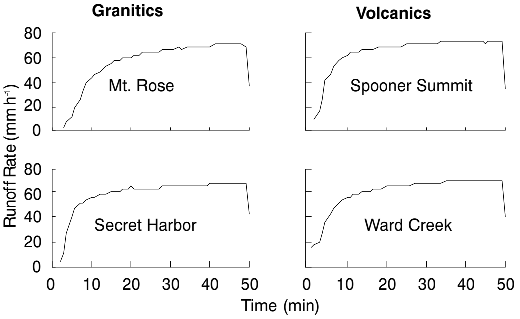

Figure 2. Composite hydrographs (n = 6) during rainfall simulations at four Lake Tahoe locations. Rainfall rates were 86 mm h^{-1}.

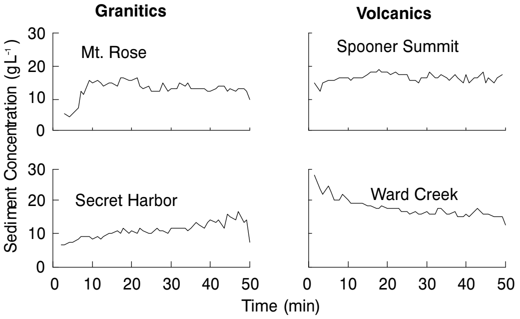

Figure 3. Composite sediment concentrations (n = 6) during rainfall simulations at four Lake Tahoe locations.

The composite runoff hydrograph and sediment concentration for each location are shown in figures 2 and 3. Each of the locations generated runoff within 3 min of initiation of rainfall, followed by a steep rising limb to steady-state runoff within 50 to 60 min. Following cessation of rainfall, runoff declined to zero within 1 min. These hydrograph characteristics are typical of small-plot rainfall simulations on native-surface roads (Foltz et al., 2009; Sheridan et al., 2008) and reflect a small depression storage, a vegetation-free surface, and a shallow soil depth. Only the Ward Creek site exhibited an initial sediment concentration peak followed by a decreasing concentration, which is typical of rainfall simulations on forest roads where the loose material on the road surface is flushed off by the initial flows (Foltz et al., 2009; Ziegler et al., 2001).

Runoff and sediment mass from the rainfall simulations are shown in table 2. The volcanic soils produced 8% more runoff than the granitic soils and 18% more sediment. Note that the coefficient of variation (CV) increased from 8% to 10% for runoff to 20% to 36% for sediment mass. These values are indicators of the degree of spatial variability for these Lake Tahoe native-surface roads.

Nearing et al. (1999) found an inverse power relationship between coefficient of variation and mass of sediment per

Table 2. Rainfall simulation averages for Lake Tahoe basin parent materials.

Parent Material	Statistic	Rainfall Duration (min)	Runoff Volume (mm)	Sediment Mass (kg)	Average Conc. (g mm^{-1})	Runoff Coeff. (%)
Granitic	Avg.	50.8	47.4	1.110	23.5	64
	CV (%)	6	10	36	36	10
Volcanic	Avg.	50.8	51.7	1.356	26.16	70
	CV (%)	6	8	20	15	9

Table 3. Effective hydraulic conductivity and interrill erodibility coefficient for Lake Tahoe basin parent materials.[a]

Parent Material	n	Effective Hydraulic Conductivity		Interrill Erodibility Coefficient	
		mm h^{-1}	CV (%)	kg s m^{-4}	CV (%)
Granitic	12	9.3	40	2.2×10^6	40
Volcanic	12	7.5	37	3.1×10^6	62

[a] WEPP:Road sandy loam uses an effective hydraulic conductivity of 3.8 mm h^{-1} and an interrill erodibility coefficient of 2.0×10^6 kg s m^{-4}.

unit area for erosion plots exposed to natural precipitation. Their equation, although not developed for simulated rainfall, predicts a coefficient of variation for the sediment mass per unit area from the rainfall simulation plots of 45% to 49%. These values are higher than our observed values of 20% to 36%. Using data from Foltz et al. (2009) for a forest road in Idaho, we calculate a coefficient of variation for the sediment mass per unit area of 25%. Data from Ziegler et al. (2001) from rainfall simulation on forest roads in Thailand have a coefficient of variation for sediment mass per unit area of 47%. We speculate that the higher degree of control over rainfall intensity was responsible for the lower coefficients of variation from the rainfall simulation studies.

EFFECTIVE HYDRAULIC CONDUCTIVITY

The effective hydraulic conductivities determined from the rainfall simulations for both parent materials are shown in table 3. Compared to the Elliot et al. (1999) sandy loam soil, the measured effective hydraulic conductivity for Lake Tahoe granitic soils were nearly 2.5 times higher, while the volcanic soils were nearly 2 times higher.

The Nash-Sutcliffe model efficiency coefficient ranged from 0.994 to 0.790, indicating good agreement between the WEPP-predicted and the observed hydrographs (fig. 4). There were no apparent differences in Nash-Sutcliffe coefficients between parent materials. We concluded that using the objective function to determine effective hydraulic conductivity in the WEPP model was well suited to modeling both the runoff depth as well as the shape of the hydrograph from these native-surface road plots.

The Lake Tahoe measured effective hydraulic conductivity values of 9.3 and 7.5 mm h^{-1} are higher than those reported by Foltz et al. (2009) for roads with moderate traffic (0.2 to 5 mm h^{-1}) but less than those of a road re-opened to traffic after 30 years of non-use (13 to 21 mm h^{-1}). The Lake Tahoe roads chosen for rainfall simulation were low-traffic roads with one to three passes of passenger car or light pickup traffic per day. In contrast, the moderate-traffic roads reported by Foltz et al. (2009) and Elliot et al. (1999) were open to heavy logging truck traffic. The increased infiltration of the Lake Tahoe roads was likely due, in part, to the amount and type of traffic.

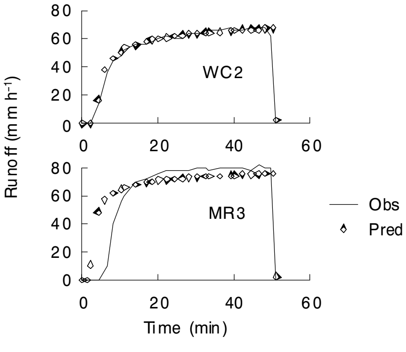

Figure 4. Observed and WEPP-predicted hydrographs for the highest Nash-Sutcliffe coefficient (0.994) for Ward Creek 2 (WC2) and the lowest Nash-Sutcliffe coefficient (0.790) for Mt. Rose 3 (MR3).

INTERRILL ERODIBILITY COEFFICIENT

The interrill erodibility coefficients determined from the rainfall simulations for both parent materials are shown in table 3. The site-specific granitic parent material value determined from the rainfall simulation was 2.2×10^6 kg s m^{-4}, an increase from the parent material/soil texture-based value of 2.0×10^6 kg s m^{-4}. The site-specific volcanic parent material value determined from the rainfall simulation was 3.1×10^6 kg s m^{-4}, also an increase from the parent material/soil texture-based value of 2.0×10^6 kg s m^{-4}.

The Lake Tahoe measured interrill erodibility coefficient values of 2.2×10^6 and 3.1×10^6 kg s m^{-4} are also higher than those reported by Foltz et al. (2009) for roads with moderate traffic (1.5×10^6 to 2.0×10^6 kg s m^{-4}) and higher than those of a road re-opened to traffic after 30 years of non-use (1.0×10^6 to 1.8×10^6 kg s m^{-4}). The higher values from Lake Tahoe roads are a reflection of the non-typical road sediment concentration changes during the simulated rainfall event, as shown in figure 3. Although WEPP does not predict a sediment rate graph, a higher interrill erodibility coefficient is required to match the amount of sediment from a constant sediment rate (the condition at Lake Tahoe) rather than from a rate that decreases with time (the condition more typical of forest roads).

STATISTICAL COMPARISON OF HYDRAULIC CONDUCTIVITY AND INTERRILL ERODIBILITY

The t-test between the parent material/soil texture-based and the site-specific effective hydraulic conductivity indicated a statistically significant difference for the granitic parent material but not for the volcanic parent material. The t-test between the parent material/soil texture-based and the site-specific interrill erodibility indicated no statistically significant difference for either the granitic or the volcanic parent material. Figure 5 shows box plots for both parameter sets to illustrate the range of variability. We chose to use the

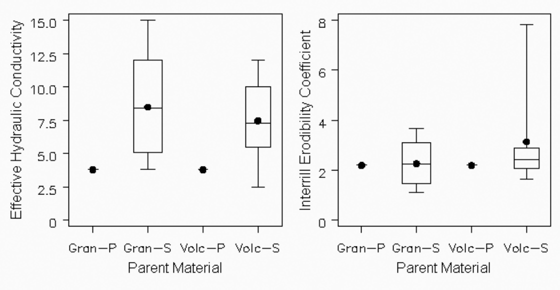

Figure 5. Box plots of effective hydraulic conductivity and interrill erodibility coefficient for granitic (Gran) and volcanic (Volc) soils from the parent material/soil texture-based parameter set (-P) and the site-specific parameter set (-S). Units for effective hydraulic conductivity are mm h^{-1}. Units for interrill erodibility coefficient are 10^6 kg s m^{-4}. The upper horizontal line is the maximum observation, the top of the box is the 75th percentile, the horizontal line in the box is the median observation, the bottom of the box is the 25th percentile, and the lower horizontal line is the minimum observation. The dot is the mean of the observations.

Table 4. Comparison of WEPP-predicted runoff using parent material/soil texture-based parameter set and using a site-specific parameter.[a]

Parent Material	Segment Length (m)	Road Gradient (%)	Rainfall Runoff Events ($year^{-1}$) PM/S-Based Parameters	Rainfall Runoff Events ($year^{-1}$) Site-Specific Parameters	Snowmelt Runoff Events ($year^{-1}$) PM/S-Based Parameters	Snowmelt Runoff Events ($year^{-1}$) Site-Specific Parameters	Runoff (mm $year^{-1}$) PM/S-Based Parameters	Runoff (mm $year^{-1}$) Site-Specific Parameters	Change (%)
Granitic	25	2	2.5	1	4.1	0.47	54	19	-81
		8	3.1	1	4.3	0.67	58	11	-80
	105	2	2.5	1	4.1	0.47	50	8.1	-84
		8	3.1	1	4.3	0.67	56	10	-82
Volcanic	25	2	2.4	1.1	3.9	0.90	53	14	-73
		8	3.0	1.2	4.3	1.1	56	16	-71
	105	2	2.4	1.1	3.9	0.90	49	12	-76
		8	3.0	1.2	4.3	1.1	54	15	-73

[a] PM/S = parent material/soil texture.

site-specific parameter values rather than the parent material/soil texture-based values to illustrate model prediction differences.

VARIABILITY OF HYDRAULIC CONDUCTIVITY AND INTERRILL ERODIBILITY

The effective hydraulic conductivity for the granitic soil ranged from 4.8 to 15 mm h^{-1} or +61% and -48% of the average (fig. 5). Corresponding variations for the volcanic soils were 2.5 to 12.1 mm h^{-1} or +57% and -66%. Rhee et al. (2011) reported coefficients of variation for effective hydraulic conductivity ranging from 37% on unvegetated top soil at a surface coal mining site in Montana to 86% on a nearby control site. Ziegler and Giambelluca (1997) reported a coefficient of variation of 52% from 18 forest road surfaces in Thailand. We attribute these variations to spatial variability of the soil. This degree of spatial variability occurs on both undisturbed sites and on what would appear to be more homogeneous, highly compacted road surfaces.

The coefficient of variation for effective hydraulic conductivity was less than that for runoff: 37% to 40% for effective hydraulic conductivity versus 47% to 52% for runoff. The lower coefficient of variation was an indication that the WEPP model removed a portion of the runoff variability due to soil moisture and saturation differences among the rainfall simulation plots.

The interrill erodibility coefficient for the granitic soil ranged from 1.22×10^6 to 3.79×10^6 or +57% and -66% of the average (fig. 5). Volcanic soil values were 1.62×10^6 to 4.44×10^6 or +80% and -34%. Foltz et al. (2009) reported a coefficient of variation for interrill erodibility of 27% for a reopened forest road. Elliot et al. (1989) found a coefficient of variation for interrill erodibility of 67% for a cropland sandy soil and 33% to 50% for a cropland loamy sand soil.

Unlike the reduction of variability in effective hydraulic conductivity compared to runoff, the coefficient of variation for interrill erodibility coefficient was greater than that for the sediment mass: 40% to 62% for erodibility coefficient versus 20% to 36% for sediment mass. In this case, the WEPP model predictions were not able to reduce the inherent sediment mass variability.

WEPP PREDICTIONS USING PARENT MATERIAL / SOIL TEXTURE-BASED PARAMETERS COMPARED TO SITE-SPECIFIC PARAMETERS

Tables 4 and 5 present the WEPP model predictions when using the parent material/soil texture-based parameter set and the site-specific parameter set. The statistically significant change in effective hydraulic conductivity from 3.8 to 9.3 mm h^{-1}, an increase of 145%, for granitic soils resulted in an average annual runoff reduction of 82%, while the volcanic soils increase from 3.8 to 7.5 mm h^{-1}, an increase of 97%, resulted in an average annual runoff reduction of 73%. The number of runoff events from rainfall and from snowmelt in 30 years also had a large change. Both parent materials averaged seven runoff events per year when using the parent material/soil texture-based parameter set, while they averaged only two runoff events per year when using the site-specific parameter set. Most of this decrease was attributable to fewer snowmelt runoff events.

Both parent materials had lower predicted average annual sediment yield when using the site-specific parameter set than when using the parent material/soil texture-based parameter set. The granitic parent material soils had 85% less sediment, while the volcanic soils had 78% less sediment. These decreases were similar to those for runoff.

Grismer and Hogan (2004) reported that runoff rates and sediment yields from Lake Tahoe road cuts were greater from volcanic soils than from granitic soils for nearly all cover conditions. Inspection of tables 4 and 5 indicates that the site-specific parameter set predictions were more representative of their observations than the parent material/soil texture-based parameter set predictions. For example, predicted sediment yield for volcanic soils was 5% higher than for granitic soils using the parent material/soil texture-based parameter set. However, when using the site-specific parameter set, the predictions for volcanic soil were 62% higher than for granitic soils.

Table 5. Comparison of WEPP-predicted sediment yield using parent material/soil texture-based parameter set and using a site-specific parameter.[a]

Parent Material	Segment Length (m)	Road Gradient (%)	Sediment Yield (kg $year^{-1}$) PM/S-Based Parameters	Sediment Yield (kg $year^{-1}$) Site-Specific Parameters	Change (%)
Granitic	25	2	24	3.7	-85
		8	83	14	-87
	105	2	130	15	-83
		8	530	74	-86
Volcanic	25	2	24	5.8	-76
		8	84	22	-80
	105	2	140	25	-75
		8	560	120	-79

[a] PM/S = parent material/soil texture.

SITE-SPECIFIC AND PARENT MATERIAL / SOIL TEXTURE PARAMETER DIFFERENCES AT OTHER LOCATIONS

This study focused on the improvement in model predictions by using a site-specific parameter set rather than a parent material/soil texture-based parameter set at Lake Tahoe. Snowmelt climates, such as Lake Tahoe, have snowmelt rates that typically range from 1 to 10 mm h^{-1}. Effective hydraulic conductivity values on road surfaces are often near this range, which makes the amount of snowmelt runoff sensitive to changes in this parameter. Inspection of table 4 shows the reduction in number of snowmelt events when changing from 3.8 to 9.3 mm h^{-1}. In the Lake Tahoe example, the change for granitic soils was from four events per year to one event every two years. Conversely, significant erosion-producing rainfall events have intensities in the 75 mm h^{-1} and above range. These events are less influenced by changes in effective hydraulic conductivity than are the snowmelt events. The balance between snowmelt events and rainfall events at other locations will determine the importance of changes between parent material/soil texture-based and site-specific road effective hydraulic conductivity.

IMPACT OF VARIABILITY OF MEASURED EROSION ON MODEL PREDICTIONS

Laflen et al. (2004) reported on a method to apply the Nearing et al. (1999) conclusion that soil erosion data measurements have an inherent variability that is an inverse power function of the mass of sediment per unit area. The suggested method is to place a 95% confidence interval around the WEPP-predicted mass of sediment based on the Nearing et al. (1999) conclusion. The confidence interval applies only to the mass of sediment.

Based on the results from the current study and the previously referenced studies, we suggest that WEPP users investigate model prediction sensitivity by making predictions at both +50% and -50% of the recommended effective hydraulic conductivity values. This provides the user with an insight into the range of model predictions based on the inherent spatial variability of effective hydraulic conductivity. Our method illustrates the prediction range for both runoff and sediment production.

We chose a road in the Glenbrook Creek watershed with an 8% gradient and water diversion structures spaced 105 m apart to illustrate our recommendation of making predictions at ±50% of the effective hydraulic conductivity. The selected road was the steepest gradient and longest spacing from table 5. Table 6 displays the predictions of runoff and sediment mass for both the parent material/soil texture and the site-specific effective hydraulic conductivity at ±50%. For both predicted runoff and predicted sediment yield, the overlap of the two ranges was small. For this example, our recommendation resulted in a range of predictions of approximately ±75% of the mean for both runoff and sediment yield. The range predicted by Laflen et al. (2004) was ±68% for sediment yield. The Laflen et al. (2004) method does not predict a range for runoff.

Table 6. Range of WEPP-predicted runoff and sediment yield using ±50% of parent material/soil texture-based and ±50% of site-specific effective hydraulic conductivity.[a]

	Runoff (mm year^{-1})		Sediment Yield (kg year^{-1})	
Parent Material	PM/S-Based Range	Site-Specific Range	PM/S-Based Range	Site-Specific Range
Granitic	130-32	33-4	1400-300	250-36
Volcanic	130-31	43-7	1500-320	370-56

[a] PM/S = parent material/soil texture.

We suggest that WEPP model users investigate the range of predictions that are a result of the inherent variability of erosion measurements used to determine model parameters. Whether the Laflen method or our method is more suitable is beyond the scope of this study.

PROCESS-BASED MODELING IMPLICATIONS

The large differences in runoff and sediment yield predictions between the parent material/soil texture-based parameter set and the site-specific parameter set for the granitic parent material soil suggest a large difference among granitic soils. Both the Welsh (2008) study in the Pike's Peak batholith and a post-fire study in four western U.S. states (Elliot et al., 2010) also concluded that WEPP erosion parameter sets for granitic soils might be different from one granitic batholith to another. These examples of widely varying erosion parameters from granitic parent material locations suggest that erosion parameters may not be consistent within similar geologies, or may be influenced by other management factors, such as time since grading or traffic levels, that were not evaluated in this study.

In a study of Lake Tahoe road cut slopes and ski areas, Grismer and Hogan (2005b) concluded that runoff and sediment yields from bare soils were strongly soil-type dependent. Our results agree that infiltration and interrill erosion were soil-type dependent, but we conclude that soil-type alone was not a sufficient predictor of infiltration and interrill erosion for forest roads. Ziegler et al. (2001) and analyses of the Rocky Mountain Research Station's 20 years of rainfall simulation on forest roads (R. Foltz, unpublished data, 2011, USDA Forest Service, Rocky Mountain Research Station) suggest that neither soil texture nor parent material are the best indicators of effective hydraulic conductivity and interrill erosion. Surface preparation in the form of amount of traffic, timing of road maintenance, and prior wetting and drying cycles appear to be more promising than soil texture and parent material. This Lake Tahoe study appears to be consistent with that viewpoint.

Process-based models mathematically describe the important processes that control infiltration and erosion, which results in a set of parameter values that need to be determined by experimentation. One of the major benefits is that the form of the prediction equation is known and only the coefficients of the prediction equations need to be determined by experiment. A second benefit is that the model can be used in locations other than where it was developed. Regression models, on the other hand, do not presuppose the form of the prediction equation but rely on site-specific experiments to reveal both the form and coefficients of the prediction equation. If, however, as this study suggests, erosion parameter sets developed at a specific location for one set of geologic parent material and soil texture differ greatly from those developed at a different location for the same set of geologic parent materials and soil texture, then the perceived advantage of a process-based model over a regression model is reduced. In this case, both models require location-specific studies to determine erosion parameter sets.

CONCLUSIONS

Runoff from the simulated rainfall exhibited a coefficient of variation from 8% to 10%. Sediment mass had a larger variation of 20% to 36%. These ranges are lower than those reported for natural rainfall events. The range has important implications for model predictions that derive erosion parameters from rainfall events.

For the granitic parent material soils at Lake Tahoe, the site-specific effective hydraulic conductivity was 9.3, a 145% increase compared to the parent material/soil texture-based value of 3.8 mm h^{-1}. Lake Tahoe volcanic soil effective hydraulic conductivity changed from 3.8 to 7.5 mm h^{-1}, an increase of 97%. The site-specific granitic soil effective hydraulic conductivity was statistically different from the parent material/soil texture-based value, but the volcanic soil value was not.

The granitic parent material site-specific interrill erodibility coefficient of 2.2×10^6 was greater than the parent material/soil texture-based value of 2.0×10^6 kg s m^{-4}, a 10% increase. The volcanic parent material site-specific interrill erodibility coefficient of 3.1×10^6 was greater than the parent material/soil texture-based value of 2.0×10^6 kg s m^{-4}, a 36% increase. Neither of the site-specific interrill erodibility coefficients were statistically significant compared to the parent material/soil texture-based values.

WEPP model predictions of runoff and sediment yield were reduced by using site-specific parameters compared to using parent material/soil texture-based parameters. The WEPP model was used to predict runoff and sediment yield using climate and road characteristics typical of the Lake Tahoe basin. Model results using the parent material/soil texture-based parameter set were compared to using the site-specific parameter set. Average annual runoff was 82% and 73% less for granitic and volcanic soils, respectively, when using the site-specific values compared to the parent material/soil texture-based values. Predicted average annual sediment yield was 85% and 78% less for granitic and volcanic soils. The number of runoff events predicted by each of the two parameter sets differed. The parent material/soil texture-based parameter set predicted seven runoff events from rain and snow per year. The site-specific parameter set predicted two rain and snow runoff events per year.

Erosion model predictions are based on parameters estimated from either natural rainfall or simulated rainfall. Even with care taken to reduce variations from plot to plot in simulated rainfall studies, there is an inherent variability in the amount of runoff and sediment mass from one plot to another. This variability translates to variability in the model parameters. Based on this Lake Tahoe study and other road studies, we suggest that WEPP users investigate predictions using ±50% of the effective hydraulic conductivity. For a typical native-surface road at Lake Tahoe, this method resulted in a WEPP model prediction range of approximately ±75% of the mean for both runoff and sediment mass.

Using locally measured soil properties for input into the WEPP model, runoff and erosion predictions decreased in the Lake Tahoe basin, where snowmelt is an important runoff-producing mechanism. The values of measured road effective hydraulic conductivities and snowmelt rates are similar (1 to 10 mm h^{-1}). In these conditions, small changes in effective hydraulic conductivity had large changes in annual runoff. In locations where high-intensity rainfall dominates erosion processes, small changes in effective hydraulic conductivity will have less impact. Applications of the Lake Tahoe example to other locations need to account for the balance between the importance of snowmelt and rainfall events.

Future erosion modeling studies on unpaved forest roads should focus on determining better proxies for erosion parameters. On road surfaces, parent material and soil texture are marginal indicators of effective hydraulic conductivity. Levels of traffic, time since road grading, and wetting and drying cycles may be better indicators. We suggest that these indicators be included in future rainfall simulation studies of water erosion parameters.

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